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Case Study: Seven-System Analysis of Thermal Comfort and Energy Use for a Fast-Acting Radiant Heating System

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ABSTRACT

The Radiant Demonstration Program (RDP) was developed for the management association of a large retirement single-family housing community in the Northeast for the purpose of providing comparative data for heating system retrofit selection. Control and pre- and post-retrofit energy consumption data were monitored for two to four years in approximately 100 occupied units of 19 designs. The heating systems involved encompassed electric concealed ceiling radiant panels; fast-acting, ceiling surface mounted radiant panels; baseboard heaters; forced air furnaces; standard air, high-efficiency air, and geothermal heat pumps; and gas forced air high-efficiency furnaces. All units had a separate air-conditioning system. Significantly lower retrofit installed and maintenance costs were demonstrated for the fast-acting radiant panels. Comparative energy use of fast-acting radiant panels was less for the systems involved, with the range of savings apparently varying in relation to previous relative comfort and interest in practicing occupancy-based room temperature control.

INTRODUCTION

Before the National Association of Home Builders Research Center (NAHBRC) radiant heating study was conducted under the Advanced Housing Technology Program (AHTP) sponsored by the U. S. Department of Energy, there were few performance data available and little distinction between ceiling radiant systems. The NAHBRC case study monitored thermal comfort and energy performance in an occupied home during the 1993-94 heating season. The project was conducted to expand the base of information on which heating systems are based. The case study found: "The magnitude of savings obtained for the working couple occupying the research home suggests that energy saving would be obtainable in a great portion of U. S. households. It is important to note that the comparative energy performance of the three systems is specific to the Adaptable Fire Safe Demonstration (AFSD) house and its occupancy by a working couple. Savings in other homes with varying numbers of occupants and their daily routines could have a significant impact on the comparative energy performance of the three heating systems."

Falling real estate prices and rising maintenance and repair costs prompted the condominium association to develop a program to enhance its competitive attractiveness as a retirement community. Therefore, the case study focused on the relative performance of various heating technologies in relation to the needs of the retirement community. The information developed in the Radiant Demonstration Program (RDP) may be used with the NAHB case study to compare the comfort and energy performance of various heating systems in new and retrofit applications.

BACKGROUND

The rural northeastern retirement community was built in the late 1960s and early 1970s for persons 55 years old or older “empty nesters." Members of the active retirement community now average 77 years of age. The bucolic 2,700-unit complex includes single- and two-story duplex and quadplex cedar-sided buildings clustered in 24 condominium groupings. The buildings are slab construction with open-air vented attics, outside wall brick fireplaces, metal-framed sliding doors and windows with thermopane glass, non-insulation certified overhead recessed lighting, and bathroom ceiling heat/fan units. Duplex units have 9-ft living and dining room ceilings; other ceilings are 8 ft. Some duplex units have garages underneath and/or crawl spaces. Four hundred units heat with electric furnaces. The rest are heated by concealed resistance heat wire pre-embedded in sheet rock serving as the ceiling. Six-inch fiberglass batts insulate the vented open-air attics. Standard correction of heating system failure involved removing the "ceiling" and reinstalling new sheet rock heater panels, which required taping, sealing, and texturing the entire contiguous ceiling area. Entry and sliding glass door areas were supplemented by 750 W or 1500 W floor heaters connected to the radiant system thermostat. Installed watt capacity was 11 kW for the quadplex units, 17 kW for the duplex, and 20 kW for the electric furnaces.

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The pocketbook issues were basically broken down into three categories: real estate value, energy cost, and condo fees. While the market value drop is partly explained by area economic indexes, the "electric heat" image and high maintenance fees were also blamed. Rising electric rates spawned increased "high bill" complaints, while the age-related repairs were escalating condo fees. Replacement of failing and drooping ceiling heat panels created a major and increasing expense. The condominium association was concerned that repairs were not taking advantage of new technologies that would improve comfort and lower costs while eliminating the problems that necessitated replacement or repair. The RDP followed a "high bill" heat pump utility initiative that had unattractive capital costs. The condominium association was searching for programs to increase the economic attractiveness of the retirement community.

The comfort deficit inherent to the original buildings was also of major concern to the aging occupants. Owners reported discomfort sitting on window seats or near living room or bedroom sliding glass doors, unused living room fireplaces, kitchen dining table windows, and in the bathrooms and dressing areas. Temperature setback is impractical due to the lengthy recovery period inherent with high mass, concealed radiant systems. Moreover, the association prohibited setback because frozen pipes were a recurring problem. Some residents didn't feel comfortable regardless of how much money they spent on heating.

METHODOLOGY

A lottery drawing was used to select one condominium to represent each of 18 building designs. A surface mounted, modular, fast-acting ceiling radiant heating system was installed in each unit. Pre- and post-energy consumption was monitored during several heating seasons. Occupants compared the new fast-acting radiant system with concealed radiant heating and electric forced air central furnaces. In addition, 12 "high bill" complaints represented four designs that were previously retrofitted with standard air-to-air, high-efficiency air-to-air, and groundwater heat pumps (four of each), with monitored pre- and post-energy consumption over the same three- or four-year period. Four units were retrofit with compact, modern gas forced air furnaces, which also provided hot water.

Separate metering was employed for the heat pumps for a period of time. The weather data normalization appeared to have very close correlation with the base bill average method during the mild 1994-95 winter. The apparent impact of the resistance backup resulted in significantly higher kilowatt hour per degree-day figures for the normal 1993-94 and 1995-96 winters, invalidating normalization as a tool for analysis of energy use. Next, a popular weatherization model, PRISM (Princeton Score Keeping Method), was employed to evaluate the 1995-96 energy use in the radiant panel installations. 'Me intent was to determine the impact of a limited weatherization program that involved caulking and sealing and the addition of attic fiberglass batt insulation to a total of R-38, which where not already in place. PRISM utilizes whole-house meter readings and average outdoor temperatures to develop normalized annual (energy) consumption (NAC) for pre- and post-weatherization periods. According to the PRISM manual, "A static mode, PRISM is not appropriate, as some dynamic models are, for the management of a building to schedule thermostat setbacks." A feature of fast-acting radiant panels is dynamic occupancy oriented setup and setback, making use of **PRISM inappropriate due to** the "interventions" characteristic of the retrofit radiant equipment.

In the absence of instrumentation and/or appropriate dynamic modeling, the method of choice for analysis is the base bill method. A large sample population monitored over a period of several years provides an opportunity to detect distortions and benefits from time period averaging. The results of this approach tracked the experience documented in the DOE AHTP Project 4183 Case Study. The information developed in the RDP shows the range of energy use that might be anticipated in an elderly population with various residential retrofit heating system alternatives. The resident energy use range relates to the "comfort" of the original system, savings motivation, life-style, and the performance features of the retrofit system.

RETROFIT EQUIPMENT SIZING AND INSTALLATION PARAMETERS

Original Concealed Ceiling Radiant and Electric Furnace

The installing contractor appears to have followed general sizing and equipment practices in use before the 1973 energy crunch led to more demanding building codes. The concealed radiant sheet rock panels (14 wsf) were sized at 10 watts per square foot (W/ft2) of floor space. Additional in-floor convection heaters (750 W - 1500 W) were installed in front of sliding glass doors. It is normal practice to employ practicable, usually space-limited, oversizing to reduce the multiple-hour system recovery from vacation temperature setback. Individual room thermostats were designed for zone control.

The electric furnaces were 20 kW units, which reflected 30% or more oversizing, again to improve setback recovery. Metal ducting was incorporated with the slab to provide heat delivery at floor level. As with most central systems, control was by a single low-voltage thermostat.

Heat Pump and Gas Furnace

Standard and high-efficiency air-to-air heat pumps, as well as geothermal heat pumps, were sized according to *Manual J* and ASHRAE methodology by the electric utility and the installing contractor. All heat pumps were installed with emergency resistance backup of 15 kW, according to standard practice in the harsh northeastern winter climate. Both equipment failure and the needs of the elderly population validated the necessity of installing emergency backup heat for all heat pumps. Due to the prohibitive cost of running new ducting, the existing air-conditioning ducts were used with appropriate modification (additional outlets, etc.). Control was by a single programmable heat pump thermostat.

The high-efficiency gas forced air furnaces were sized by the installing contractor. Installation was in the former electric water heater "closet," requiring continuous mechanical ventilation. Again, due to cost, existing air-conditioning ducts were used with minor modification. Sizing reflects current multiple-equipment capacity options and setback recovery oversizing of 30%. Control is by a single low-voltage thermostat.

Fast-Acting Surface Radiant System

The fast-acting surface radiant system was sized by the manufacturer based upon extensive field experience in relation to established ASHRAE heat loss calculations. Sizing was consistent with the methodology used for the NAHBRC case study, which incorporated thermal comfort monitoring based upon ASHRAE Standard 55 (ASHRAE 1992). The Building Comfort Analysis Program (BCAP) was employed to fine-tune installations. The unique characteristics inherent in the retirement complex construction and the occupant requirements necessitated sizing review. Yet installed capacity was 40% to 60% less than the comparative system. The multi-sized, higher watt density (50 W/ft2), surface radiant panels are sized to the nearest 100 W of heated area and located in relation to heat loss requirements. Ceiling coverage is approximately 15%, compared to 80% for the concealed radiant. Control is by replacement, radiant sensing line voltage controls.

Thermal Comfort and Mean Radiant and Operative Temperatures

ASHRAE design philosophies continue to be focused upon obtaining a specific indoor air temperature for a given "design" outdoor air temperature. Referred to as the "envelope" calculation, the designer requires information on the number and type of walls, windows, and doors, the ceiling, and floors-but does not need information detailing the relative locations of these building components. An "energy balance" is then performed using regional weather data to determine the "design" outdoor temperature.

The thermal comfort approach incorporates the philosophy of providing occupant thermal comfort in the built environment rather than simply establishing a design air temperature. This procedure is not new. In fact, ASHRAE Standard 55 has stood the test of updating every 5 years for more than 25 years. The complexity of radiant heat transfer calculations was an obstacle to implementation of the standard until ASHRAE Research Project 657, Simplified Method to Factor Mean Radiant Temperature (MRT) into Building and HVAC System Design (Jones and Chapman 1994), produced the Building Comfort Analysis Program (BCAP). MRT is defined as "the uniform temperature of an imaginary enclosure in which the radiation from the occupant equals the radiant heat transfer in the actual nonuniform enclosure" (Fanger 1967).

Thermal comfort is defined in the standard as "the state of mind that expresses satisfaction with the thermal environment." The standard defines thermal comfort as a function of air temperature, MRT, air velocity, relative humidity, clothing, and activity level. Activity level and clothing requirements are normally consistent with the building environment, air velocity is maintained low enough to prevent drafts, and the effect of humidity on thermal comfort is usually a function of the overall HVAC system. Therefore, the air temperature and MRT are the parameters controlled by the design engineer in a specific built environment. Nonuiniformity in the radiation field, which leads to occupant discomfort, is expressed in terms of the difference between the mean radiant and mass-averaged air temperatures. While MRT provides an indication of the radiation field in the room, Fanger (1967) found that the ambient air temperature cannot be ignored. Operative temperature, which combines the relative effects of the air temperature and the MRT by weighting convective and radiative heat transfer coefficients, is the best parameter to judge local thermal comfort.

The BCAP model incorporates radiation, conduction, convection, and air infiltration. This preciseness leads to enhanced, reliable MRT calculations coupled with calculated dry-bulb temperatures that provide an excellent indication of thermal comfort. The methodology provides a myriad of results in addition to the MRT and operative temperature, including radiant asymmetry and air and surface temperatures. This methodology was useful in selecting heater output and design location for the fast-acting radiant panels to optimize room thermal comfort signature (TCS).

FIELD TEST RESULTS

A substantial quantity of electrical meter data were collected over several years to assess the results of the modified heating system. Table I presents the difference in unit electrical consumption in 1993-94 (before the modification) and in 1995-96 (after the modification). The electrical consumption records are for the November through April billing periods. The first column in the table lists the housing unit style, and the second column lists the actual kWh difference between the two billing periods (before and after). The last two columns express this difference in a percentage of the "before modification" electrical consumption. The last column bases this percentage on the "heating only" electrical consumption, which was calculated to be 64% of the total winter electrical consumption.

From the first column in Table 2, the difference in electrical consumption between the "before" and "after" heating systems ranges from a seasonal high of 5,956 kWh to a low of 286 kWh. The average savings were 1736.75 kWh per unit, which is indicative of several of the units. The highest percentage of savings was 29.8%, with an average percent savings of 10.3% (14.6% over the "heating only" electrical consumption). The extreme range of savings indicates the difficulty in designing heating systems. The distribution of the savings is also illustrated graphically in Figure 1. This figure shows a histogram of the number of units that fall into each range. As shown, three samples fall into the negative category, i.e., required additional energy for operation. However, the majority of the 16 samples fell into the 500 kWh to 2500 kWh savings categories.

TABLE 1
Comparison Between the Various Units Before and After the Heating System Upgrades

Unit	Concealed 1993/94	Surface Radiant 1994/95	Surface Radiant 1995/96	Surface Radiant 1996/97
Berkshire	2.52	2.46	2.43	2.00
Carriage H	1.89	1.92	1.72	N/A
Country H	1.87	1.80	1.80	1.66
Country H	2.59	2.11	1.76	1.70
Ethan Allen	0.90	0.69	1.00	.8
Franklin	1.62	1.69	1.75	1.61
Heritage	1.23	1.04	0.89	N/A
Kent	1.68	1.64	1.84	1.65
Hawthorne	1.72	1.76	1.51	1.72
Twain L	0.85	0.71	0.59	.73
Twain U	1.06	0.86	1.02	.9
New England	1.64	1.49	1.53	1.51
Roxbury II	3.23	1.90	2.29	1.96
Sherman	2.92	2.64	2.39	2.06
Sherman	1.93	1.84	1.81	1.82
Winthrop	1.94	2.03	2.02	N/A

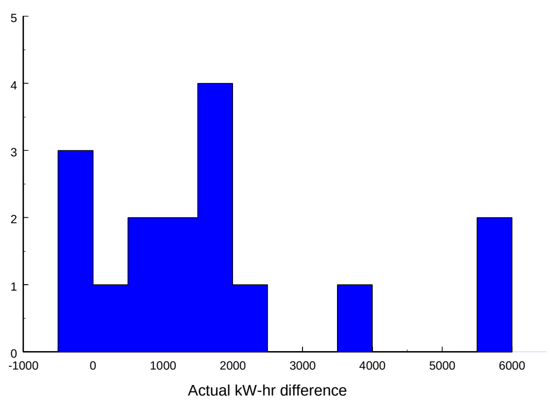
TABLE 2
Radiant Demonstration Program Comparison of 16-Unit Composite Sample Size
Data for November through April Billing periods (October through March Degree-Days Equal approximately 5500

	Actual kWh Difference	Difference Compared to Gross kwh	Difference Applied to Heating kWH Only*
Country House	5606	29.8%	36.3%
Roxbury II	5956	29.2%	31.9%
Heritage	2274	22.6%	31.2%
Mark Twain L	1875	18.5%	35.9%
Sherman	3973	16.0%	26.2%
Carriage House	1698	12.0%	15.0%
Hawthorne	1658	11.5%	16.4%
Sherman (cir)	1665	8.5%	14.3%
New Englander	1291	8.4%	10.9%
Country House (cir)	1136	6.4%	10.3%
Mark Twain U	527	4.4%	8.2%
Berkshire	719	3.6%	5.0%
Winthrop	85	-0.1%	0.8%
Franklin	-217	-1.8%	-2.3%
Kent (crest)	-286	-1.9%	-2.8%
Ethan Allen	-172	-2.0%	-3.1%
Average:	1736.75	10.3%	14.6%
Total Gross Savings:	27788		

*Base bill estimate method used to determine heating kWh. Total heating kWh averaged 64% of six-month winter gross kWh used.

Figure 1 *Histogram showing the distribution of actual kWh differences between the examined units*

This broad range is due mainly to the operational choices of the occupants, which can be explored more by referring to Table 1.



This table shows a wide range of information based on the kWh consumption per heating degree-day (HDD). As this index increases, so does the electrical consumption. Again, the first column shows the housing unit style, followed by the electrical consumption before modification (concealed radiant). The second and third columns list the kWh/HDD for each unit during the 1994-95 and 1995-96 heating seasons. In some cases, the electrical consumption is greater for the modified system than for the original concealed system. For example, the occupants of the Ethan Allen style unit showed substantial savings from 1993-94 to 1994-95. The kWh/HDD decreased from 0.9 to 0.69, a change of 23.3%. However, the next heating period, shown in the table as 1995-96, resulted in an increase to 1.0, a change of 11.1%. The differences in the second and third columns are suspected to be due to the operational differences of the occupants. The occupants of the Kent, Twain U, New England, and Roxbury II units experienced this same trend.

In general, the Ethan Allen occupants knew that the original concealed system was extremely expensive to operate. Consequently, they chose to remain thermally uncomfortable when facing the prospect of receiving large electrical bills. As stated earlier, the original concealed radiant system, relying primarily on high thermal mass, exhibited poor thermal response. This characteristic was due to the combination of high thermal mass and a low power level of 14 W/ft2. Because of this long thermal response, thermostat setback was rarely used. Instead, the occupants kept the thermostat at a constant "cool" setting. The radiant surface panel system, however, responds quickly to thermostat adjustments, allowing the residents to use thermostat setback features at night and during unoccupied periods. Following the setback period, the occupants experienced comfortable conditions in minutes instead of hours. By operating the system in this manner, the occupants found they could stay thermally comfortable for the same, or often lower, cost as with the concealed radiant system. During this re-education process, the residents learned to use the radiant system to attain thermal comfort in a cost-effective manner.

TABLE 3
Radiant Demonstration program Comparison of 50-Unit Composite Sampling (kWh/DD) for the Entire Heating System

Equipment	92/93	93/94	94/95	95/96	96/97	AVERAGE	NAHB
Heat Pump	n/a	2.78	2.07	2.48	1.96	2.32	2.29
Electric Furnace	n/a	2.59	n/a	n/a	n/a	2.59	n/a
Concealed Radiant	2.34	2.23	2.25	2.66	n	2.37	n/a
Surface Radiant	n/a	n/a	2.04	1.96	1.49	1.83	1.54
Baseboard	n/a	n/a	2.14	2.33	n/a	2.33	3.21
Gas	n/a	n/a	n/a	3.66	n/a	3.66	n/a

The heat pump, baseboard, and gas installations replaced concealed radiant units. As shown in Table 3, the heat pumps averaged 2.07 kWh/DD in the mild 1994-95 winter compared to the concealed radiant of 2.25. In the harsh 1995-96 winter, the relationship was still favorable at 2.48 to 2.66, although the resistance backup significantly reduced the overall efficiency. Both systems were higher than the fast-acting radiant, which averaged, respectively, 2.04 kWh/DD and 1.96 kWh/DD. Four heat pump owners have since converted to fast-acting radiant units and one to a baseboard unit.

The four gas conversions averaged the same actual annual dollar expenditure, adjusted to include the summer minimum charge necessitated by the hot water conversion to gas. The actual Btu (British thermal unit) consumption averaged almost 50% higher than the concealed radiant, presumably due to the required furnace ventilation and increased building forced air infiltration and exfiltration.

Baseboard electric averaged 2.36 kWh/DD compared with 2.00 kWh/DD for fast-acting radiant. The controls and setback for the baseboard units were not known. Baseboard heating was seldom used due to safety concerns, building design, and the reluctance to sacrifice wall space-characteristic of occupants with a lifetime of possessions.

CONCLUSIONS

In general, the data obtained from the electrical consumption records showed that the upgrade from the high mass concealed radiant heating system to the fast-acting radiant panel systems decreased the installed wattage and electrical consumption over a heating season. The ability of a radiant panel system to heat people instead of conditioning space contributed to the wide range of energy variation. Using as large a sample as practical offset the lack of extensive detailed instrumentation.

However, the data also show the difficulty in comparing field data. The fact that the occupants changed the way they operated the system (after gaining experience) was difficult to incorporate into the analysis and, in fact, was only determined through personal interviews with the residents. Other obstacles to conducting the energy analysis were

- inadequate funding to set up a formal, instrumented monitoring and measuring protocol;
- a variety of learning curves in the education and training of residents in the use of a different and/or new technology;
- health, travel, death, and other occurrences characteristic of a retired elderly population;
- construction and heat loss differences in units with otherwise identical layouts;
- different occupant profiles, not only in terms of resources, habits, and life-styles, but also by upgrade selection criteria (one of each type of unit chosen by lottery);
- radiant panel weatherization being coincident with the second year of operation.

The Radiant Demonstration Program demonstrated the importance of considering all building features and installation constraints in determining a retrofit system.

REFERENCES

ASHRAE. 1992. *ANSI/ASHRAE Standard 55-1992, Thermal environmental conditions for human occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Jones, B., and K.S. Chapman. 1994. Simplified method to factor mean radiant temperature (MRT) into building and HVAC system design. Final Report of ASHRAE Research Project 657. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Fanger, P. 1967. Calculation of thermal comfort: Introduction of a basic comfort equation. *ASHRAE Transactions* 73(2): 1-20.

BIBLIOGRAPHY

Chapman, K.S., J. DeGreef, and R.D. Watson. 1997. Thermal comfort analysis using BCAP for Retrofitting a Radiantly Heated Residence. *ASHRAE Transactions* 103 (1): 959-965.

Chen, Qingyan. 1990. Comfort and energy consumption analysis in buildings with radiant panels. *Energy and Buildings* 14: 287-297.

Pederson, C.O., D.E. Fisher, and P.C. Lindstrom. Impact of surface characteristics on radiant panel output. *ASHRAE Transactions 104 (1).*

Watson, R.D. 1994. Basic principles of radiant heating. *ASHRAE Journal*, Dec.

Watson, R.D., and K.S. Chapman. 1996. Radiant heating for thermal comfort. *ASHRAE Journal,* June.

Yost, P.A., C.E. Barbour, and R. Watson. 1995. An evaluation of thermal comfort and energy consumption for a surface-mounted ceiling radiant panel heating system. *ASHRAE Transactions 10* 1 (1): 1221-1235.