ASHRAE Research Strategic Plan 2010- 2018

Navigation for a Sustainable Future

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

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Overview and Vision

The ASHRAE Research Strategic Plan for 2010-2018 consists of 11 strategic goals that were chosen to address technical challenges that limit our ability to maximize building performance, energy efficiency and indoor environmental quality while minimizing our impact on the environment. Meeting any of the 11 strategic goals will require coordinated effort among multiple technical committees.

Who is ASHRAE?
ASHRAE, founded in 1894, is an international organization of 55,000 members. It is the world's foremost technical society in the fields of HVAC&R. Through its meetings, research, standards writing, publishing and continuing education, the Society helps keep indoor environments comfortable and productive, deliver healthy food to consumers and preserve the outdoor environment.

ASHRAE's Research Vision
ASHRAE conducts timely research to remain the foremost, authoritative and responsive international source of technical and educational information, standards and guides on the interaction between people and the indoor and outdoor environment through the operation of HVAC&R systems in buildings and other applications.

Purpose of the Plan
The ASHRAE Board of Directors requires that a Strategic Plan for ASHRAE Research be prepared and updated every five years. The plan identifies key HVAC&R research needs and provides that information to ASHRAE members and technical committees as guidance while they develop research projects and to the Research Administration Committee as it approves and funds research proposals. The Research Plan is not meant to take the initiative for research design from the cognizant committees, but rather to use input from ASHRAE members to identify strategic research needs that are appropriate for many committees to collaborate on, that may require larger budgets, and for which additional outside funding may be available to supplement ASHRAE's budget.

Navigating the Plan
For each goal, specific objectives are given and the current technical challenges to be addressed by the research are explained. This is followed in each case by a discussion of the needed research. As the goals vary significantly in their scope, current state-of-the-art and technical challenges, the needed research also varies widely. Many of the goals are outcome-based, which means that rather than specifying the type of research that should be conducted, the outcomes in terms of performance are specified. This approach will provide flexibility and encourage innovation in research. Needed research for other goals is specified in terms of specific projects that are needed. In all cases, though, specific projects will be defined and scoped by one or more ASHRAE technical committees. The Research Administration Committee in turn will evaluate and prioritize these topics against the plan so the topics that best address these goals are funded first. The plan will be updated every five years following the same broad input collection process so that it remains pertinent in a rapidly changing HVAC&R research environment.

Development of the Plan
The plan was developed collaboratively over a three-year period by ASHRAE's Research Advisory Panel. Input was provided by ASHRAE chapter members, technical committee (TC) members, research fund contributors and representatives from HVAC&R-related organizations throughout the process via surveys, meetings, forums and e-mail. Once an initial list of goal topics was formed based on the input and deliberations of the Research Advisory Panel, ad hoc committees, primarily made up of volunteers from TCs, were formed to work on each of the goal topics. Goal topic descriptions developed by the ad hoc committees underwent several review and editing cycles prior to final approval by ASHRAE Technology Council.

Research Advisory Panel Members

The Research Advisory Panel members are listed below. Research Advisory Panel members that served over the duration of the panel's existence each championed one of the goals and, for those members, their goal number is listed parenthetically.

Martha Hewett, Center For Energy and Environment, Minneapolis, MN (1)
Jim Brodrick, Ph.D., U.S. Department of Energy, Washington, D.C. (2)
Larry Markel, Sentech Inc, Knoxville, TN (3)
Steve Taylor, P.E., Taylor Engineering LLC, Alameda, CA (5)
Hywel Davies, Ph.D., CIBSE, London, United Kingdom (6)
Jeffrey Spitler, Ph.D., P.E., Chair, Oklahoma State University, Stillwater, OK (7)
Zahid Ayub, Ph.D., P.E., Isotherm Inc, Arlington, TX (8)
Wayne Reedy, Retired, Monticello, IN (9)
Alison Kwok, Ph.D., University of Oregon, Eugene, OR (10)
Jim Braun, Ph.D., Purdue University, West Lafayette, IN
Donald Colliver, Ph.D., P.E., University of Kentucky, Lexington, KY

In addition, the panel was augmented by two other ASHRAE members who championed goals:
William Fisk, Lawrence Berkley National Laboratory, Berkley, CA (4)
Richard Fox, Honeywell (11).

Goal 1:

Maximize the actual operational energy performance of buildings and facilities.

Objective: Sharpen the understanding of the technical, economic, institutional and human factors that contribute to the gap between potential and actual energy performance. Develop additional tools and methods to maximize the actual energy performance of buildings. Document the energy savings and improvements in performance that can be realized through use of these tools and methods.

Technical Challenges: Available data strongly suggest that the actual energy use of buildings is often higher than design energy use and/or higher than necessary to deliver the required services. At the same time, indoor air quality, thermal comfort, noise and other performance attributes (e.g., infection control, food refrigeration temperatures) may not meet target levels. Many factors contribute to this, including but not limited to:

General industry and decision-making factors

1) Increasing complexity of building enclosure, mechanical, control and other systems without a corresponding increase in the sophistication and ease of use of tools and building operator knowledge and training to manage this complexity.
2) Aggressive energy standards not coupled with standards for actual energy use and non-energy performance of the building as constructed and operated.
3) “One-off” building design and construction, which prevents optimization of design and execution in prototypes followed by high levels of quality control in production.
4) Focus on first costs and low bid in selection of design firms and contractors and in subsequent selection of design features. Difficulty for decision-makers to evaluate quality, value (quality/price), and life cycle costs in design and construction, leading to an overemphasis on price in selection.

Design and construction factors

1) Failure to integrate design across disciplines, leading to sub-optimal designs.
2) Lack of optimization of control strategies.
3) Focus on energy use without sufficient attention to building performance (comfortable, productive working/learning environment, good Indoor air quality (IAQ), lack of mold problems, durability, etc.)
4) Lack of sufficient feedback to design professionals on the effectiveness of their designs.
5) Lack of sufficient site-specific documentation and training to communicate the design intent to building operators. Difficulty for decision-makers to quantify the value of such documentation and training.
6) Insufficient quality control (e.g., peer review, commissioning) in design and construction; difficulty for decision-makers to reliably quantify the benefits of commissioning and reliably compare quality and value of commissioning providers, leading to an overemphasis on price in selection.

Operation and maintenance factors

1) Lack of meaningful feedback to owners, facility managers and operators on energy use.
2) Lack of sufficient feedback on other performance parameters to ensure that energy savings are not achieved at the expense of functionality.
3) Inadequate benchmarks for energy use (e.g., not sufficiently matched to the target building in terms of climate, size, age, space uses, processes or types of Heating, ventilating, air conditioning and refrigerating (HVAC&R) systems, nor disaggregated by end use).
4) Inadequate benchmarks for non-energy performance parameters.
5) Prioritization of short-term Operation and maintenance (O&M) cost control over long-term management of energy use and building performance. Complaint-driven Operation and maintenance (O&M) focused on quick fixes rather than resolution of underlying issues. Failure to employ predictive and preventive maintenance approaches. Difficulty for owner to determine whether the maintenance contractor does the work that is actually needed and does it correctly.
6) Lack of sufficient diagnostic tools and easy-to-use, intuitive interfaces to facilitate evaluation of system operation by Operation and maintenance (O&M) staff. Lack of sufficient training of Operation and maintenance (O&M) staff/contractors to enable them to optimally operate and maintain buildings and systems. Operation based on rules of thumb from prior experience or previous operator. Insufficient number of Operation and maintenance (O&M) staff to allow proactive operation and maintenance.

7) Difficulty for decision-makers to reliably evaluate Operation and maintenance (O&M) staff/contractor skills and knowledge or to quantify the value of these skills/knowledge.

8) Under-utilization of continual commissioning or periodic retro-commissioning to reduce energy use and improve building performance.

9) Lack of ongoing systematic feedback from occupants regarding building performance.

Needed Research: Sample research projects that address these challenges include:

1) Accelerate application of building information modeling (BIM), and to ensure that BIM systems are designed to meet information needs for commissioning and operations and maintenance. (Coordinate with building SMART alliance, Construction Operations Building Information Exchange).

2) Education and outreach to understand decision-makers' perspectives on investments in energy efficiency and in design features that enhance building performance. (Coordinate with (U.S. Department of Energy) DOE Energy Alliances).

3) Improve building energy labeling systems. Develop and validate practical methods to model and measure building energy and non-energy performance. Metrics must be relevant to building owners and would likely vary by market segment (e.g., student performance for schools, control of airborne infections for hospitals, worker productivity/absenteeism for owner-occupied office buildings, comfort for leased office buildings).

4) Develop more accurate methods to relate building energy simulation models to actual building energy use.

5) Improve alignment between energy standards, energy models and utility bills.

6) Document actual energy savings and building performance improvements realized through integrated design.

7) Document actual energy savings and performance impacts for selected energy measures, and identify key design, construction, installation and operational factors that influence savings and performance.

8) Document the impact of design alternatives on building performance metrics important to owners.

9) Expand the capabilities of dynamic simulation models to integrate modeling of building loads, mechanical systems, electrical systems and controls. These models could be used to develop improved control strategies and fault detection and diagnostics algorithms, or as the basis for a building simulator used for Operation and maintenance (O&M) training or a building emulator used to test control systems.

10) Identify optimum and practical near-optimum control strategies for various systems (simulation followed by field validation). Develop additional "best practice" sequences of operation to improve the quality of control design and implementation.

11) Further quantify and optimize the energy savings and other benefits of commissioning and retro-commissioning for HVAC&R, enclosures, lighting and service water heating. Study persistence of savings. Develop effective commissioning procedures for newer and emerging technologies (e.g., integrated daylight-dimming and automated window shading systems, wireless controls, smart grid strategies, etc.).

12) Quantify and optimize the energy savings and other benefits of pro-active maintenance approaches. Develop automated diagnostics algorithms for more types of systems and document the energy savings and other benefits they provide. Develop successful processes for moving from reactive to proactive maintenance.

13) Develop automated (and semi-automated) tools to support commissioning (Cx) and retro-commissioning (RCx). Development of tools to: Run continuous diagnostics on overall system- and building-level performance (not just Fault Detection & Diagnostics (FDD) of components or equipment); run "pushbutton" performance checks to check key status points on-demand; optimize setpoints and operating parameters; effectively manage the data generated during commissioning. Standardization of Building Automation System (BAS) trend data file formats to facilitate extraction and processing of trend data by Cx/RCx authorities, building operators and others. Research to develop and demonstrate tools and processes that allow operators to conduct "commissioning" activities as part of routine operating activities.

Goal 2:

Progress toward Advanced Energy Design Guides (AEDG) and cost-effective net-zero-energy (NZE) buildings.

Objectives: Developing net-zero-energy buildings can produce technologies and designs for improving efficiency of energy use in all buildings. In the United States, the current installed base of about 5 million commercial buildings and 120 million residential dwelling units consumes about 40 quads of energy every year. By 2030, floor space in commercial buildings is expected to grow by 48 percent and residential units will grow by 27 percent.[1] Even limited deployment of NZE buildings in this timeframe will have a beneficial effect by reducing the pressure for additional energy and power supply and the concomitant reduction of green-house gas emissions. A further need related to advanced energy designs is development of energy efficiency retrofit systems for the current installed base. While NZE may not always be economically practical, especially for retrofit, aspects of NZE designs will offer significant energy reduction opportunities.

Objectives for the strategic research plan period of 2010-2018 support developments and improvements of Advanced Energy Design Guides (AEDG) for near-term impact. The objectives also lay the groundwork for achieving NZE buildings after 2018.

1) Provide AEDG on techniques to achieve by 2012 a 50 percent reduction in annual energy consumption relative to ANSI/ASHRAE/IES 90.1-2007 [or other baseline] – all building types.

2) Provide AEDG on techniques to achieve by 2018 a 70 percent reduction in annual energy consumption relative to Standard 90.1-2007 [or other baseline] – four commercial building types.

3) Coordinate with (Energy Information Administration) EIA at DOE on enhancements to all buildings surveys by 2018.

4) Incorporate solar-thermal design principles into AEDG for one building type by 2018.

5) Achieve use of Standard 90.1 by 75 percent of practitioners by 2015.[2]

6) Publish design approach for energy reduction by retrofitting buildings by 2018.

7) Obtain energy use of "as-built" versus "as-designed" for 12 operating commercial buildings by 2018.

1 From National Science and Technology Council Subcommittee on Building Technology R&D at http://www.bfrl.nist.gov/buildingtechnology/ or http://tinyurl.com/5eugok

2 Note, recently published Standard 189.1, Standard *for Design of High-performance, Green Buildings except Low-Rise Residential Buildings*, should also be presented to practitioners and developed further for use in this strategic plan.

Technical Challenges: Complexity and interaction among building subsystems represents an essential challenge to NZE design solutions; detailed energy modeling is expensive and may still miss important matters. Design guides are convenient, but not optimal. Furthermore, energy reduction methods, systems and operations are highly dependent on the climactic conditions in which the building is located; this increases the complexity of developing energy design guides that capture dependence on climate and weather variability.

Specific shortcomings that need to be addressed include the following:

1) Variability in building loads is not well characterized, which leads to variability of performance for any one (fixed) design; passive or adaptive management of building load variability is a challenge, but would improve overall energy performance.

2) Current installed base of buildings will dominate energy use during the strategic plan period and beyond; technical challenge is development of cost-effective retrofit approaches that combine technology, operations, and maintenance.

3) Diffuse community of relatively small design companies leads to long delays in bringing a large community in alignment with new standards and practices.

4) Building technology combines the often conflicting characteristics of engineering and architecture to produce a functional, high performance, aesthetically attractive system.

Needed Research: Meeting this goal requires both ASHRAE-funded research projects and research projects funded by other entities such as the federal government.

ASHRAE funded projects (examples) to achieve objectives

1) Develop design methodologies for the incorporation of solar-thermal cooling, heating and dehumidification technologies and their integration with other building components including HVAC&R, water heating and envelope systems. Methodologies should be developed for new build and retrofit.

2) Identify and assess solar-thermal energy technologies that can cost-effectively provide the energy required to fill the gap between energy reduction measures and remaining thermal energy demand to achieve

NZE building performance. For retrofit applications, the design guides should identify approaches to reduce energy use to the extent possible, even if NZE performance is not achievable.

3) Continue to support the AEDG series.

4) While NZEB refers to net-zero annual energy use, it neglects the benefits of thermal or electrical storage or of using energy during night or off-peak times to increase use of renewable or other clean energy sources. Develop a metric other than annual NZEB that takes such source energy characteristics into account.

Non-ASHRAE funded projects (examples) to achieve objectives

1) Develop a design approach that incorporates statistical characterization of variable building loads, e.g., occupancy, lighting, plug loads, weather and climate. Design approach should be able to predict mean aggregate energy use and variability in a statistical sense (e.g., 1-σ or 2- σ) for different scenarios; the approach should be able to be used as a tool for design trade-off studies and to evaluate what-if scenarios.

2) Develop envelope strategies for existing buildings and simulate building performance; catalog strategies as design guidelines for different building types. For retrofit applications, parameterize performance metrics by region, climate, life cycle, etc.

3) Develop methodologies for new or existing buildings to measure critical parameters so that actual building performance can be compared to predicted performance. In the case of new buildings, sensors for parameter measurement can be incorporated into the building design. For retrofit applications, the sensor suite must be installed in a cost effective manner without adversely causing degradation in building performance. Minimization of purchase and installation cost is important.

Goal 3:

To reduce significantly the energy consumption for HVAC&R, water heating and lighting in existing homes.

Objectives: The U.S. housing sector consumes approximately 11 quads of energy annually (4.4 for heating, 0.9 for air conditioning, 2.2 for water heating, 2.8 for lights and appliances, 0.5 for refrigeration). The objective is to reduce the energy for low-rise residential space conditioning and water heating while maintaining or improving the homes' comfort and indoor air quality. While current residential energy efficiency measures are well-understood by the industry, the average home is not energy efficient. In addition to developing improved energy efficiency technologies, improvements are needed in deployment of new and existing techniques. This includes educating and motivating homeowners, facilitating the identification of appropriate measures and properly training contractors to install them and financing retrofit energy efficiency.

Technical Challenges: There are both technology and deployment challenges.

Technology challenges

1) "Technology" includes materials, equipment, practices and systems, particularly for retrofits. "Materials" could include better ways to apply insulation to an existing home. "Equipment" covers such items as improved air-conditioning efficiency or perfecting new types of appliances, such as heat pump water heaters. "Systems" focuses on having appliances, controls and building structures work well together, a sort of residential integrated design and commissioning process. This goes beyond eliminating built-in bypasses and air leaks; there's much more opportunity in improving the forced air distribution than the forced air equipment. The interaction between envelope, HVAC&R, lighting and appliances should be better understood.

2) A significant technology challenge is that most of our equipment rating methods are (at best) obsolete, and ASHRAE must think about a collaborative role with the federal government to get funding to remedy this. The rating methods and the federal standards derived from them discourage innovation that would make a difference. Standards aren't really useful to figure out the energy budget of a house with a combination system or an integrated heat pump. Water heater standards systematically favor tank-less over tank type, because of a test artifact. We are not able to meaningfully compare energy use of a ground source heat pump (COP, EER) with a split system (HSPF, SEER), much less a mini-split.

3) A major challenge to development and adoption of improved materials or appliances is that there is no clear business model for product vendors to invest in their development or foster their implementation. The residential market is typically low-margin and high-volume, so a markedly different product represents a risk in terms of retooling costs for manufacturers, possible erosion of existing "conventional" product sales and having to compete for space in retail stores.

Deployment challenges

1) Homeowners are often unaware of energy consumption and waste, and what improved-efficiency represents in terms of added comfort and potential money savings. Some websites, especially utility-sponsored ones, help homeowners go through a checklist of energy-related items in the home, provide some energy audit diagnostics and list qualified contractors. These websites are usually not well-utilized, possibly because of lack of publicity, lack of interest by homeowners or the results not being particularly useful. The need to motivate homeowners and to provide them with actionable information is not being met. ASHRAE should work closely to identify research needs of those on the "front line" such as Air-Conditioning Contractors of America (ACCA), Home Energy Rating Systems (HERS), Building Performance Institute (BPI), weatherization contractors, etc.

2) Economics affects deployment. Residential retrofit jobs are small, typically repair projects. The "transaction cost" is high, so to be profitable to vendors and affordable to homeowners, neighborhood energy retrofit approaches would be more economic. However, the energy efficiency market does not "purchase" in this way, except for low-income weatherization programs. A means of delivery that can reduce the homeowners' costs – and inconvenience – could address this.

3) Additional field studies are needed of residential occupant behavior, perceptions and actual use to understand the most promising retrofit paths for each significant housing stock type, by climate. Slab-built with equipment in the attic has different energy losses

than basement houses with ducts below the living space. No forced air house can maintain the same temperature upstairs as downstairs. We don't even have an adequate taxonomy of the housing stock (types, and numbers per type). Ideally, a house doctor (potentially a HERS rater), not a building scientist, could be trained to identify and deal with the most common housing types in a particular metro area. New England tenements are not the same as New York row houses.

Needed Research

Technology improvements

1) Integrated space conditioning and water heating appliances, following both electric and fossil paths.
2) Improved insulation materials and systems for retrofit.
3) Tighter "box" HVAC&R equipment with improved gaskets and seals and improved "box" insulation, especially when boxes are located in unconditioned spaces.
4) Dispatchable appliances that can take advantage of utility price signals or other aspects of the "Smart Grid" in scheduling their operation.
5) Better control systems, including programmable thermostats and remotely accessible thermostats (e.g., Smart Grid- or demand response-compatible).
6) Improved humidity control
7) More efficient space heat, water heat, air-conditioning systems. The big savings may be from better energy distribution rather than marginal gains in SEER.
8) Better building simulation ventilation models, to specify the type and size of vents and fans for a specific building
9) An improved understanding of the interaction between envelope, HVAC&R, lighting and appliances can be used to improve both standard installation procedures and codes.
10) Development of simple home energy management systems or home energy use tracking and report/display (to the homeowner) systems.
11) Metrics for home energy efficiency that recognize the time-value of energy use
12) Most home energy retrofits focus on low-cost weatherization or furnace tuning. Develop methods to lower the cost of "deep retrofit" measures that reduce energy use by over 40 percent.

Deployment improvements

1) Energy efficiency guide for existing residential buildings.
2) Quality assurance checklist for energy-related projects.
3) Better (e.g., accurate but easily exercised) assessment procedures – such as residential building energy efficiency rating systems.
4) Publicity and education campaigns (including K-12) to inform the public about energy efficiency and what they can do to implement energy saving measures in the home.
5) Programs for encouraging residential energy efficiency retrofits, such as reporting requirements when selling a house or mortgage qualification credits for lower utility costs.
6) Innovative policies, programs and training integrating efforts of U.S. Department of Housing and Urban Development (HUD), DOE, U.S. Environmental Protection Agency (EPA), housing authorities and local code bodies, etc.
7) Contractor training.
8) Development of mobile weatherization vans to perform minor insulation and weather stripping.

Goal 4:

Significantly advance our understanding of the impact of indoor environmental quality (IEQ) on work performance, health symptoms and perceived environmental quality in offices, providing a basis for improvements in ASHRAE standards, guidelines, HVAC&R designs and operation practices.

Objectives: The objectives for this goal are divided into two priority levels:

1) 1st priority – must address: Quantify the impact of outdoor air (OA) ventilation rates and thermal comfort parameters (air temperature and velocity, radiant temperature, humidity) on the following outcomes:
   - high level cognitive, e.g., decision making, performance (highest priority);
   - speed and accuracy of simulated office work tasks, e.g., proof reading, typing;
   - perceived indoor environmental quality (PIEQ); and
   - acute building-related health symptoms.

2) 2nd priority – desirable to address: Quantify the impact of particle and/or gas-phase air cleaning, noise levels and other IEQ conditions or control measures on the same outcomes as listed above.

The objectives stated above clearly imply several hypotheses, for example that OA ventilation rates affect aspects of work performance, health and PIEQ. The research should test these hypotheses. Additionally, to the degree possible, the research should develop information to quantitatively relate the selected IEQ parameters with the identified performance, health and perception outcomes.

Technical Challenges: ASHRAE's strategic research efforts must support ASHRAE's mission, which is "To advance the arts and sciences of HVAC&R to serve humanity and promote a sustainable world." In most buildings, the major purpose of HVAC&R is to provide acceptable IEQ that maintains the comfort, satisfaction, health, productivity and promotes the education of the building's occupants. The primary dimensions of IEQ are: thermal comfort conditions (temperature, air velocity, humidity); types and concentrations of indoor air pollutants; acoustic and vibration conditions; and lighting conditions. Of these, ASHRAE has the greatest impact on thermal comfort conditions and indoor air pollutants, with a lesser but still significant impact on acoustic and vibration conditions.

Prior research has provided substantial evidence that changes in IEQ conditions and OA ventilation rates, within the normally encountered ranges, can affect PIEQ (e.g., thermal comfort sensation, satisfaction with indoor air quality), the risks of experiencing various adverse health effects and the speed and accuracy of work performance. The evidence of effects of indoor air temperatures and OA ventilation rates on PIEQ, health and work performance is most robust. However, there are many limitations to our related existing knowledge. Much of this knowledge is based on cross sectional studies of sets of buildings with variable IEQ, work and psychosocial factors, making it difficult to confidently determine the influence of any single factor. Experiments, i.e., deliberate changes in specific IEQ parameters, within occupied buildings have provided findings with less ambiguity, but these studies are expensive and rarely performed and still suffer from less than ideal control of IEQ factors. Experimental research performed in environmental chambers that simulate typical occupied spaces has enabled precise control of IEQ factors and precise control of the occupants present and their activities. Environmental chamber research has proven useful in assessing how IEQ affects PIEQ, acute health symptoms and work performance, although effects of IEQ on infrequent outcomes (e.g., absence rates) and the impacts of long-term indoor exposures cannot practically be studied in environmental-chamber studies. Also, the extent to which findings from environmental chamber studies apply to workers in real buildings, e.g., where work motivation is different, is uncertain. Despite these limitations, environmental chamber studies provide opportunities for well-controlled reasonable-cost research on how a range of IEQ factors affect people.

Needed Research: In the development of a recommendation of priority research pertaining to the effects of IEQ, the authors considered the relative importance of different IEQ factors and human outcomes to ASHRAE's mission. Studies of the effects of OA ventilation rates and thermal comfort conditions were considered the highest priority for ASHRAE because OA ventilation rates and thermal conditions are highly dependent on HVAC&R. Research on the effects of gas- and particle-phase air cleaning were considered a high priority, despite the absence of clear evidence of effects on health and performance, because a survey of ASHRAE members indicated a strong interest in the effects of air cleaning. Research on the effects of indoor sound levels was considered a slightly lower priority, but still significant given the high prevalence of acoustic-related complaints by occupants of buildings. Among the range of possible human outcomes, work performance was the highest priority because of its clear economic implications likely to affect actual HVAC&R practice. Health outcomes were considered only slightly lower in priority. Among various aspects of work performance, high-level cognitive performance, e.g., complex decision making, was considered of higher priority than speed and accuracy of simulated work tasks (e.g., typing) or indirect indicators of performance such as reaction times. High-level cognitive performance was considered a priority because most real work was judged to be complex and because tests of high level cognitive performance are available but have not been significantly applied in IEQ research. The office work environment was selected as the most critical for research on how IEQ affects high-level cognitive performance. The environmental-chamber research approach was considered the highest priority because the environmental-chamber approach enables relatively economical highly-controlled experimental research on the effects of the priority IEQ factors. The environmental chamber(s) employed should be similar in appearance and occupancy to a typical indoor office space(s) and have typical indoor pollutant sources. Over the longer term, the findings of the highly-controlled research in environmental chambers recommended here should be subject to confirmations via field studies in occupied buildings.

Given the prioritizations discussed above, the goal and objectives in the first two sections of this document were developed. The following text elaborates further on the recommendations.

The potential for confounding error should be reduced to the degree possible via strong study designs. One approach is to base conclusions on changes in PIEQ, health, and performance outcomes within subjects, i.e., each subject should experience multiple IEQ conditions with all other factors held constant. Other strong experimental designs to achieve the same goal are acceptable.

Decision making performance has been assessed through computer-based tests that present subjects with complex life-like scenarios and have them make decisions. The scenarios may include some ambiguity or provide incomplete information and involve mild stress, much like real work. These tests have been employed over many years to study the impacts of licit and illicit drugs on decision making performance. Other methods of evaluating high level cognitive performance may be available and should be considered.

If research is performed on the effects of particle air cleaning, it may be best to utilize air drawn from a real office as we lack a sufficient understanding of particle sources in offices to emulate them in an environmental chamber. Because the particle concentrations in the real office will vary over time, it may be desirable to employ two simultaneously-occupied environmental chambers for the research. The two chambers would utilize different particle air cleaning systems.

Goal 5:

Support the development of ASHRAE energy standards and reduce effort required to demonstrate compliance.

Objectives: The primary objective of this research is to provide knowledge and tools to facilitate the continuing development of ASHRAE energy standards (the 90 series for new buildings and 100 series for existing buildings) and tools to assist designers in showing compliance.

Technical Challenges: ASHRAE energy standards continue to be developed by standing standards project committees (SSPCs) with ever increasing stringency. The increased stringency has placed pressures on both the developers of the standards and designers who must comply with them. For instance, earlier versions of the standards were, to a large extent, based on the judgment of SSPC members, but now that all the "low hanging fruit" have been incorporated into the standards, finding additional cost effective measures requires more detailed analysis which presents a challenge to the volunteer committee members with limited time and budgets. The push toward net NZEB buildings and the use of the standards in utility rebate and green building rating programs also presents challenges to the SSPCs since the standards were generally intended for building codes to establish minimum performance, not as performance metrics for high performing buildings. Users of the standard also are challenged by the increasing complexity of requirements and the lack of tools to help them demonstrate compliance.

Specific shortcomings that need to be addressed include the following:

1) The Energy Cost Budget Method (Chapter 11 of Standard 90.1) was originally developed to allow trade-offs to be made among prescriptive requirements, e.g., offsetting excess window area with more efficient lighting. In 1989, the procedure changed from fixed source energy area-based budgets (Standard 90B-1980) to "custom budgets" developed from the proposed design but adjusted to meet prescriptive requirements. The procedure included strict modeling rules to prevent "gaming" and attempted to be neutral with respect to design choices allowed by the prescriptive path. For instance, if water-cooled equipment were proposed, the baseline design also is water-cooled. The procedure works well for its intended purpose (to allow trade-offs among prescriptive requirements), but it did not work well as the basis of utility rebate and green building rating programs that rewarded exceeding the standard (e.g., exceeding 90.1 by x percent). Appendix G was developed to address the shortcomings, including loosening some modeling rules and creating a baseline that was more typical of standard practice rather than minimum code. Still, the percent-savings metric has been applied inconsistently (e.g., unregulated energy usage such as plug loads may or may not be included) and has a constantly changing baseline as the standard is updated. Results of the simulations also cannot be compared to actual performance due to modeling rules that may not apply to the actual building. A new performance approach procedure should be developed.

2) The "low hanging fruit" have been plucked so any enhancements to energy standards must include more complex measures that require detailed evaluation in order to verify their cost effectiveness. This can be a burden on SSPC members, who are unpaid volunteers. The regression analyses and cost databases used in the development of Standards 90.1 and 90.2 in the past are out of date, plus the form of the energy regressions did not allow them to be easily maintained. Computer tools that can automate or semi-automate evaluation of new measures should be developed, including calculation of both first costs and energy costs.

3) The complexity of ASHRAE energy standards, in particular the performance approach, places a burden on designers who must demonstrate compliance, and to enforcement agencies who must confirm compliance. Tools that automate compliance demonstration are needed. These tools can also assist designers evaluate energy conservation measures, reducing the cost of engineering high performance buildings.

Needed Research: Sample research projects that address the above technical challenges include the following:

1) Develop a different approach to overall building energy performance than the current Standard 90.1 and 90.2 Energy Cost Budget methods, one that includes an absolute (rather than relative) scale and more realistic results that can be compared to actual performance (e.g., ASHRAE's Building Energy Quotient program), while addressing the limitations of various computer simulation tools and the need for clear rules for consistent application.

2) Develop prototype energy models of the most common building types and batch processing tools that allow for very quick energy savings estimates of proposed energy conservation measures over multiple climate zones, occupancy types, etc. This tool also can be used to quickly evaluate the overall effectiveness of new versions of the Standards.

3) Develop updated first cost databases of envelope, lighting and mechanical systems and equipment for use by SSPC 90.1 and 90.2 in life cycle cost analyses.

4) Create detailed descriptions of the rules and energy model input parameters required to properly implement Energy Cost Budget methods for software developers to develop automated user interfaces to building energy analysis calculation engines.

5) Continue to develop BIM to automate the creation of energy models from architectural/mechanical/electrical BIM data files.

6) Update existing energy analysis calculation engines to model building components and systems that will be needed to meet current and future energy standards, including the ultimate NZEB goals. Presumably co-funding will be available from DOE.

Goal 6:

Building Information Modeling of energy efficient, high performing buildings. BIM is a rapidly developing field of knowledge which stretches beyond the traditional boundaries of the HVAC&R industry to the wider construction sector.

Objectives

1) Embrace and embed interoperability in the development and execution of ASHRAE Research and the standards, guidelines and technical publications which are based on that research.
2) Develop the information, guidance and examples needed to support the adoption of BIM in the wider technical activities of the Society.

Technical Challenges: BIM seeks to integrate design, construction, operation, maintenance and refurbishment processes, making them interoperable. Although BIM uses IT to deliver interoperability and integration, BIM is not a software tool, nor is it an information technology (IT) solution: It is far more pervasive than that.

BIM, interoperability and integration will impact on almost everything ASHRAE and its members do, as a technical society or as practicing engineers, including the processes of developing, delivering and using ASHRAE standards and guidelines.

BIM has the potential to reduce errors, improve the quality of our products and services, enhance the built environment in which we live and make it more sustainable. It will play a critical role in achieving our goals of reducing energy use, minimizing waste and delivering better buildings. It can also reduce costs and increase productivity through the life cycle of constructed assets. It is a valuable tool in facilitating successful collaboration and coordination during pre-design, design, construction, operation and maintenance of both new and existing buildings.

The foundation of BIM, interoperability, integrated building design and related initiatives is the exchange, application and use of building data between software applications. Studies have shown a significant waste of time and money in the design, construction, commissioning and operation of buildings due to a lack of interoperability. New IT applications are changing current processes and creating new ones, address the whole building life cycle. BIM is likely to be a pervasive technology which impacts across much of ASHRAE's current activities. ASHRAE has many different initiatives relating to buildings, many guided by ASHRAE research. BIM presents ASHRAE with two challenges. The first is internal and cultural, and is the challenge of adopting an interoperable mindset to ASHRAE technical activity. This is a major task, because it will impact the activity of all the Councils and cuts across all the technical work of the Society. The second challenge is to develop interoperable ASHRAE products through the technical programs of the Society.

If ASHRAE is to meet the challenge of BIM in the future it must:

1) Ensure that research projects address the increasingly cross cutting requirements of BIM, interoperability and information exchange.
2) Stimulate greater awareness of the implications of BIM on Society technical activities.
3) Develop interoperable tools and products of its own to support member adoption of BIM.
4) Work effectively with external bodies such as the buildingSMART alliance and Open Green Building XML Schema, Inc. (gbXML).

Needed Research

1) Develop data exchange protocols for HVAC&R information within ASHRAE, consistent with the standards and protocols being adopted by other BIM communities, in particular architectural and structural engineers.
2) Develop reference use cases for HVAC&R applications in support of ASHRAE Guideline 20, *Documenting HVAC&R Work Processes and Data Exchange Requirements*.
3) Produce guidance for ASHRAE TCs on the deployment of BIM processes and tools, and on the information exchange requirements for HVAC&R related information within a broader BIM environment.
4) Develop guidance and exemplars for use cases in a BIM environment.

Goal 7:

Support development of tools, procedures and methods suitable for designing low-energy buildings.

Objectives: Fundamental changes have been made in the way we view our responsibility regarding energy consumption. Over the last few years there has been an increasing awareness of the large potential for energy conservation in the building/HVAC&R sector. This awareness and a fundamental shift in thinking about energy-related and environment-related responsibility are evident in the increasing number of building projects where an incremental effort is being made to achieve superior energy efficiency. The success and prominence of the Leadership in Energy and Environmental Design (LEED) certification program highlights the idea that there is change taking place in this industry. Many practitioners are already involved in the effort to design energy efficient buildings. Many struggle with some of the more innovative features necessary to push performance levels in the direction of the NZEB. Therefore, the primary objective is to improve the capabilities of engineers to design low energy buildings, by increasing the usability, capability and accuracy of existing tools and developing new tools where needed.

Technical Challenges: Design engineers use a variety of tools to design low-energy buildings, ranging from load calculation programs to whole building simulation programs used to analyze the energy consumption of candidate designs. Whole building simulation programs are not routinely used in practice because of their inherent complexity and the high cost to create building and system models. This is particularly true for a small projects; the cost to accurately model the building and various energy conservation alternatives can rival the cost to design the entire mechanical system. Furthermore, when it comes to low energy buildings, currently available tools often do not provide analysis for the innovative features that are utilized, nor do they support design except in an inefficient trial-and-error fashion.

Specific shortcomings that need to be addressed include the following:

1) While some whole building simulation tools can be used, in a trial-and-error fashion, to design natural and hybrid ventilation systems, true design procedures are not available, but are needed to support implementation of these systems. Such procedures could help determine the best configurations and strategies for natural and hybrid ventilation and, in many locations, the impacts of hybrid ventilation schemes on peak zone cooling loads and coil loads.

2) With many innovative designs, there may be significant implications for the indoor environment that require analysis of thermal comfort, visual comfort, indoor air quality, etc. Yet tools that handle all of these aspects along with the relevant controls and resulting building loads and energy are not available.

3) Looking forward to the possibility of NZEB, the incorporation of renewable energy resources, whether grid or point-of-use generated, will be essential to their eventual realization. Buildings that incorporate renewable energy sources without energy storage present a remarkably poor load factor to the utility, further aggravating already serious generation/distribution inadequacies. Yet, the capability to analyze the interaction between renewable energy sources and thermal energy storage in the building is lacking.

4) Many innovative low-energy designs rely on unusual system configurations and control strategies that cannot be modeled with existing whole building simulation tools. Whole building simulation tool developers cannot add new capabilities at a rate that can keep up with the pace of the design process.

5) Many low-energy strategies utilize natural sources such as the sun, ambient air, ground or water to provide heating or cooling. Standard practice in HVAC&R design is to size the system to meet peak loads. Due to the highly varying heating or cooling capacity of these natural sources, the standard approach is often not applicable.

6) The modeling tools that do exist are too complex to be easily used, and hence they are not used for a majority of buildings, particularly small buildings where design fees are proportionally small. User interfaces need to be developed to allow models to be created more quickly and accurately, including the ability to import building information from design drawings (CAD and BIM). The market for these interfaces is currently very small, discouraging commercial development, which in turn discourages the use of these programs, which then keeps the market small. Research is needed to make product development less expensive to spur commercial development to break this cycle. Examples are developing standards for conveying information from Computer Aided Design CAD and BIM models to energy models and developing generic graphical interface engines that can be used at no charge as the basis of commercial products.

Needed Research: Sample research projects that address the above technical challenges include the following:

1) Create templates for software developers to develop simple user interfaces that sit on top of building energy analysis calculation engines.
2) Create guidelines that specify the minimum number of building inputs that are most critical for determining accurate building energy usage for specific types of buildings.
3) Develop models and design procedures for natural and hybrid ventilation systems.
4) Improve whole building simulation tools to simultaneously analyze energy consumption, thermal comfort, visual comfort, indoor air quality and other performance metrics.
5) Develop whole building simulation tools and design procedures that can evaluate the time dependent value of renewable energy sources and the effectiveness of energy storage technologies in resolving the conflicts of availability and use.
6) Develop a rapid prototyping capability that will allow power-users of whole building simulation tools to add custom models quickly and easily.
7) Investigate how innovations in the computational science field might be used to develop significantly improved building simulation programs.
8) Develop a procedure for making a decision on whether it is feasible to forego perimeter heating with a thermally improved envelope.
9) Develop models for dynamically operated shading devices in whole building simulation tools that quantify thermal comfort, visual comfort and energy consumption, including the impact of internal shading devices on coupling of solar heat gains with thermal mass.
10) Develop of a simple rating tool that will allow a designer to examine and/or compare the effect of shading attachments in combination with specific glazing systems and solar/weather conditions.

Goal 8:

Facilitate the use of natural and low global warming potential (GWP) synthetic refrigerants and seek methods to reduce their charge.

ASHRAE has a strong interest in promoting the use of safe, environmentally friendly, naturally occurring refrigerants and synthetic low GWP refrigerants. Because of its alignment with sustainability initiatives, ASHRAE will support research, assessment and strategic growth in the use of such refrigerants in refrigeration systems and related technologies with emphasis on efficiency, safety and economic viability. ASHRAE and its members will contribute to improved sustainability of refrigeration and air conditioning technology by conducting research and disseminating knowledge in order to promote the responsible use of sustainable refrigerants. ASHRAE will continue research in developing methods to reduce the refrigerant charge per unit ton of refrigeration. This is in line with the ASHRAE's overall environmental sustainability goal. Reducing charge will reduce the risks associated with refrigerants that are toxic or flammable but have low environmental impact. Low charge also has an economic impact especially with systems that use high cost synthetic refrigerants.

Objectives

1) Effectively incorporate natural and low GWP synthetic refrigerants in Air Conditioning & Refrigeration (AC&R) equipment.
2) Seek optimized equipment to minimize refrigerant charge per unit ton of refrigeration.
3) Study the overall economics of these optimized equipment designs.
4) Study the impacts of different natural and low GWP synthetic refrigerant choices on overall system efficiency.
5) Study safety and health issues related to these equipment/systems.

Technical Challenges

1) Use of natural refrigerants that are identified as toxic or flammable by regulatory authorities.
2) Definition of "low" GWP. The automotive industry has adopted a GWP of 150 and lower; would this be an industry norm for AC&R?
3) Identifying appropriate measures of "total environmental impact" for refrigerants.
4) Identifying the total potential for reducing environmental impact through utilization of natural and low GWP synthetic working fluids.
5) Determination of risks associated with naturally occurring and low GWP synthetic refrigerants that have properties that make them "less safe" than the current refrigerants. What changes in equipment will need to be made? What changes will need to be made in codes and standards to allow safe usage of these refrigerants?

Needed Research

1) Conduct experimental system performance tests on practical equipment designs to assess "real" system performance of various natural and low GWP synthetic refrigerants, and identify design optimizations based on results.
2) Develop and study technologies to improve the total life cycle cost and reduce the total direct and indirect environmental effects of naturally occurring and low GWP synthetic refrigerants viz., mini-channel, micro-channel, plate and other compact heat exchangers and explore methods for developing compact heat exchangers around the properties of these refrigerants and to achieve a minimal charge, e.g., less than 20 grams/Ton of Refrigeration (TR).
3) Develop new materials and study existing materials with enhanced heat transfer characteristics that are compatible with naturally occurring and low GWP synthetic refrigerants. Compatibility needs to be determined for metals, polymers, seal materials, hoses and other materials in direct contact with the working refrigerant.
4) Research in state-of-the-art nano-technology and development of smart exchangers.
5) Study the heat transfer and pressure drop performance of compact heat exchangers with naturally occurring and low GWP synthetic refrigerants.
6) Identify work already done on heat and fluid flow characteristics for low GWP refrigerants and support work to fill in the blanks, viz., with and without lubricants.
7) Support research in reduced charge air-cooled natural and low GWP synthetic refrigerant systems through various methods including improved low-charge condensers and controls for critical charge operation.
8) Explore low-leak system designs – identify sources and causes of leak and design better components, better fittings, better connections and better system configurations to provide more effective means of refrigerant containment. This research will support ASHRAE Standard 147.
9) Develop basic data to support industry risk assessments to determine what types of applications can use flammable or toxic refrigerants safely and what system modifications could be made to improve safety.

Goal 9:

Support the development of improved HVAC&R components ranging from residential through commercial to provide improved system efficiency, affordability, reliability and safety.

Objectives: The improvement of HVAC&R components is a continuous, never ending process, with the current state-of-the-art being the collective result of much work by numerous organizations and companies over the last several years. There will continue to be opportunities for component improvements, and the projects below have been identified as current opportunities for focused ASHRAE effort.

Technical Challenges: Equipment and system designers, installers and maintenance personnel face numerous tradeoffs and challenges in their efforts to provide efficient and long term cost effective solutions for HVAC&R.

Specific shortcomings that need to be addressed include the following:

1) There is a general lack of knowledge when it comes to seismic and wind restraints for HVAC&R equipment and some gaps related to piping and duct.

2) Duct leakage in unconditioned spaces is a major energy loss. Standard methods to test air leakage for HVAC&R accessories and equipment are inadequate or difficult to measure in the field. Allowable leakage levels for accessories and equipment that are reasonable, obtainable in the field and testable in the field have not been established.

3) Data is lacking to determine optimal duct insulation and static pressure levels in terms of life cycle costs for residential HVAC&R systems with the ductwork located in unconditioned and conditioned spaces.

4) Several common rules of thumb in cabinet design restrict thinking and hinder progress. New approaches (think "outside of the box/cabinet") to identify ways to add additional heat exchanger area apart from traditional designs needs to be investigated.

5) The seal effectiveness of thermal breaks and gaskets for the doors of refrigerated cabinets degrade over time, resulting in increased air infiltration that reduces efficiency. In addition, improved thermal break and gaskets may be applied usefully to any other cooled space having an access panel (like a maintenance access panel to the evaporator or chilled water coil and indoor air blower space in an AHU or a packaged system).

6) Improving the heat transfer of heat exchangers, and making heat exchangers more compact could provide great overall increases in system efficiency. This would include different heat exchanger materials, configurations and working fluids.

7) Heat exchanger fouling is a problem that affects the real world efficiency in almost every HVAC&R application. Standards defining fouling and recommended test procedures for comparing heat exchangers in fouling conditions are lacking.

8) Standardized residential communication protocols to permit the interface and coordination of appliances with the electric grid to minimize power demand and energy cost do not currently exist.

9) Potential system contaminates in new refrigerants and their effects on system performance and reliability have not been fully investigated.

10) Applications where commercial size heat pumps could provide efficient and economical advantages have not been fully investigated.

11) The impact of low GWP refrigerants on heat exchanger design/performance, especially with the enhanced surfaces used in current equipment have not been adequately identified and quantified.

12) Means to improve refrigerant compressor performance at off-design and part load performance conditions have not been fully investigated.

13) Ways to improve the efficiency of fans and blowers used in HVAC&R systems have not been fully investigated.

Needed Research: Sample research projects that address the above technical challenges include the following:

1) Develop a summary of the need and code requirements for seismic and wind restraints, along with prescriptive methods for providing the required restraints for equipment.

2) Conduct experimental measurements and modeling on the effects of wind on exposed equipment to develop analytical algorithms for determining restraint requirements.

3) Conduct experimental measurements and modeling to establish practical, achievable and quantifiable equipment and accessory air leakage levels as a percent of system design or other parameter. Create a measure for leakage of accessories and equipment which will provide designers with information that is comparable and useful.

4) Conduct field measurements and analyses to quantify the annual heating & cooling energy use in residences for typical size homes as a function of various levels of duct insulation and static pressures.

5) Conduct studies and experimentation to identify ways to push the heat exchanger efficiency envelope in a number of different applications using various next generation heat exchanger technologies, as well as identifying novel ways to increase the efficiency of existing heat exchanger technology.

6) Conduct studies and measurements to develop and verify thermal models of heat flow past thermal breaker strips and door gaskets that take material properties and geometry into account, to support development of test methods for measuring the heat flow past the door perimeter, both in total and for separately measuring the gasket contribution.

7) Conduct studies and experiments to investigate novel heat exchanger material, heat exchanger configuration and fin designs that reduce airside pressure drop while maintaining heat transfer. Coil configuration within the cabinet should also be evaluated.

8) Conduct studies and measurements to identify fouling particles and develop test methods in a systematic way to quantify the effects of heat exchanger fouling.

9) Conduct studies and analyses to support design of an affordable, reliable and secure residential communications protocol to provide a comprehensive set of messages for conveying binary, analog and alphanumeric data between devices and the electric grid.

10) Conduct studies and experiments to support development of maximum allowable levels for individual or combinations of contaminates in refrigerant systems that use newly developed refrigerants. These studies should include the impact of the contaminants on system performance and durability.

11) Conduct studies and analyses to support the development of an application guide for commercial size heat pumps identifying instances where they are a good economic choice as well as identifying any operational issues/technical constraints, etc.

12) Conduct studies and experiments to support the proper evaluation of low GWP refrigerants, including exploration of methods for developing compact heat exchangers around the properties of these refrigerants and the impact of low GWP refrigerant heat exchangers on equipment sizing.

13) Conduct studies and experiments to examine the possibilities for cost effective improvements in compressor performance related to refrigeration and air conditioning.

14) Conduct studies and experiments to support improvement of fan efficiency by identifying and eliminating adverse system effects which directly impact their performance.

15) Conduct studies and experiments to fully optimize system performance.

Goal 10:

Significantly increase the understanding of energy efficiency, environmental quality and the design of buildings in engineering and architectural education.

Objectives: It is widely understood that engineering and architectural education is where concepts and principles of building systems and design are taught with the intention of fostering successful generations of engineers and architects. However, the two disciplines seldom reach across departments, interact within the curriculum or collaborate on research projects. Yet, in practice, the collaboration between design team members is essential to the design and delivery process of high-performance buildings. This gap reveals a need to develop information about both disciplines in order to define resources, tools and opportunities for collaboration. The objectives for the education goal of the strategic research plan period will support the development of research activities and training to lay the groundwork for achieving net zero energy buildings:

1) Foster research interactions (e.g., design processes) between engineers and architects

2) Increase ASHRAE involvement amongst architecture students

3) Build collaboration between future engineers and architects within the existing curriculum

4) Train engineering and architecture faculty with the latest knowledge, resources and tools

Technical Challenges: One difficulty in incorporating new ideas into engineering/architecture programs is *lack of time*. Faculty say there is not enough time to get through the basics. Students consider the capstone design project – where they put all the process steps together – as the most valuable lesson in how it all comes together. But the number of requirements and credits are at an upper limit in most programs and any new activities, courses or ideas must replace existing material or be integrated within the fabric of current offerings.

Another obstacle to change is the "disconnect" between higher education and professional practice. In academia, each decision is analyzed ad nauseam, whereas in practice, design proposals must be completed in a short time frame. Simulation tools can predict very detailed building performance measures but in practice, we rarely examine the performance of buildings. To address this barrier, activities are needed that foster "closing the loop" between education and practice.

Designers lack clear guidance on the direction of design decisions. With so many variables in play, only large projects in practice can afford to have detailed analysis completed. Consequently, with such a large gap between education and practice, teaching and topical offerings potentially lack needed tools, software expertise, trained faculty and systems integration.

Needed Research: ASHRAE funded projects to achieve the above objectives include the following:

1) Development of *case studies of successful collaborations* between architects and engineers on commissioning and integrated building design (see AIA Upjohn Research Project Case Studies of Carbon Neutrality – narratives of the design and delivery process for six firms/buildings; potential co-sponsorship with the USGBC to develop narratives of LEED certified projects). Develop prototypical case studies to "prime the pump" for the development of a larger case study database.

2) Development of *case studies of building performance*, net zero energy buildings (see AIA Upjohn Research Project Case Studies of Carbon Neutrality; co-sponsorship with the USGBC). Develop prototypical case studies to "prime the pump" for the development of a larger case study database.

3) Survey and white paper of current state of engineering and architectural education, in terms of tools, equipment, textbooks, resources, faculty training and preparation, principles, concepts and topics taught related to building systems. Are there commonalities? How can resources be shared? What kind of training is needed for faculty, practitioners and graduate students? What kind of common goals can engineers and architects share?

4) Design competition on technology innovation to foster collaboration between architecture/engineering student partnerships. Competitions can be run at several different scales: design competition (existing with Student Activities); as regional design-build competition events (e.g., Decathlon, "shipping container," housing) events that align with ASHRAE regions; as Internet-based, weekend design charrettes for architecture/engineering student partnerships. Each competition would require design proposals, research and innovation for new methods, materials and measurement.

5) Curriculum resource materials development for engineering programs on net-zero design. This

includes energy simulation tools (EnergyPlus, IES, computational fluid dynamics (CFD), Radiance, Revit, DesignBuilder, and TRNSYS, etc.), training and case studies. (See http://www.architecture.uwaterloo.ca/faculty_projects/terri/carbon-aia/)

6) Short courses for the ASHRAE Learning Institute that focus on integrated design of high-performance buildings. This course or series of courses would be developed for both architects and engineers and would employ the latest software tools (research topic 5) and include several case studies identified under research topics 1 and 2.

7) National training sessions for engineering and architecture faculty and graduate teaching assistants to conduct case studies in building system performance and discuss potential collaborations with the professions.

Goal 11:

Understand influences of HVAC&R on airborne pathogen transmission in public spaces and develop effective control strategies.

Objectives: Multiple mechanisms of infectious disease transmission involving transport in air include a) droplet transmission (close range) – when the momentum of expelled particles influences exposure; b) medium- to long-range transport and subsequent inhalation of droplet nuclei; c) airborne transport of pathogens to surfaces, or contamination of surfaces by physical contact, followed by resuspension and inhalation, or contact with surfaces. The second mechanism is of primary interest to ASHRAE. Airborne pathogens consist of airborne particles (bioaerosols) generated by persons with infectious disease coughing, sneezing, breathing and talking, that remain airborne for a period of hours to days. Infectious airborne particles range from 1 to 8 µm in diameter, and may contain viable fungi, bacteria or virus suspended in respiratory secretions. Improved HVAC&R system design, maintenance and operation will reduce the incidence of human-generated APT in public spaces such as hospitals, schools, shopping malls, offices and intermodal transportation. It is not clear how these bioaerosols affect disease transmission and how HVAC&R systems and structures/vehicles should optimally be designed and operated to practically reduce the risk of Airborne Pathogen Transmission (APT). Accordingly, specific objectives are:

1) Develop a multi-disciplinary approach and establish collaborations to address the APT problems which impact many TCs within ASHRAE and also are being studied by other professions and organizations such as universities, Centers for Disease Control and Prevention (CDC), National Institute for Occupational Safety and Health (NIOSH), National Institutes of Health (NIH) and Federal Aviation Administration (FAA). Such an approach will obtain maximum utilization of research dollars, and allow each profession to focus on its expertise while benefitting from the guidance from others in related issues.

2) Improve understanding of droplet nuclei short and long range transport characteristics, APT in buildings and transportation vehicles, and the role HVAC&R or environmental control systems (ECS) might play through both field and laboratory studies.

3) Promote the development of protocols and methods for characterizing HVAC&R systems and building science factors that impact APT in a simple and cost effective manner.

4) Develop differential pressure controls and space isolation methods and air cleaning and disinfection methods for reducing APT in spaces of interest to ASHRAE membership.

5) Recommend HVAC&R equipment and building science systems that reduce energy consumption while reducing APT for each setting.

Technical Challenges: Changes in building characteristics and HVAC&R system operation could likely reduce incidences of respiratory illness by at least 5-10 percent, which, utilizing 1996 data, would result in the avoidance of millions of cases of common cold or influenza, resulting in annual societal cost savings of several billion dollars. Modifying ventilation, humidity and filtration to meet infectious disease control criteria could result in significant energy and equipment savings as well. Occupancy densities (OD), as well as ventilation rate per person (V), are important factors affecting AP exposure with a higher OD increasing exposure for the same V in both intermodal transportation and building environments. In this regard transportation systems such as trains, buses and passenger aircraft ODs are uniquely high in comparison with OD in public buildings such as theatres and classrooms. The diversity of sources and lack of immunity to the various AP exposures encountered in passenger aircraft with the intermixing of persons from different population centers and continents is unique in comparison with other transportation systems with the exception of cruise ships, or with other high OD venues such as subway cars, theatres and classrooms where the occupants tend to be from one geographic region.

The relationship between HVAC&R and structure conditions and APT rate is largely unknown. A large scale epidemiology study is needed to develop the methods and tools needed to answer the question: Is there an association between HVAC&R design and operation and the transmission of airborne pathogens? For example, the relationship between APT and respirable aerosols that contain pathogens has not been evaluated. Airborne particle sampling studies in hospitals have focused on obtaining colony forming units (CFU) counts from impaction plates for pathogen measurements. This method has been used to determine airborne pathogen concentrations, but is limited in many regards, including the specificity of the substrate on which the collected fluid is plated, and the fact that the sample is integrated over a period of minutes to hours. In some cases independent measurements of the particle characteristics in the test environment have been made, but these measurements, although conducted for shorter time periods (on the order of seconds) have determined the pathogen carrier size distribution but also other non-pathogenic materials found in the air. Methods to be explored for HVAC&R application include quantitative polymerase chain reaction (PCR) assays and other molecular techniques, as well as qualitative techniques such as the Wisconsin Upper Respiratory Symptom Survey of subjects. Higher cost biological and chemical detection methods are in use by the Department of Homeland Security (DHS). DHS sensors need to be evaluated for applicability to AP detection in commercial HVAC&R systems. Low cost, long life biological sensors are needed to provide building ventilation control, pressure control or rapid response filter or air purification control to reduce transmission of infectious materials. Multiple TCs will be involved and research projects will build upon previous ASHRAE research. Significant research progress will require outside funding and collaboration to accomplishing the diverse research objectives.

Needed Research: Engineering data is needed to specify minimum ventilation rates, humidity limits, air purification and other HVAC&R/ECS parameters to prevent APT in high risk building and transportation environments. This research will require strong partnerships and collaboration and will include an environmental "sampling" group (ASHRAE, universities, NIH, American Industrial Hygiene Association (AIHA), others), an infectious disease/ epidemiology group (Universities, NIH, CDC, Association for Professionals in Infection Control and Epidemiology (APIC), others), and a building science/HVAC&R systems group (ASHRAE and others). The development of effective sampling methodologies for quantifying APs or at least APT is critical to the other proposed research. Researchers must evaluate available models and measurement methods that quantify the relationships between ventilation, air movement, humidity, moisture and occupancy density conditions and APT. ASHRAE technical committees will need to partner on projects with other researchers specializing in building sciences and infectious disease control to ensure that building science/systems issues and human factor issues are appropriately reflected. Researchers need to consider methods for sampling in HVAC&R systems, including isokinetic sampling in moving airstreams; and evaluation or development of test protocol and modelling tools. Researchers will apply and validate models and methods in field measurements and assessments of the role of HVAC&R operation in APT. ASHRAE needs to participate in the transmission group studies to ensure that system performance and engineering controls are appropriately monitored and controlled. One outcome would be the development of a "standard" system performance documentation spreadsheet to ensure that design and operation conditions are fully assessed during an epidemiology study. ASHRAE needs to develop effective means of characterizing system performance and effectiveness in removing APT risks. Researchers will incorporate mitigation method modelling from early research activities into future technology demonstration designs and evaluate the models and measurement methods of individual, hybrid or system integrated APT mitigation methods. Research projects should target air and surface sampling and analysis protocols for pathogens of interest in different environments. Research should correlate infectious disease epidemiology with HVAC&R parameters. Research will demonstrate utilization of technology that will receive input from biological sensors to control HVAC&R, provide real time protection and optimize energy consumption. The product of this research will be field tested, ASHRAE recommended system engineering approaches.

To download the plan or for more information about ASHRAE's research program click www.ashrae.org/research

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