Advanced Integrated Systems Technology Development

Final Deliverable
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Submitted by
Fred Bauman, Tom Webster, Edward Arens, David Lehrer, Hui Zhang, Katie Ackerly, George Anwar, Gail Brager, Paul Raftery, and Tiefeng Yu
Center for the Built Environment
University of California
Berkeley, California 94720-1829

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Purpose: Create tools, information sources, and standards that encourage the adoption of improved techniques and technologies for the planning, design, and operation of buildings. This scope of work primarily covers work during a six-month period leading up to a planned three-year comprehensive research program on advanced integrated building systems that seek to achieve large energy reductions in support of climate change goals.

Background: The State of California is calling for radical improvements in building energy efficiency. The goals will *not* be met without an integrated approach involving new designs, new technologies, new ways of operating buildings, new tools for design, commissioning and monitoring, and new understanding of what comprises a comfortable and productive indoor environment. Many of these new developments are being worked on at the Center for the Built Environment and elsewhere, but the pace is not adequate to support the great changes rightfully being demanded of the building industry.

These new systems-- natural-ventilation and mixed-mode building conditioning, underfloor air distribution, displacement ventilation, radiant heating/cooling, personal environmental conditioning--have the potential to dramatically improve traditional levels of energy efficiency without compromising, and possibly increasing, occupant satisfaction and thermal comfort, and increase the flexibility and useful life of the conditioning systems. All of them function by producing thermally asymmetric environments, which require new approaches to operation, and a reexamination of how comfort performance is quantified in standards and design tools. They also require a higher level of sensing and feedback to produce the efficiency gains they are capable of. Finally, the building professions need training to be aware of and proficient in these new developments.

Task #1. Radiant and other hydronic cooling systems

Task #1 Objective:
Develop test plan and prepare for laboratory testing to characterize key unresolved fundamental heat transfer and condensation mechanisms, primarily using the laboratories at Price Industries.

Deliverable: Hydronic-based Cooling Test Plan
The following topics have been selected as the highest priority research areas for testing and analysis using the Price Radiant Test Chamber located in Winnipeg, Manitoba. These were discussed and agreed upon by Fred Bauman, Tom Webster, and Charlie Huizenga of CBE, Julian Rimmer and Brad Tully of Price Industries, and Timothy Moore of IES (former CBE graduate student researcher).

1. Ventilation effectiveness and room air stratification with overhead (OH) vs. displacement ventilation (DV) systems in combination with radiant chilled ceilings (panels or slab). The key fundamental question to investigate will be the impact (and possible disruption) of cooled ceiling temperatures on the stable stratification and enhanced ventilation performance of DV systems.
2. Condensation formation and avoidance. With the ability to control humidity in the test chamber, some carefully controlled tests could be conducted where humidity is ramped up, just to see how long it takes to form enough condensation to cause a drip under realistic simulated failure conditions.
3. Performance testing of distributed hydronic systems, such as chilled beams (passive and active) and chilled sails. These tests will investigate cooling capacity, room air stratification, ventilation performance, and comfort conditions for a variety of operating conditions (primary supply airflow rate and temperature, heat loads, etc.). Measurement data from these tests may be used to compare and validate models being developed for energy simulation programs, such as EnergyPlus.
4. Investigation of chilled ceiling and floor slabs. This will require consideration of how to simulate thermal mass and/or representative surface temperature boundary conditions. Tests will be done in combination with both DV and OH air distribution systems. Since simulation of transient conditions are difficult, different approaches may be used, such as different combinations of more moderate surface/air temperature differences (typical for chilled slab applications), or controlling the radiant panels in the test chamber to mimic the expected behavior of a thermally massive slab.
5. Comfort control with radiant systems. Using detailed measurements of thermal comfort conditions in the test chamber investigate and compare different approaches for controlling thermal conditions. For example, compare air temperature vs. mean radiant temperature or operative temperature control. The Berkeley Thermal Comfort Model will also be used to analyze the collected data.

CBE's first testing session at the Price Radiant Lab is scheduled for the week of Nov. 2-6, 2009. We expect to focus on the first test configuration described above, investigating the combination of a chilled ceiling with a stratified displacement ventilation (DV) system. The Price Radiant Lab is currently being used 24/7 to conduct performance testing of various Price radiant and chilled beam products. The planned schedule for the week is as follows:

Monday: Observe ongoing Price tests, become familiar with system
Tuesday: More familiarization and discussion of upcoming tests
Wednesday: Convert lab setup to chilled ceiling panels, insulated walls, and DV diffuser in one corner of test room. Begin testing.
Thursday: Testing
Friday: Conclude testing and convert back to Price test configuration

The experiments will be conducted over a range of low to high office cooling load levels using the available Price (EN) heat sources. The goal is to investigate the amount of stratification and ventilation effectiveness as a function of load to airflow ratio and ratio of load removed by DV vs. the chilled ceiling. During the relatively short available testing time of our first visit, we may attempt to bracket the range of expected performance by selecting a few tests that cover everything from maximum stratification (and best ventilation performance) to the point where the radiant chilled ceiling destroys the stratification, leading to more of a mixing airflow distribution.

The test variables that we will want to control during these experiments will include:

- Cooling load
- DV supply air temperature and flow rate
- Room setpoint temperature
- Surface temperature of radiant chilled ceiling

The following variables would be monitored during the experiments:

- Room air stratification
- All surface temperatures
- Cooling loads (heat sources)
- Airflow rate and supply temperature
- Ventilation effectiveness (if available using tracer gas)
- Smoke visualization to characterize airflow patterns

Task #2. Natural ventilation (NV) and mixed-mode (MM) design

Task #2 Objective:
Conduct scoping study of retrofit potential of NV and mixed-mode systems.

Deliverable: Scoping study report on NV and M-M retrofit potential
This task was part of a larger project to develop case studies of mixed-mode buildings, with a focus on finding buildings with interesting controls systems that would warrant further study. As a subset of that exploration, we focused on retrofit opportunities for existing buildings, to understand the range of work that is being done to reduce mechanical loads in the retrofit market, and in what cases if any natural ventilation is being introduced.

Listed below are 33 non-residential retrofit projects, including 19 in California (mostly Bay Area), in which natural ventilation was maintained and enhanced in the retrofit. Sources for this ongoing case list include interviews with architects, design engineers, development companies, consultants and property management firms operating in California or knowledgeable of historic or energy-efficient retrofit projects, as well as a review of USGBC, DOE, Building Green and CBE high performance building case studies.

The purpose of compiling this database is to understand the scenarios in which natural ventilation is most commonly retained/introduced in an existing building, including

a) Which levels of intervention are most common;
b) What changes to the HVAC system, if any, accompany the retrofit; and
c) Whether control strategies are employed that maximize the efficiency of existing HVAC systems with operable windows.

According to cases collected so far, it is rare to find projects that do not involve a major change in program or ownership, making it very difficult to evaluate the potential for energy reduction in the existing building stock from this approach. We also found no cases in which natural ventilation was introduced to eliminate or reduce air conditioning in a deep-plan office building undergoing a façade renovation. We came across one such case in the UK—the renovation of Ashburton Court—which is a $4 million renovation of a 1960s era concrete office block. The Carbon Trust funded the project in order to showcase the potential for converting this type of building. There is another project underway in Seattle

We classified projects according the extent of the retrofit or renovation, changes in programming, and whether air conditioning was added or removed. A breakdown of the 33 cases into these categories is listed below, followed by a full tabulation of projects and retrofit parameters that we documented.

1. **Minor interior renovation to naturally ventilated building with no programming change**

The CBE review did not find any projects in which minor enhancements to the interior explicitly prevented the installation of new air conditioning. Seismic retrofits of a number of urban, historically-significant, multi-story buildings in the Bay Area, as in many similar urban areas with low cooling degree-days, involved the installation of higher-efficiency heating and lighting equipment and sometimes improvements to the thermal envelope but the installation of air conditioning was never considered as a need in the general office space unless specifically requested by a tenant. In nearly all of the buildings, some traditional air-conditioning capacity was added to serve specific spaces (often retail or IT-intensive tenants), a change which was similarly not up for debate. Manual control is retained on the operable windows.

Bohemian Club, San Francisco
Oakland City Hall
Historic Central Building
Flood Building
Thoreau Center for Sustainability
Presidio Building 38

2. **Interior renovation plus window or façade replacement with no programming change**

Only a few buildings featured changes to the façade without a major strategic re-programming of the interior, although in most cases the interior renovation was extensive and occupants were relocated. These projects were motivated by the desire to project a “green” image while undergoing a planned seismic modernization. Both of these buildings, like scenario one, are 1920s buildings. Like scenario 1, all of these buildings are zoned for spaces served by either exclusive natural ventilation or mechanical cooling, manual window operation and one-sided ventilation is the primary mode of cooling and ventilation.

Chicago Center for Neighborhood Technology
Pasadena City Hall
Clark and Savery Halls, University of Washington

3. **Removal of air conditioning**

The few examples of buildings that were converted from air-conditioning to natural ventilation were historic, shallow-plan buildings that were returned to their original design as a purely naturally ventilated building.

Joseph Vance Building, Seattle, WA.
Montgomery Hall, San Francisco Theological Seminary, San Anselmo, CA
Berkeley Civic Center, Berkeley, CA

4. Major re-design, re-use or addition with programming change

These projects are largely “green” or LEED major renovation projects that involve a complete re-design and re-programming of the interior space plus some refurbishment of the building fabric. Many are initiated by a need for facilities modernization or a planned addition. Others are adaptive re-use projects that gut and dramatically re-interpret the building’s function. This category is set apart by the fact that their cost-effectiveness is likely to be determined relative to demolition and/or new construction, which is often favorable[1].

This category is where the more automated and integrated mixed-mode strategies are employed. Several of these projects involve the addition of ventilation openings and strategic programming to extend the use of natural ventilation over a greater number of days. Other strategies such as new radiant cooling systems and control solutions maximize the efficiency of using operable windows.

Continuous ownership

UCLA Kinsey Hall, Los Angeles, CA
Jean Vollum Natural Capital Center, Portland, OR
Georgina Blach Intermediate School, Los Altos, CA
Navy Building 850, Port Hueneme, CA
Lavin Bernick Center for University Life, New Orleans, LA
Herman Miller Building, Zeeland, MI
Compton Union Building, Washington State University, Seattle, WA

Change in ownership/adaptive re-use

StopWaste.org, 1537 Webster, Oakland, CA
Chicago Center for Green Technology, Chicago, IL
BPA Ampere Annex, Vancouver, BC
Berkeley YMCA Teen Center, Berkeley, CA
UCSF 654 Minnesota Avenue, San Francisco, CA
NRDC Offices, Santa Monica, CA
San Francisco Friends School, San Francisco, CA
Pier One Building, San Francisco, CA

[1] Advantages of re-use over new build include potentially lower capital costs, shorter completion times, and avoidance of planning constraints. Kendrick, C., A. Martin, Andrew; and W. Booth. 1998. *Refurbishment of Air-conditioned Buildings for Natural Ventilation.* The Building Services Research and Information Association. Technical Note TN 8/98. Berkshire, United Kingdom.

Table 2.1. Natural Ventilation and Mixed-Mode Case Study List

Building Name	**City**	**Date (pre)**	**Date (post)**	**Type**	**Construction Activity**	**Motivation for Retrofit**	**Size(s.f.) (post)**	**Control**	**Retrofit Strategies**	**HVAC Description**
Bohemian Club	San Francisco	1933	2008	Office, Assembly	Equipment Replacement	Equipment Replacement	100,000	manual	Retain operable windows	No cooling, NV only. Replaced radiant heat
Oakland City hall	Oakland	1914	1995	Office, Assembly	Interior Renovation	Seismic Upgrade	100,000	manual	Retain operable windows	No cooling, NV only, Original radiant heat upgraded
Historic Central Building, 436 14th Street	Oakland	1926/ 1946	2000	Office, Retail	Interior Renovation	Modernization (Restoration)	150,000	manual	Retain operable windows	4-pipe fan-coil units serving 4 of 14 floors Original radiant heat upgraded.
Flood Building	San Francisco	1904/ 1952	1992	Office, Retail	Interior Renovation	Modernization (Restoration)	300,000	manual	operable windows	Cooling tower added for retail space (Gap, Anthropologie)
Joseph Vance Building	Seattle	1929/ ~1960	2006	Office, Retail	Interior Renovation	Modernization (Restoration)	120,000	manual	unsealed original operable windows, add micro-shades, light shelves, ceiling fans	Original radiators, installed valves for improved local thermal control, AC units are being decommissioned with tenant turnover
Montgomery Hall, San Francisco Theological Seminary	San Anselmo	1880	2000	Office, Classroom	Interior Renovation	Seismic Rehab, Historic Restoration	22,500	manual	unsealed operable windows, added ceiling fans	No cooling, NV only
Berkeley MLK Jr. Civic Center / City Hall (2180 Milvia)	Berkeley	1940	1999	Office, Assembly	Interior Renovation	Seismic Rehab, "Green" Image	77,000	manual	operable windows, ventilation shafts (old dumbwaiters); narrow floor plates + fans enable cross-ventilation; open floor plan; exposed thermal mass	Perimeter radiant heating, window AC taken out during retrofit, packaged units installed in new IT center on fourth floor and converted penthouse (on timer)
Pasadena City Hall	Pasadena	1927	2006	Office	Interior Renovation	Seismic Rehab, "Green" Image	132,500	manual	some windows sealed, some kept operable	Sealed areas: High-efficiency chiller with VFDs, 4-pipe fan-coil units with DOAS, also some AHUs with VAV terminal re-heat. Water-source heat pumps for off-hour operation capability
Thoreau Center for Sustainability	San Francisco	1899/ 1933	1996	Office	Major Renovation	Historic Redevelopment	73,000	manual	operable windows, reduce internal gains	Forced air in select zones only
Presidio Building 38	San Francisco	1899	2001	Office	Major Renovation	Historic Redevelopment	60,000	manual	operable windows	Forced air in select zones only
UCLA Kinsey Hall, aka Humanities	Los Angeles	1930	2007	Office, Classroom	Major Renovation	Seismic Rehab, Change of use, Energy	142,000	manual	operable windows retained	Radiant ceiling panels, UFAD/displacement, forced air

Building						Optimization				
2020 Milvia	Berkeley	1980	On hold	Office	Major Renovation	Modernization	44,000	manual	operable windows	radiant ceiling panels
Center for Neighborhood Technology	Chicago	1920	2003	Office	Major Renovation	Modernization, "Green" Image	15,000	manual	increased insulation, installed efficient equipment	ice storage central chiller
Herman Miller Building	Zeeland, MI	1977/1988	2002	Office	Major Renovation	Modernization, Change of Use, "Green" image	19,100	mechanical	Interior and exterior shading, controlled operable windows for stack/cross ventilation in the event of outage	Forced air; rooftop VAV
Jean Vollum Natural Capital Center	Portland	1895	2001	Retail, Office, Assembly	Major Renovation	New Site	70,000	manual, interlock, occupancy, CO2	new high-performance operable windows, occupancy sensors reduce HVAC use when vacant, window lockouts on HVAC; CO2 sensors control ventilation rates	Forced air; rooftop VAV
BPA Ampere Annex	Vancouver	1943	2004	Office, Industrial	Major Renovation	New Site	3,000	manual	operable windows	Forced air; rooftop VAV
StopWaste.org, 1537 Webster	Oakland	1926	2008	Office	Major Renovation	New Site	14,000	manual, Red/Green Light	operable windows, red/green light control	Packaged RTU, VAV, CO2 sensors
Chicago Center for Green Technology	Chicago	1956	2002	Office, Assembly	Major Renovation	New Site	40,000	manual	operable windows	geothermal
Lavin-Bernick Center for University Life	New Orleans	?	2007	Assembly, Office, Classroom	Major Renovation, Addition (33% new)	Modernization	101,170	manual	shading, insulation, reduced internal gains everywhere; increased setpoints, operable windows, air turbulence and radiant cooling in tempered zones; standard cooling in "thermal refuge" zones	radiant cooling, thermal zoning and set-point modification used to reduce loads
Navy Building 850	Port Hueneme	1940	2001	Office	Major Renovation, Addition (40% new)	Modernization, "Green" Image	10,000	manual	provide vents strategically located for stack vent and cross-vent, operable windows, open plan, reduced internal gains	gas absorption chiller/heater, VAV underfloor air distribution
Georgina Blach Intermediate School	Los Altos	1958	2002	Classroom	Major Renovation, Addition (45% new)	Modernization, Energy Optimization	75,000	manual, mechanical	new operable windows and clerestories, relaxed setpoints, intermittent fan operation, door contacts for HVAC shut-off	rooftop VAV; ductless heat pumps

Sidwell Friends	D.C.	1950/ 1971	2006	Classroom	Major Renovation, Addition (54% new)	Expansion, Modernization, "Green" Image	33,000	manual, interlock	solar-ventilation chimneys plus automated and operable windows in new addition; mechancially-assisted ventilation (exhaust fan pulls outdoor air through operable windows) in renovated portion when conditions are right	district heat,VFDs on fans, heat recovery ventilation
Berkeley YMCA teen center	Berkeley	~1960	2010	Assembly, Office	Gut Rehab, Addition (33% new)	New Site	8,000	manual	No Information Available	No information available
UCSF: 654 Minnesota Ave	San Francisco	1984	2007	Office, Laboratory	Gut Rehab	New Site	65,000	manual, Red/Green Light	operable windows, red/green light control	Dual fan, dual-duct VAV, with heat recovery
NRDC Offices	Santa Monica	1920/ 1975	2003	Office, Retail	Gut Rehab	New Site	15,000	manual, interlock	operable windows, stack ventilation via light wells with rooftop louvers and fan assist, cellular plan	Plinthe diffusers in each office for ventilation, interlocked to windows. Other spaces are zoned for NV only.
San Francisco Friends School	San Francisco	1906/ 1970	2009	Classroom , Assembly, Office	Gut Rehab	New Site	88,000	manual	operable windows, thermal towers	Radiant ceiling panels
Pier One Building	San Francisco	1930	2001	Office	Gut Rehab	New Site, Historic Rehabiliation	115,000	manual	operable windows	Radiant floor slab, optional AHU depending on tenant preference
Clark Hall, U of Washington	Seattle	1899	2009	Classroom, Office, Lab	Major Renovation	Seismic Rehab, Modernization (Restoration, IT)	29,240	Manual	No information available	No information available
Miller Hall, Western Washington U	Bellingham	1943/19 67	2011	Classroom, Office, Assembly	Major Renovation	Equipment Replacement, Modernization (Restoration)		Manual	No information available	No information available
Savery Hall, U of Washington	Seattle	1925	2009	Classroom, Office, Assembly	Major Renovation	Seismic Rehab, Modernization (Restoration, IT)	104,590	Manual	No information available	No information available
Nathan Hale High School	Seattle	~1960	2011	Classroom, Office, Assembly	Major Renovation, Addition (10% new)	Expansion, Modernization	235,000	Manual	No information available	No information available

S.R. Crown Hall Renovation, Chicago Institute of Technology	Chicago	1956/?	2005	Studio, Classroom	Major Renovation (Façade Reconstruction)	Modernization (Comfort problems)		automated	Automated concave perforated blinds; low-e windows; floor-level vent flaps were automated; improved control system for radiant floors.	No information available
Washington State University Compton Union Building	Seattle	1951/19 67	2009	Retail, Office, Assembly	Gut Rehab, Addition (10% new)	Expansion, Modernization, Equipment Replacement	200,000	manual, Red/Green light	Operable windows in certain areas with red/green light control. Sun shades. DCV in public/assembly spaces	radiant panels and chilled beams (corridors) for heating and cooling.

Key

Construction Activity

- **O&M**: Commissioning of the building systems without major equipment replacements
- **Equipment replacement**: Old/failing mechanical equipment is replaced without disruptive tenant improvements
- **Tenant Improvement**: Renovations to the interior are made without a change of use, program or zoning, although occupancy may be disrupted.
- **Major Renovation**: Strategic whole-building changes; programmatic/zoning reconfigurations or partial modifications to façade
- **Shell/Gut Rehab**: Building is entirely re-interpreted for a new use, non-structural elements are removed and a whole façade is refurbished or replaced.
- **Addition**: Existing building makes up >50% of the total gross square footage.[2]

Motivation For Retrofit

- **Equipment Replacement**: Mechanical, electrical, IT or plumbing systems have become insufficient to serve needs of the building
- **Seismic Upgrade**: The building was in need of structural repair or reinforcement.
- **Modernization**: Standard renovations intended to increase lease rates; goals could be aesthetic, comfort-related, etc. For historic buildings, “modernizing” is interpreted as similar to restoring and enhancing original look and feel.
- **Green Image:** “Being green” is a primary driver (e.g. project receives program funding to become a demonstration)
- **Energy Optimization:** Owner wishes to realize operational benefits of retrofits that reduce energy consumption
- **Change of use:** Owner wishes to adapt existing space to a different function (e.g. converting labs to office/classroom space)
- **Expansion:** Need for increased space prompts a whole-building renovation
- **New Site:** An existing building is purchased and re-developed for a new purpose in lieu of a new build project

[2] With the exception of Sidwell Friends School (55% new) because it presents one example where ventilative cooling was enhanced in the existing portion of the building (a separate strategy is employed in the addition) with no dramatic changes in space or use.

Task #3. Integrated systems design and analysis

Task 3 Objective:
Develop within EnergyPlus a prototype commercial building with both underfloor air distribution (UFAD) and hydronic radiant slab.

Deliverable: Sensitivity study status report
The ability to simulate a novel combination of HVAC systems has been added to the existing CBE EnergyPlus toolkit. To implement radiant slab cooling and heating (along with UFAD) two major changes were made to a development version of UFAD EnergyPlus based on CBE's UFAD prototype:

1. Hydronic tubing in the ceiling slab of each zone.
   This radiant hydronic slab system is served by chilled and hot water systems with the aim of cooling or heating the space directly below. The chilled water system uses a heat exchanger to directly link the cooling tower and the demand side of the chilled water system, bypassing the need for a chiller during times when the outdoor wet-bulb temperature is low.
2. System controls.
   To thoroughly investigate the UFAD/Radiant system, several changes were made to the control methods in EnergyPlus v3.1. Two new control options based on the lowest slab surface temperature or the temperature at a depth within the slab and the ability to simultaneously operate both the UFAD and the radiant system at any time of day were added.

Adding these features to EnergyPlus provides the capability to model the following:

- The use of radiant slabs combined with underfloor air distribution (UFAD), including the mitigating effects of the radiant system on thermal decay in the supply air plenums above the slab;
- The use of night-time 'free-cooling,' i.e., use of the cooling tower to supply chilled water directly to the slabs at night, removing the need for a chiller;
- The effects on energy consumption due to the radiant slab parameters, such as tubing depth, length and diameter of tubing, flow rate and control method;
- The extent of improved occupant thermal comfort due to lower summer radiant temperatures and higher winter radiant temperatures.

These new capabilities (after thoroughly testing the new control methods) will allow the following types of sensitivity studies to be conducted:

- Optimizing the UFAD/Radiant design
- Examine integrated systems energy consumption when compared to existing systems such as standard UFAD and overhead

This work also prepares us to accomplish the following (under other contracts):

- Preparing a paper for the International Conference on Applied Energy (ICAE) 2010, for which an abstract has been accepted.
- Conduct a case-study of the David Brower Center, Berkeley, CA, that will begin later this year

Task #4. Monitoring, commissioning, and benchmarking tools development

Task #4a Objective:
Design and develop software to support a new prototype portable data acquisition system based on advanced wireless technology.

Deliverable: Prototype portable data acquisition software

Background
In a previous study (Advanced Systems Technology development, BOA-99-200-P) we developed a system architecture that would support a diverse application of wireless sensors for commissioning and performance monitoring purposes. This architecture is shown in Figure 4.1. To develop the application software for this prototype system it is necessary to obtain a reliable wireless network platform. We conducted a study of various options and determined that the ArchRock system potentially represents one of the best "state of practice" technologies readily available. To ensure that this system would meet our needs we embarked on a test and evaluation study using components loaned to us by ArchRock.

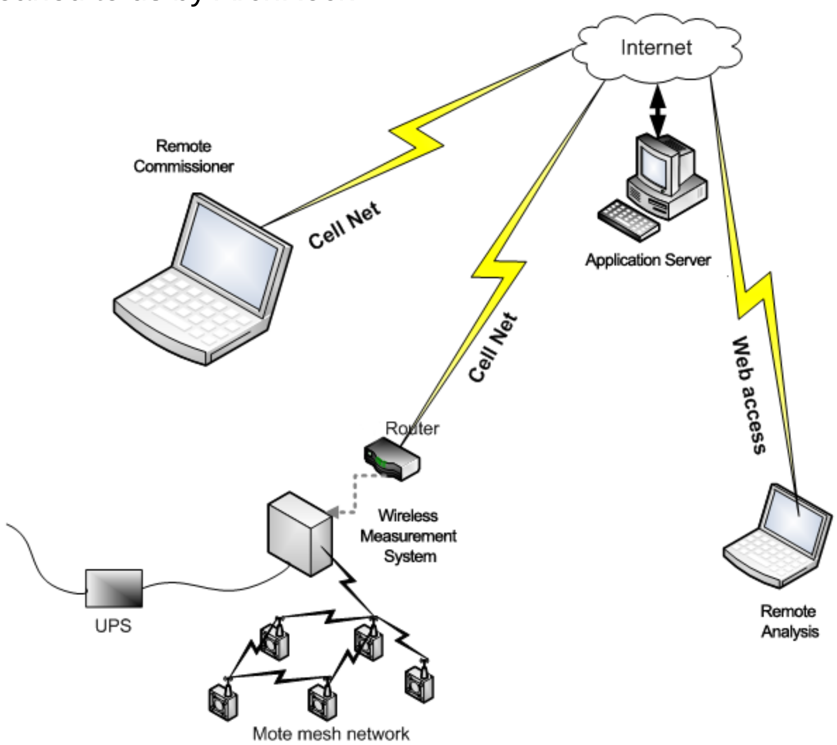


Figure 4.1 Wireless monitoring and data acquisition system architecture

System characteristics:
Wireless Measurement System: The system containing the motes, mote manager, and control PC
Application Server: A PC that hosts the master data base and the applications software for performing analysis and data presentation

Remote Commissioner: A remote PC from which a testing agent can initiate and terminate data collection, as well as review and analyze collected data.
Remote Analysis: A remote PC from which a user can review and analyze collected data.

Evaluation Hardware Summary

Hardware Received:

2 Phynet Routers (RSS-2020)
15 IPThermal Nodes (RSN-3040-XT) with 15 Thermal Probes (RSA-3002-XT)
2 IPThermal Nodes (RSN-3040-XT) with 6 Thermal Probes (RSA-3002-XT)
1 IPThermal Node (RSN-3040-HT) with 3 Temperature and Humidity Probes (RSA-3004-HT)
1 IPPressure Node (RSN-3045-DP) with 1 Differential Pressure Probe (RSA-3006-DP)
3 IPsensor Nodes (RSN-3012)
1 IPsensor N4X Node (RSN-3010-N4) with Power Pack N4X (RSN-DCPA-N4)
1 Power Node XT (RSE-1010) with single monitored office outlet

Hardware Description:

Phynet Router – An IP-based 802.15.4 wireless sensor networking device that connects 6LowPAN mesh networks via Wi-Fi and Ethernet interfaces to diverse WAN links.

IPThermal Nodes – A series of 802.15.4 wireless temperature and humidity monitoring nodes.

IPpressure Nodes – A series of 802.15.4 wireless differential pressure monitoring nodes.

IPsensor Nodes – A series of 802.15.4 wireless of temperature and humidity monitoring nodes.

IPpower Nodes – A series of 802.15.4 wireless power sub-meter provide a detailed, real-time, remote view of electric consumption.

IPsensor N4X Nodes – A series of 802.15.4 wireless analog sensors ruggedized for outdoor use. This node is used in conjunction with **Power Pack N4X**.

Testing Hardware Architecture

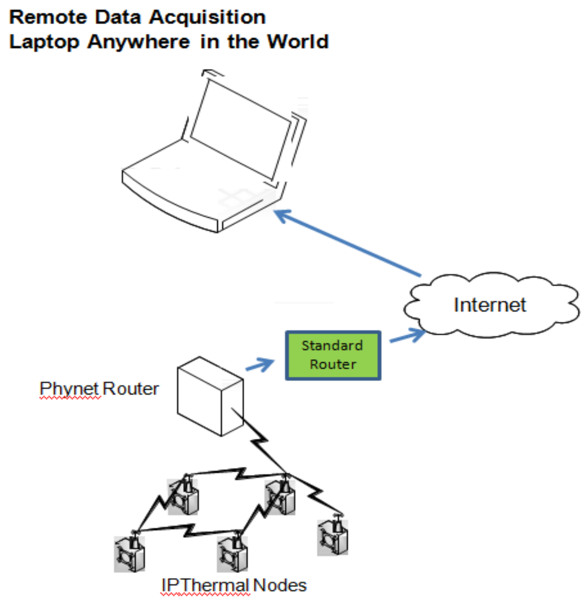


Figure 4.2 Testing Hardware Architecture

Figure 4.2 illustrates the hardware architecture used for testing and evaluation. This system consists of the following Arch Rock nodes: 15 IPThermal Nodes, 3 IPSensor Nodes, 1 IPpressure Node, and 1 IPPower Node and a Phynet Router. All sensor data is communicated to the PhyNet Router via the 6LowPAN wireless mesh network. The Phynet Router is linked to the internet through a standard router. The data can then be viewed, gathered and analyzed remotely via the internet.

The Phynet Router Software is used to configure the Router and established the mesh network. Figure 4.3 illustrates the Phynet Router System setup screen.

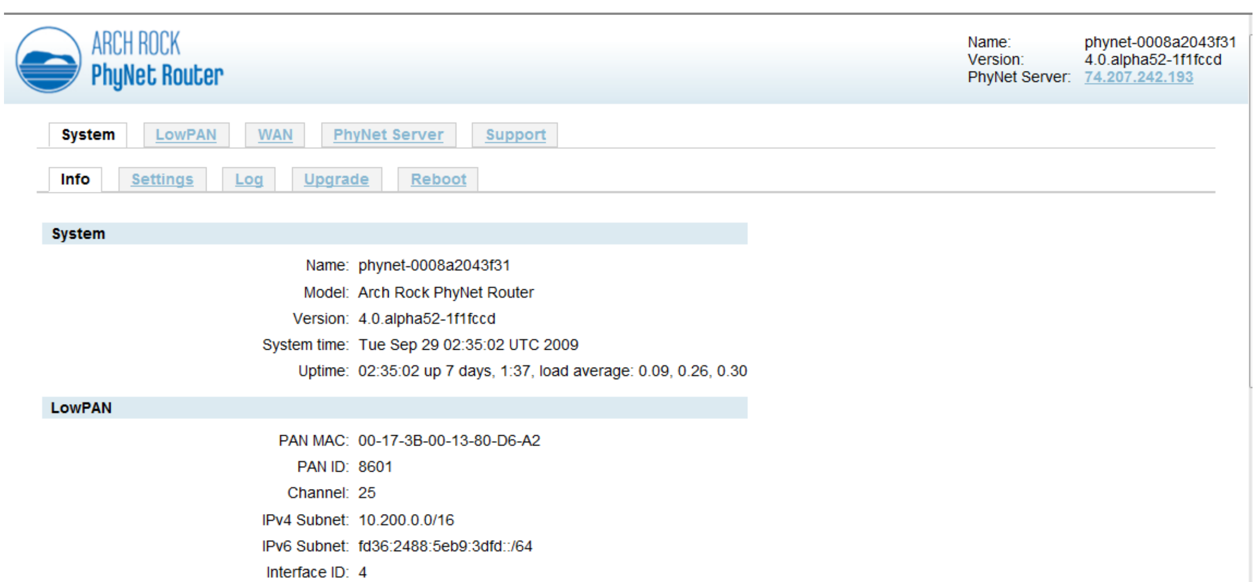
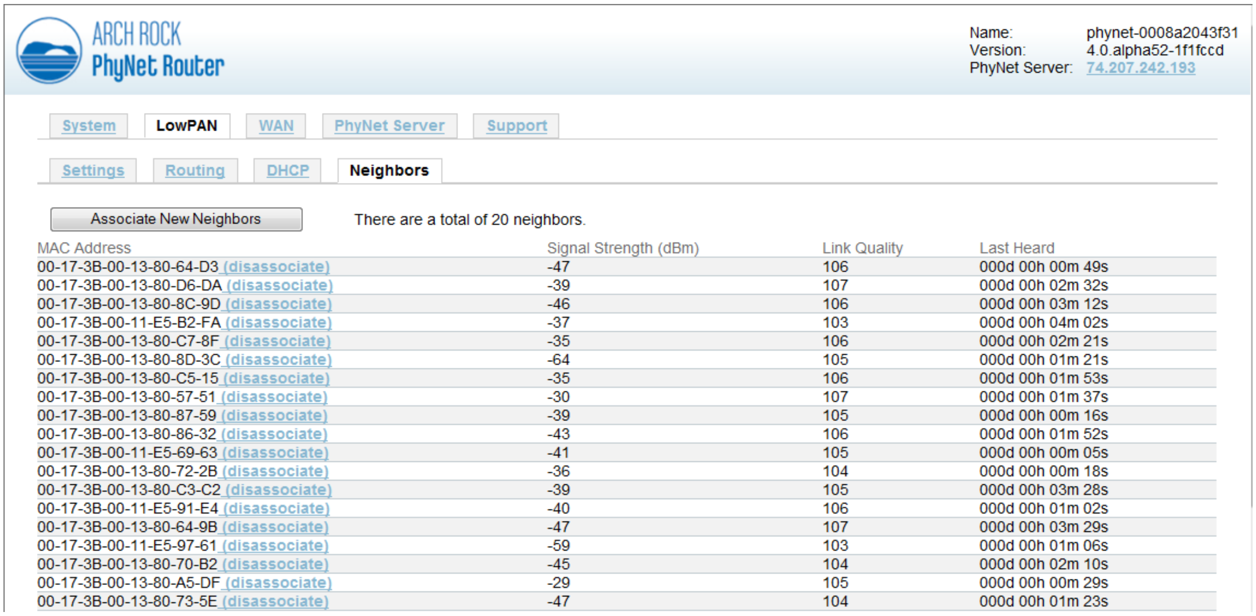


Figure 4.3 Phynet Router System Setup Screen

Figure 4.4 illustrates a partial screen showing the association of various wireless sensor nodes. Each wireless node must appear on this list in order to transmit data to the server.


ARCH ROCK
PhyNet Router

Name: phynet-0008a2043f31
Version: 4.0.alpha52-1f1fccd
PhyNet Server: 74.207.242.193

System | LowPAN | WAN | PhyNet Server | Support

Settings | Routing | DHCP | Neighbors

Associate New Neighbors

There are a total of 20 neighbors.

MAC Address	Signal Strength (dBm)	Link Quality	Last Heard
00-17-3B-00-13-80-64-D3 (disassociate)	-47	106	000d 00h 00m 49s
00-17-3B-00-13-80-D6-DA (disassociate)	-39	107	000d 00h 02m 32s
00-17-3B-00-13-80-8C-9D (disassociate)	-46	106	000d 00h 03m 12s
00-17-3B-00-11-E5-B2-FA (disassociate)	-37	103	000d 00h 04m 02s
00-17-3B-00-13-80-C7-8F (disassociate)	-35	106	000d 00h 02m 21s
00-17-3B-00-13-80-8D-3C (disassociate)	-64	105	000d 00h 01m 21s
00-17-3B-00-13-80-C5-15 (disassociate)	-35	106	000d 00h 01m 53s
00-17-3B-00-13-80-57-51 (disassociate)	-30	107	000d 00h 01m 37s
00-17-3B-00-13-80-87-59 (disassociate)	-39	105	000d 00h 00m 16s
00-17-3B-00-13-80-86-32 (disassociate)	-43	106	000d 00h 01m 52s
00-17-3B-00-11-E5-69-63 (disassociate)	-41	105	000d 00h 00m 05s
00-17-3B-00-13-80-72-2B (disassociate)	-36	104	000d 00h 00m 18s
00-17-3B-00-13-80-C3-C2 (disassociate)	-39	105	000d 00h 03m 28s
00-17-3B-00-11-E5-91-E4 (disassociate)	-40	106	000d 00h 01m 02s
00-17-3B-00-13-80-64-9B (disassociate)	-47	107	000d 00h 03m 29s
00-17-3B-00-11-E5-97-61 (disassociate)	-59	103	000d 00h 01m 06s
00-17-3B-00-13-80-70-B2 (disassociate)	-45	104	000d 00h 02m 10s
00-17-3B-00-13-80-A5-DF (disassociate)	-29	105	000d 00h 00m 29s
00-17-3B-00-13-80-73-5E (disassociate)	-47	104	000d 00h 01m 23s

Figure 4.4 Associated Wireless Sensor Nodes

Once all of the wireless sensor nodes are associated through the Phynet Router, the data can be viewed and gathered by logging on to the Phynet Server.

As noted above for the intended system architecture, application software would reside on a remote server which would run LabVIEW Data Acquisition software (or equivlatent) by accessing the Phynet Server database to retrieve all of the data from the wireless nodes. The LabVIEW software in turn would anlayze the gathered data and, for example, could determine pass/fail criteria based on a set of predetermined metrics or calculate various performance metrics.

Sample Screen Capture

The following section includes several screen captures of actual data gathered from a few types of wireless sensor nodes.

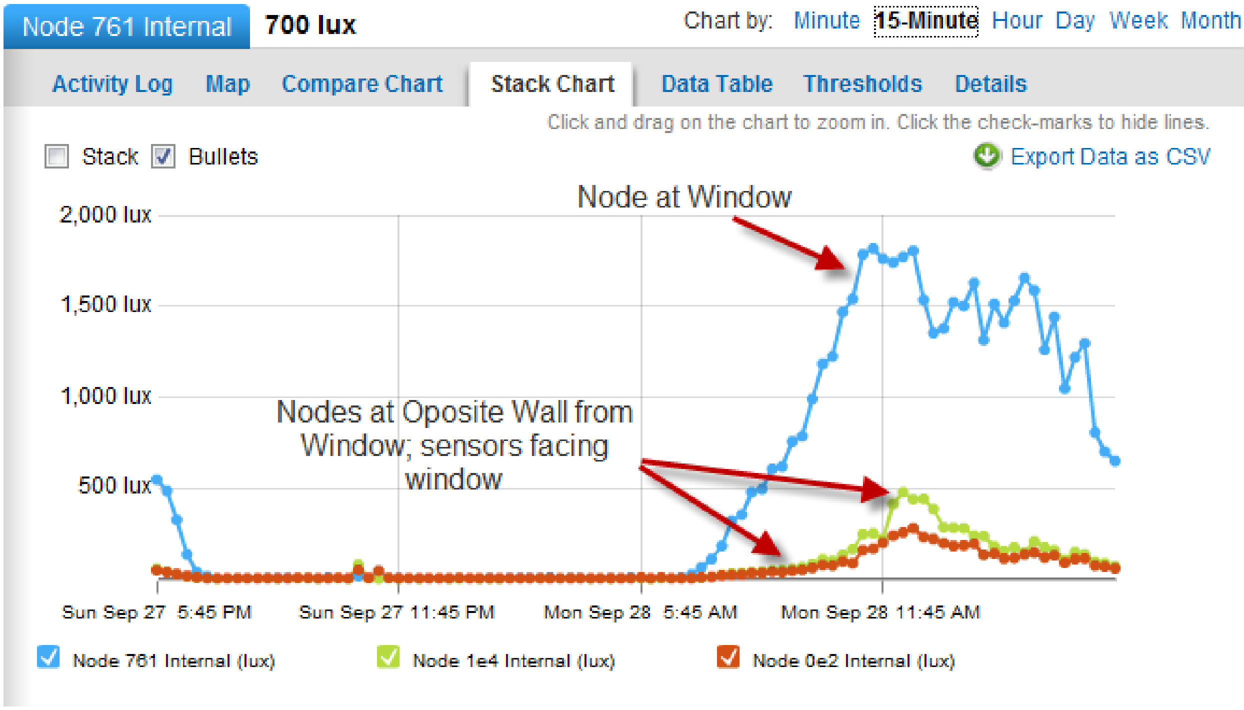


Figure 4.5 Light intensity measurements for the 3 IPsensor nodes

Figure 4.5 illustrated light measurement over a 24 hour period. The 3 sensors are placed in various locations within the office. The sensor with the largest signal strength (light blue) is closest to the window. Each measurement is averaged over a 15 minute interval. Note the small glitches just before 11:45 pm on Sunday, these are most likely the lights being turned on.

Figure 4.6 is the same as Figure 4.5 with the addition of the average temperature data from all of the IPThermal nodes. The system currently has 15 IPthermal nodes, 3 IPsensor nodes, and 1 IPpressure node. Each IPthermal node has 3 temperature sensors, 2 external and 1 internal. The 3 IPsensor nodes and the IPpressure node each have a single internal temperature sensor. The average temperature is the average of all 49 temperature sensors currently active in the system.
Note the correlation between daylight entering the room and the rise in average room temperature.

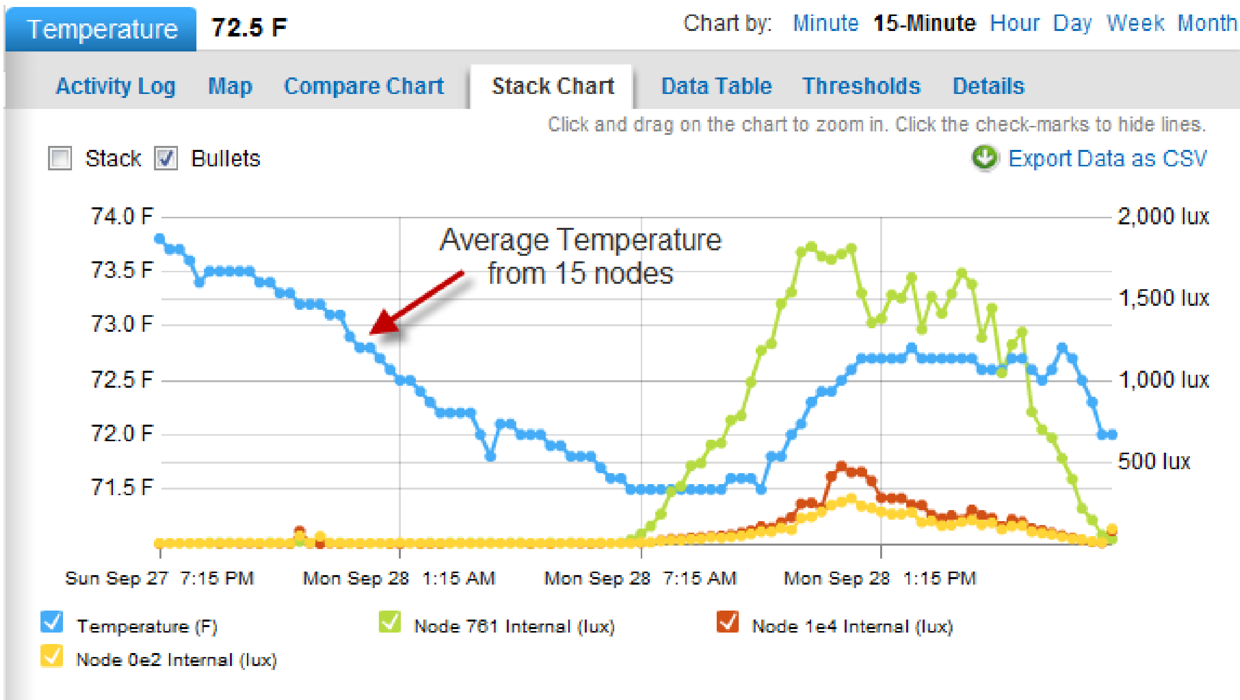


Figure 4.6 Light intensity measurements for the 3 IPsensor nodes along with average of 15 thermal probes

Figure 4.7 is a graph of the humidity measurements from 9 nodes as well as the average from all 18 nodes. The Phynet server is capable of displaying only 10 graphs at a time.

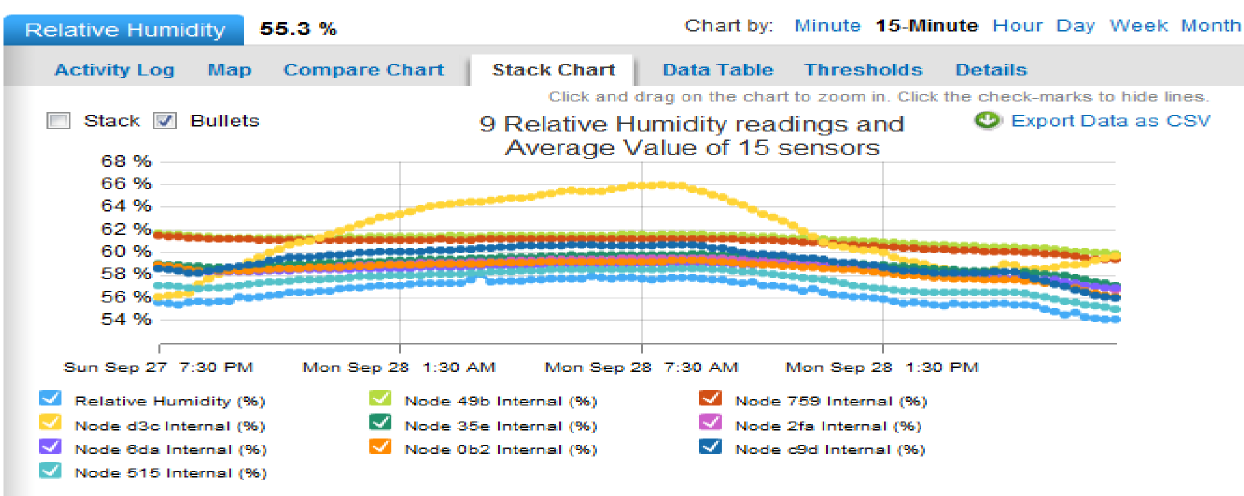
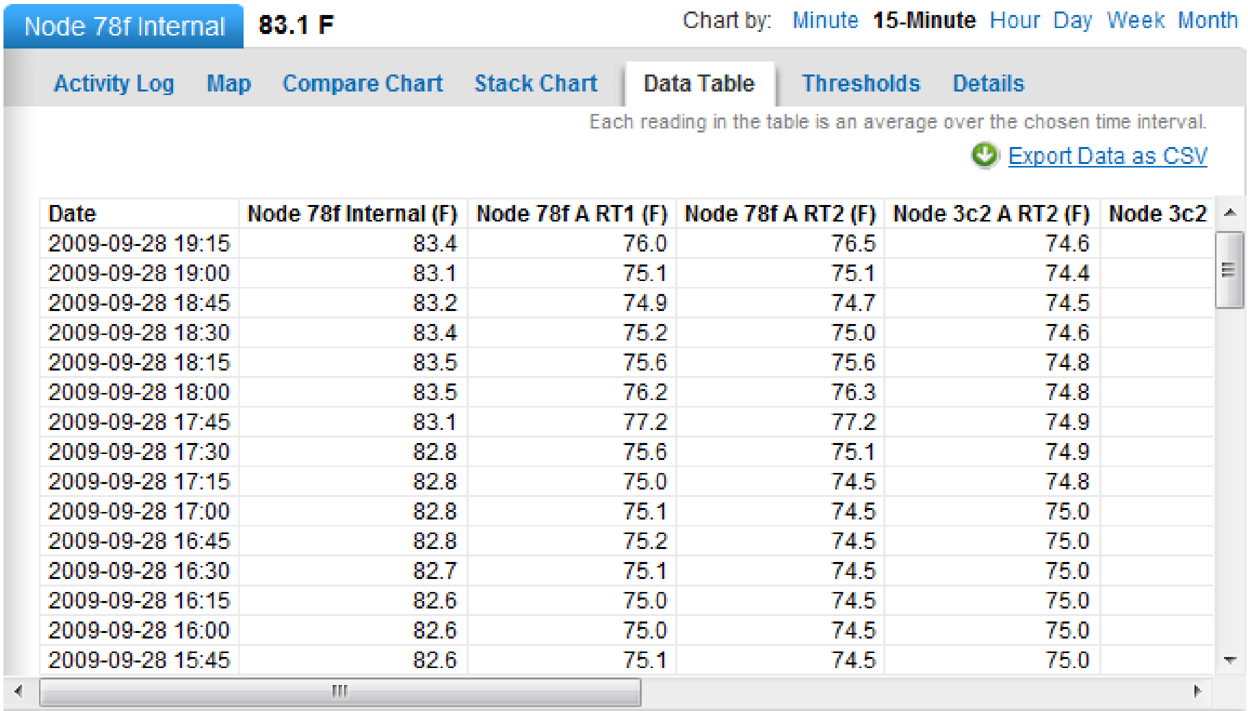


Figure 4.7 Humidity measurements for the 9 nodes along with average of all 18 nodes



Date	Node 78f Internal (F)	Node 78f A RT1 (F)	Node 78f A RT2 (F)	Node 3c2 A RT2 (F)	Node 3c2
2009-09-28 19:15	83.4	76.0	76.5	74.6	
2009-09-28 19:00	83.1	75.1	75.1	74.4	
2009-09-28 18:45	83.2	74.9	74.7	74.5	
2009-09-28 18:30	83.4	75.2	75.0	74.6	
2009-09-28 18:15	83.5	75.6	75.6	74.8	
2009-09-28 18:00	83.5	76.2	76.3	74.8	
2009-09-28 17:45	83.1	77.2	77.2	74.9	
2009-09-28 17:30	82.8	75.6	75.1	74.9	
2009-09-28 17:15	82.8	75.0	74.5	74.8	
2009-09-28 17:00	82.8	75.1	74.5	75.0	
2009-09-28 16:45	82.8	75.2	74.5	75.0	
2009-09-28 16:30	82.7	75.1	74.5	75.0	
2009-09-28 16:15	82.6	75.0	74.5	75.0	
2009-09-28 16:00	82.6	75.0	74.5	75.0	
2009-09-28 15:45	82.6	75.1	74.5	75.0	

Figure 4.8 Temperature data in table format

The Phynet Server can also display the data in a table format as shown in Figure 4.8. Only a total of 10 data can be displayed at any given time. All data can be exported to a CSV file for additional post processing.

Temperature sensing accuracy

Analysis of the collected temperature data has revealed a resolution of 0.2°F. Although greater resolution would be desirable, for most intended monitoring purposes this resolution appears to be adequate. Higher resolution could be achieved with add-on components, if necessary.

Task #4b Objective:
Review literature and available building dashboard products. Identify modifications to improve functionality based on CBE experience. Such improvements should include, integration of open-source software protocols, new visualization methods (intra-building and geo-spatial), and ways of capturing more precise occupant sentiment through survey instrument design.

Deliverable: Scoping study report on building dashboard systems
CBE conducted a literature review and survey of several commercially available energy interface products. We conducted interviews with leaders of software companies to document the capabilities, intended markets and audiences, number and types of implementations, and technologies used in these products. Preliminary findings on these efforts were published in CBE's *Centerline Magazine* in January 2009, as "Visualizing building information: using information feedback to educate and influence building managers and occupants." This work was continued over the summer of 2009, and has been summarized in the attached *interim report*, "Research scoping report: visualizing information in commercial buildings." An abstract of this paper is included below.

ABSTRACT: Research scoping report: visualizing information in commercial buildings

New data acquisition technologies and information visualization methods provide great opportunities to monitor and display building performance data. Together they provide the building industry with the potential to give feedback to commercial building occupants, managers, and other parties, and to encourage energy-saving behaviors.

A great deal of research has been conducted to evaluate the potential for energy conservation using information feedback to influence occupant behavior in residential buildings. Results of these studies show that immediate energy feedback from meters or display devices can provide savings of 5-15%. However, little research has been conducted on such feedback in commercial buildings, which present a greater challenge due to their greater complexity.

Researchers at CBE propose to contribute to this information gap by conducting research on effective visualization of building information in commercial buildings. The goals of this work are: (1) to identify the optimal methods for displaying building performance information, in order to influence commercial building occupants to reduce resource use; and (2) to identify methods to provide actionable information in order to assist building operators in achieving improved building performance; (3) to develop methods to include occupant feedback in these information displays, based on previous work conducted at CBE on occupant comfort and workplace satisfaction; and (4) to develop and test user interfaces for building data with various building stakeholders.

Task #5. Thermal comfort modeling

Task #5 Objectives:

1. Program the Berkeley Thermal Comfort Model (BTCM) to exchange inputs/outputs with EnergyPlus.
2. The BTCM will also be connected to commercially available solid modeling software to allow input of complex geometries.
3. Program the BTCM to allow the user to input environmental conditions data into buildings created by BTCM's existing Room Editor. .
4. Our goal is to improve the ability of the BTCM to import body-part-specific clothing values. The user will have the ability to choose clothing assembles from a database. As the first step toward that goal, we will program this interface and data file structure, prior to making manikin measurements to fill the database. The manikin measurements will be conducted later, under separate funding.

Deliverable: Improved Berkeley Thermal Comfort Model capable of exchanging data with EnergyPlus, and with an expanded clothing database structure

1. We added an XML function in the Berkeley Comfort Model. The XML function allows the Berkeley Comfort Model to exchange data with other models. Following is the brief description of the XML function and the work that we have accomplished.

   A phase-base XML data interface is defined to exchange simulation conditional information and result between Berkley Comfort Model and other building design models. Through the XML interface, building design models can send a simulation request to the comfort model. The comfort model then converts the xml data to its internal data format and executes the simulation. Then simulation result will be sent back to design models.

   According to the comfort model, simulation condition parameters are based on the phase, a slice of simulation period which allows the different simulation conditions to be indicated. Multiple phases can be defined in the XML data. In each phase, detailed ambient parameters about simulating building environment and manikin can be defined such as air temperature, panel temperature, air velocity, glass type, humidity, view factor, solar load, and body builder.

   The following are the element structures of the interface XML data.

- pubPhaseModel
  - phaseData
    - global
      - output
      - bodyBuilder
    - phases
      - phase
        - control
        - body
        - environment
        - solarload
        - viewfactor

This XML version basically covers all necessary information to run the comfort model.

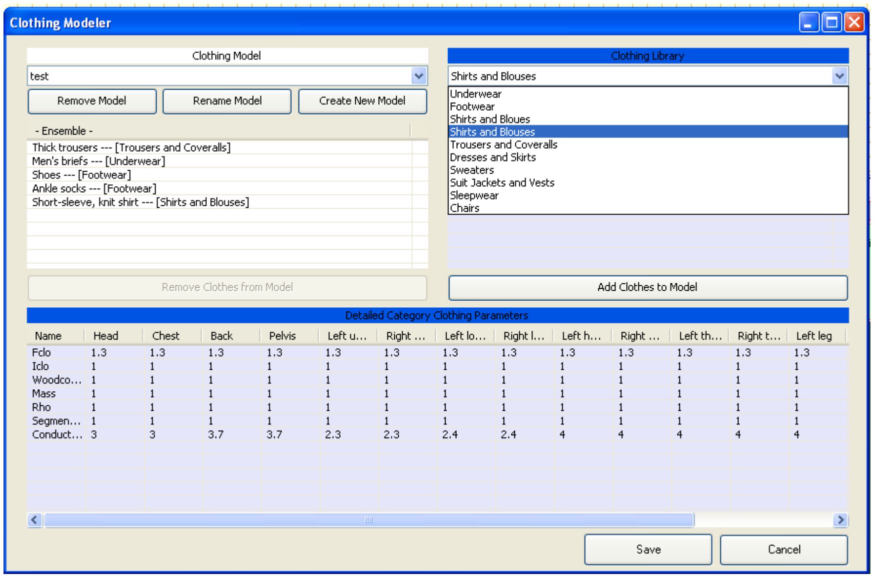
2. UC Berkeley has acquired the NX software suite which meshes geometrical models in hypermesh format. We are currently installing it at CITRIS, and should be using it in this next period.

3. The BTCM was programmed to allow the user to input measured data for a geometry created by the RoomEditor.

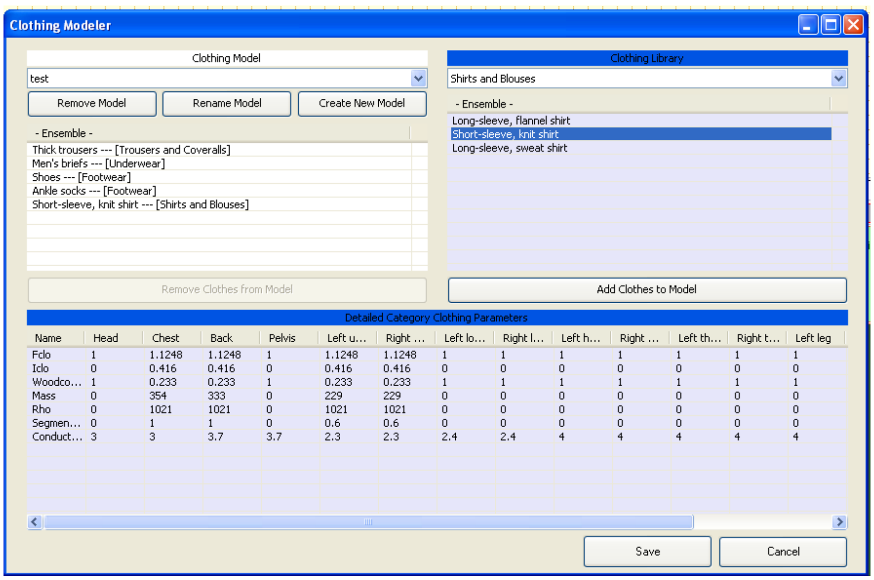
4. In the current version of the BTCM, the default clothing ensemble has been based on summer office wear, consisting of cotton pants and long-sleeved shirt, with a clo value of 0.6. Although it is possible to model other clothing options, doing so has been cumbersome (and could only be done by CBE research staff).

   We first developed algorithms to calculate the characteristics of each clothing part and clothing ensembles. We then developed a new interface that allows users to select clothing options, displaying detailed information for each clothing element and the entire ensemble as it is created.

   An interface of the "clothing editor" is shown in Figure 5.1. Clothing is grouped as different categories under "Clothing Library" (right top box in the figure a), such as "shirts and blouses", "footwear". Once selecting the category, the individual clothing pieces would appear (Figure b), which allows user to pick up to create a clothing ensemble. If the user clicks on one individual piece of clothing, the interface shows the characteristics of the clothing, such as insulation level and moisture resistance. If the user clicks on several pieces together, the interface presents the combined results for these pieces and for the ensemble.



a. Selecting clothing category



b. Selecting individual clothing pieces to make an ensemble

Figure 5.1 Berkeley thermal comfort model clothing editor

We completed the new interface, and are currently validating the clothing data algorithms and testing a beta version. Once it is validated, we will expand the database to include a large number of clothing categories, from office wear to outdoor casual outfits.

Task #6. Codes, standards, handbook, and guidelines support

Task #6 Objectives:

- Continue development of advanced systems modeling support for T-24 ACM procedures
- Work with Standard 55 committee to make sure the class structure is fully evaluated and discussed before being adopted by ASHRAE.
- Work with committee revising the 2003 UFAD Design Guide, originally authored by Bauman, incorporating subsequent PIER-sponsored research results obtained by CBE.
- Author selected chapter sections in ASHRAE Handbooks currently undergoing revision to include new research results and guidelines on advanced building technologies.

Deliverable: Research status report

1. The revision to ASHRAE Standard 55 allowing air movement to compensate for warm air temperature has been adopted. A paper describing the new standard was published in the *ASHRAE Journal* May 2009 issue (attached).
2. The paper “Are ‘class A’ temperature requirements realistic or desirable?” is scheduled to be published in the January 2010, *Building and Environment* 45(1), with the online version available now.
3. We are participating in a subcommittee to propose new IEQ performance classifications for the standard. The form of such classifications is unclear, but high performance will not be based on narrow ranges of temperature control.
4. ASHRAE Standard 55 Committee is planning an informative appendix for personal environmental control systems (PECS). Ed and Hui are on the sub-committee to prepare this work. As the first step, we are writing a review paper to describe all published PECS’ ability to correct ambient air temperature, thermal sensation, and thermal comfort.
5. The ASHRAE PMP document is now in the printing preparation stage. The CBE satisfaction survey is designated as the primary measurement instrument for all IEQ variables.
6. Work has continued on the ASHRAE TRG7-UFAD committee to revise and update the ASHRAE UFAD Design Guide published in 2003. Progress has been slower than originally anticipated so no first draft is available yet. Currently, smaller working groups are developing revised chapters on specific topics for inclusion in the final draft Guide. To date, first drafts have been completed of the following sections:
   - Section 1.3: Introduction – Basic System Description
   - Section 2: Room Air Distribution Principles
   - Section 5: UFAD System Configurations
   - Section 6: Room Air Supply Units and Outlets
   - Section 7: Indoor Environmental Quality Considerations
   - Section 9: Standards, Codes, and Ratings
   - Section 14: Guidance for Building Commissioning
   - Section 15: Guidance for Maintenance and Operations