FINAL REPORT

ENERJOY CASE STUDY

An Evaluation of Thermal Comfort and Energy Consumption for the Enerjoy Radiant Panel Heating System

Prepared for

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It is our hope and belief that the results of this study will broaden the understanding of the home-heating options available to the U.S. home owners and, in the process, contribute to the greater energy efficiency of U.S. housing.

PREFACE

The NAHB Research Center under the auspices of the Advanced Housing Technology Program (AHTP) sponsored by the U.S. Department of Energy (DOE), selected Enerjoy PeopleHeaters^{TM} as a promising and innovative emerging technology. Enerjoy PeopleHeaters^{TM} are surface-mounted, ceiling radiant heat panels. The Enerjoy system represents an innovative approach to space heating because of the panel's low power density and focus on the principles of radiant heat transfer, to be discussed in detail. The Enerjoy radiant system was identified as having potential for contribution to greater energy efficiency and productivity in housing.

The first phase of the AHTP investigated the underlying dynamic of diffusion of innovation in the housing industry, devised an innovative method for assessing emerging innovations, and recommended industry-wide strategies for accelerating diffusion of innovations.

In this, the second phase of AHTP, the Research Center offered to undertake technology assessment and commercialization assistance by conducting case studies of specific innovations with individual firms on a competitive, cost-sharing basis. The Research Center chose innovations that offered the most potential to improve product energy efficiency, quality, and cost-effectiveness in the U.S. home building industry. Another consideration in the selection was the extent to which such innovations allowed the Research Center to investigate and validate in more detail the assessment methodology and give it an opportunity to implement and test the effectiveness of some of its recommended strategies for facilitating commercialization of innovations.

EXECUTIVE SUMMARY

Heat can be transferred in three ways--by conduction, convection, and radiation. Most conventional heating systems in U.S. housing are convective systems--thermal comfort is delivered by heating the indoor air which then conveys heat to objects and occupants. Thermal comfort is, however, determined as much by the mean radiant temperature as the ambient air temperature. Interior spaces can be heated with a radiant source in much the same way as the sun heats the earth. With radiant heating systems such as the ceiling, surface-mounted Enerjoy system in this study, there is the potential for significant energy savings by warming objects and occupants and only indirectly heating the air. With fast-acting, radiant panels and thermostat control in each room, heat is supplied to the home in a manner similar to lighting.

A review of the literature revealed little relevant, empirical evidence for energy savings and thermal comfort associated with ceiling, surface-mounted, radiant heating systems such as the Enerjoy system. Empirical studies used to discuss the energy and thermal comfort performance of radiant heating systems made little or no distinction among the various types of radiant heating systems. Since ceiling, surface-mounted radiant panels in contrast to other radiant systems are fast-acting and deliver a much higher proportion of their output as radiant heat, they can have substantial impact on both energy and thermal comfort performance. Additionally, many studies were performed in commercial or light industrial buildings. The dimensions, building materials and design, and heat loss characteristics of these buildings can be very different than residential structures. Computer models used to hypothesize energy or thermal comfort performance were not equipped to accurately characterize radiant systems or transient heating conditions. Clearly, testing the energy and thermal comfort performance in an occupied home could serve to expand the base of information on which discussions of various heating strategies are based.

To this end, an Enerjoy radiant heating system, an air-to-air heat pump system, and a monitoring data acquisition system were installed in an occupied research home. Information on thermal comfort and energy consumption for alternating operation of the two heating systems was collected for approximately one-half of a heating season. This allowed a comparison of the Enerjoy radiant system and the more conventional, air-to-air heat pump system. Also, data on energy consumption from a zoned, electric baseboard heating system previously installed in the same house was available for comparison.

Fast-acting, radiant heating systems such as Enerjoy that can recover quickly from setback and target the delivery of heat to objects and occupants have a significantly reduced installed capacity in comparison to more conventional heating systems. In this study, for the same system operating and outdoor design conditions, the installed capacity of the Enerjoy system was 2.5 times less than the electric baseboard system and two times less than that of the heat pump system. Generally comparable levels of thermal comfort were provided by the radiant and heat pump systems. And the capacity of the installed Enerjoy system was sufficient to meet outdoor design conditions. As a result, the significantly reduced installed capacity of the Enerjoy radiant system should be of particular interest to utilities whose capacities are stressed or whose territories are experiencing rapid growth and development.

Energy consumption savings of 33 percent were estimated for a typical record year in the Washington, DC area for the Enerjoy radiant system in comparison to the air-to-air heat pump

system and an estimated 52 percent energy savings in comparison to the electric baseboard system. The energy consumption data indicated that the Enerjoy radiant heating system would outperform both the heat pump and the electric baseboard systems regardless of climate. Because a portion of the energy savings with the Enerjoy system was related to room by room setback and the specific number and routines of the research home occupants, savings for other households may be different than those obtained in this study. The magnitude of the savings obtained for the working couple occupying the research home suggests that energy savings would be obtainable in a great portion of U.S. households.

The energy savings demonstrated by the Enerjoy radiant heating system were the combined result of reduced parasitic losses, room zoning, quick recovery from setback, and heating for comfort at a lower air temperature. Both heating systems were operated for energy conservation with day and night setback strategies; the major difference being that heat pump operation was determined by state-of-the-art, programmable thermostat and radiant panel operation was occupant-controlled based on actual room occupation. Occupants of the monitored research home set room thermostats forward 8°F upon entering a room and returned the thermostat to setback upon exiting. In this way, the radiant system was operated like a lighting system with ambient background lighting in each room at all times and higher levels only activated when occupancy required. Achievement of local thermal comfort conditions in approximately ten to fifteen minutes and room wide conditions in approximately 45 minutes was confirmed by data analysis and acceptable to the occupants. Although not used in this field study, light or motion-sensitive thermostats would reduce occupant involvement in system operation and programmable thermostats would eliminate any transition period between setback and recovery conditions for occupants preferring more immediate and automatic system operation. The occupants of the test home preferred the radiant heating system over the forced-air system. They cited greater flexibility and lack of sinus irritation with the radiant system.

Specific operating characteristics of the radiant system discussed in the literature were also addressed in the field study. Some thermal discomfort experienced due to panel cycling could be addressed with careful radiant panel location and distribution or an energy management system that modulates panel status. Vertical air temperature differences were well within standard comfort limits and less than differences experienced during operation of the forced air system.

The energy savings demonstrated in this study indicate that fast-acting radiant systems such as the Enerjoy system have a role to play in increasing the energy efficiency of U.S. housing. The operation of a ceiling, surface-mounted radiant system in conjunction with ductless cooling or a cooling system with the air handler and all ducts inside the conditioned space may provide a more efficient combination heating and cooling system for areas of the U.S. where more than task cooling is required. Several areas of research that deserve further investigation are outlined in the final section of this report.

1.0 INTRODUCTION

Because most homes in the United States are conditioned by forced-air systems, there is a tendency to define heat transfer in buildings with almost exclusive emphasis on convection. Principles of radiant heat transfer are not well understood by the general public and the dynamic interplay in buildings among the three forms of heat transfer will, for a long time to come, generate discussions among heat transfer experts. The Enerjoy case study provided the opportunity to further the understanding of heat transfer in residential structures.

Enerjoy radiant heating panels have been commercially available for over ten years. The panels consist of a base of high-density fiberglass insulation board, a patented solid state heating element with a textured surface coating, and an aluminum frame. The panels are lightweight, have a one-inch profile, and are available for either 120V or 240V installations in dimensions ranging from 2 feet by 2 feet to 4 feet by 8 feet. The panels have been installed in residential and commercial buildings, both new construction and retrofit.[1] Their ability to function on either direct or alternating current makes them well-suited to all locations, including remote ones. The Enerjoy system operates silently, cleanly, and with little to no required maintenance. Despite ample anecdotal evidence of both delivered thermal comfort and energy savings with Enerjoy radiant heating panels, market penetration of the system has not been significant. Surface-mounted, ceiling radiant heating systems such as the Enerjoy system often suffer from two general pre-conceived notions:

- All-electric heat is always expensive.
- Heat rises, so the ceiling is no place for a heating system.

The overall objective of this case study was to determine the technical and energy performance of the Enerjoy heating system in providing thermal comfort in residential structures, in this way addressing these two concerns. Although the overall objective of the second phase of the AHTP was to perform both technical and commercialization assistance of selected innovative technologies, the resources required to perform a technical assessment of a little-studied innovation such as fast-acting, surface-mounted radiant ceiling panels precluded any study of commercialization. The implications that the results of the technical assessment have for the diffusion of this technology will be discussed in the conclusions and recommendations of this report.

The Enerjoy case study was comprised of two tasks. The purpose of Task 1 was to review the literature to determine the basis for energy and thermal comfort performance claims with radiant heating systems and to use the results of this review in the design of a field test in which the radiant and a conventional heating system would be compared.[2] In Task 2, evaluation of Enerjoy performance was based on energy consumption and thermal comfort data obtained and analyzed from an occupied research home. In this home, the Enerjoy panels were compared to

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[1] The panel dimensions allow them to be used in suspended ceiling grids without modification.

[2] The "Task 1 Report: Literature Review" is available as a separate NAHB Research Center document.

a forced-air, air-to-air heat pump system. The field test was designed to seek answers to questions generated by the literature review.

2.0 BACKGROUND

Most conventional heating systems in U.S. housing rely primarily on convection and provide thermal comfort by directly heating the interior air space and subsequently heating the space's contents. Radiant heating systems target surfaces within the space, including occupants, for heating and only indirectly heat the air space. Proponents of radiant heating systems claim the systems have the potential for energy savings without sacrifice of thermal comfort by lowering the air temperature and heating people rather than entire buildings. In theory, significant energy savings are possible, but some research and resulting discussions in the literature questioned the soundness of the energy savings claims and raised questions regarding thermal comfort.

Early residential radiant heating systems were popularized in Europe. The radiant systems were hydronic and either embedded in plaster ceilings or installed just behind the interior finish. The metal piping systems installed for radiant heat distribution were expensive and susceptible to leaks. Significant advances in piping, temperature sensing and monitoring electronics, and the advent of solid state radiant panels have resulted in renewed interest in both floor and ceiling radiant heating systems.

There are several different types of radiant heating systems and distinction among them is important because their differences, when ignored, can result in misleading conclusions with regard to their appropriate use and performance. Radiant floor and ceiling systems can be located within the floor/ceiling materials or located directly behind the floor/ceiling surface material. All of these electric-resistance or hydronic systems are considered high-mass systems whose considerable thermal inertia require steady-state operation. Only surface-mounted ceiling panels are considered low-mass systems whose response time makes transient operation with substantially reduced installed capacity possible. Although there are several different types of radiant heating systems that claim greater comfort and/or energy savings, the Enerjoy surface-mounted, ceiling radiant panels have a unique combination of qualities.

1. Quick recovery time - panels reach operating radiant surface temperature of 150°F to 170°F in less than 5 minutes.

2. Zoning - room zoning with thermostats that are designed to sense both air and radiant temperatures for more effective operation.

3. Ease of installation - the electric-resistance panels are wired in the same manner as residential lighting, are lightweight, and have an extremely narrow one-inch profile.

4. Versatility - the panels are suitable for primary or supplemental heating in new construction and retrofit.

5. Panel design - Enerjoy panels are Solid State Radiant Panels^{TM} that deliver more than 90 percent of heat output as radiant. Dense insulation reduces conductive losses through the

backside. The low panel profile and surface composition reduces convection. The result is a truly radiant heat exchange system.

If significant energy savings can be added to the list of other Enerjoy attributes, the accelerated diffusion of this technology could represent a contribution to the improvement of the overall energy efficiency of housing in the United States.

The operation of ceiling radiant heating systems is not well understood by the general public. Questions consistently arise as to the wisdom of locating the heating system on the ceiling since it is "common knowledge that heat rises." In point of fact, heat does not rise, hot air rises. Radiant heat transfer, in which energy is transmitted by electro-magnetic waves, is unaffected by gravity. As with lighting, which travels by electro-magnetic wave, the best place for a truly radiant heating element is the ceiling or perhaps high on a wall where the emitting source has the best view of the space to be heated. It is perhaps the general public's lack of understanding and experience with a truly radiant heating system that represent the biggest hurdles to greater commercialization of radiant systems.

The confusion regarding the operation of ceiling radiant heating systems is apparently not limited to the lay public. While the mechanics of heat transfer are well researched and documented, the application of these principles to the actual heating of buildings is less well understood. The dynamics of heat transfer in actual structures are exceedingly complex, particularly under transient conditions. It is possible for well-informed proponents of various heating strategies to disagree on how the principles of heat transfer actually play out in the heating of interior spaces. The literature review, in seeking to clarify the issues concerning the performance of radiant heat, found that much of the discussion in the literature is based on insufficient evidence from the field or does not convey the important differences among radiant heating systems.

3.0 TASK 1 SUMMARY

The literature search, in seeking to clarify the issues concerning the energy savings potential of radiant heat, found that much of the discussion in the literature is based on insufficient evidence from the field. Although the literature in general did not support significant energy savings with radiant heating, most of the discussions did not involve fast-acting, surface-mounted, ceiling panels and/or involved tests performed in non-residential buildings. Because both the type of radiant heating system and the structure in which the system is installed can have significant impact on the system's performance, the absence of actual data on the performance of fast-acting, ceiling panels in residential structures results in only hypothetical discussions. The potential energy savings with Enerjoy panels arise from the cumulative effect of:

- reduced parasitic losses;
- room zoning;
- quick recovery from setback; and
- reduced air temperature.

The effects listed above do not represent special conditions but rather represent the conditions under which the Enerjoy radiant system is designed to operate in a residential setting. No studies provided the testing conditions that would allow simultaneous demonstration of all the above effects.

The actual energy savings to be expected in a home cannot be accurately predicted or even estimated with the documented information available. The computer modeling and field studies to date neither support nor refute the energy and thermal comfort performance claims specific to surface-mounted, radiant ceiling panels. Although much of the dynamics of home heating and the thermal comfort of occupants are understood and can be quantified, there is uncertainty with regards to local thermal comfort conditions and the dynamics of thermal comfort and energy performance for various heating systems under transient as compared to steady-state conditions. The following issues were raised in the literature without resolution:

1. When the mean radiant temperature is elevated during recovery from setback to provide thermal comfort, for what period of time does a lower air temperature persist?

2. Can thermal discomfort be associated with radiant panel cycling?[3]

3. What kind of vertical air temperature differences are to be expected with fast-acting radiant panels in structures with low (7 to 10 feet) ceiling heights?

4. How will the delivery of thermal comfort compare between surface-mounted, ceiling radiant heat and conventional warm air systems?

5. What will the seasonal energy consumption be for the radiant panels compared to a conventional warm air system?

6. How will empirical data from a radiant system operated in a residential structure compare to computer modeling data from the Building Comfort Analysis Program, a program developed to accurately account for radiant heat exchange?

Little to no field research was found on the comparative energy efficiency of and delivery of thermal comfort by ceiling radiant systems and conventional forced-air systems in residential structures. Research often cited in discussions of the energy efficiency and thermal comfort claims associated with radiant heating systems involved computer modeling and/or field studies limited to light commercial and industrial buildings. In terms of heating, residential buildings can be clearly distinguished from commercial/industrial buildings by lower air change rates, lower ceiling heights, greater levels of insulation, and different occupants' habits and thermal comfort requirements. These differences suggest the need for field study in residential structures.

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[3] The radiant panels were either on or off; power to the panels was not graded; proportional control is, however, possible.

4.0 TASK 2 COMPARATIVE FIELD TEST

Task 2 of the Enerjoy case study was designed to address the lack of data on the relative energy efficiency and delivery of thermal comfort by surface-mounted radiant heating systems and more conventional forced-air, convective heating systems in residential structures. The specific assertions made by the manufacturer regarding surface-mounted, ceiling radiant panels to be evaluated were:

1. ten to twenty percent less air infiltration than conventional convective systems.
2. significantly reduced installed BTU capacity of the radiant system in comparison to a conventional forced-air, convective system at a given design load.
3. significantly lower electricity consumption than zoned, electric baseboard heating.
4. significantly lower energy costs than conventional convective systems, under transient conditions.
5. maintained thermal comfort with quick recovery from a 6 to 8°F temperature setback.

4.1 Experimental Design

4.1.1 The Test House

Prior research has demonstrated the acceptability and even the desirability of testing two heating systems in a single home. The method involves an alternating schedule over the course of one-half of the heating season, the half-season including a shoulder and conditions at or approaching design conditions for the location.[4] This method has the distinct advantage of eliminating confounding variables that are present when tests are conducted in more than one home.

The *Adaptable Fire-Safe Demonstration House* (hereafter referred to as the *AFSD* House), a research home located in Bowie, Maryland, was selected for this case study because of the existence of a database on energy consumption from a previous research project and its occupancy by the family of a Research Center employee prepared for the demands of the field study. The *AFSD* House, built in 1990, is a two-story house approximately 2,200 ft^2 in size. The *AFSD* House is fairly typical of contemporary, single-family detached homes in the mid-Atlantic region of the United States: two by four wall construction, fiberglass insulation, 8-foot ceilings, and gypsum board interior walls and ceilings (see Appendix A for more complete documentation on the *AFSD* House). Unique features of the *AFSD* House were its modular construction, three foot passageways and hallways, and three-story elevator. The only one of these felt to have potential for significant impact on the field study was the elevator--this was disabled and the shaft sealed.

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[4] The winter design temperature is the outdoor air temperature that is exceeded 97.5 percent of the time.

The forced-air heating system of the *AFSD* House was zoned by two heat pumps,[5] the ducting runs for the two floors being independent because of the structure's modular construction. The air handler and ducting for second floor heating was located in the unconditioned attic space. All ducting was wrapped and taped with ducting insulation. Ducting for the first floor was located in the semi-conditioned space of the basement. Ducting in the basement was not insulated. The exception to this was the family room. Because this room was over a crawl space foundation, the ducting for this space was wrapped and taped with ducting insulation. Both zones of the forced-air system were equipped with state of the are programmable thermostats for separate weekday and weekend setback strategies. The thermostats are described as "predictive" because of their ability to incorporate previous daily energy requirements into the ramping up of interior temperatures when recovering from setback.

4.1.2 The Radiant Heating System

The number, size, and location of radiant ceiling panels installed in the *AFSD* House were specified by the manufacturer.[6] Research has indicated that standard heating design procedures established by the American Society for Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) may require modification for certain types of radiant heating.[7] Although calculation of the heating load of a structure is independent of the type of heating system to be used in a structure, fast-acting systems such as the Enerjoy radiant heating system provide the opportunity for greater reduction in the installed BTU-capacity if the heating load on a room-by-room basis can be accurately estimated. The Research Center provided the manufacturer with information from previous research on the heating of the *AFSD* House for calculations. The Enerjoy heating system installation consisted of 20 panels, 160 square feet in thirteen zones, with a resulting power density of approximately 4 watts per square foot of floor area. Panel and thermostat locations are included in Appendix B. The panels can be wired as either 240V or 120V--all panels in the *AFSD* House were wired 240V.

All 13 zones of the radiant system were equipped with Enerjoy hydraulic line voltage thermostats. These thermostats were specified by the manufacturer because of their narrow operating differential (1°F) and the ability of the exposed knob to sense both radiant and air temperature effects. The thermostats were located according to manufacturer's directions--their location being determined by considerations of user convenience and viewing angle with respect to the radiant panels.

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[5] Both heat pumps were new units installed for this study and had Seasonal Energy Efficiency Ratings (SEERs) of approximately 10.25. The units were selected by a local contractor as typical for the area.

[6] Because the *AFSD* House was a retrofit installation, existing ceiling features (paddle fans, light fixtures, exhaust vents, sprinkler heads, and a skylight) prevented the location of some panels per manufacturer's specification.

[7] Howell, R.H. and S. Suranarayana, "Sizing of Radiant Heating Systems, Part I Ceiling Panels," *ASHRAE Transactions*, 96:652-665, 1990.

4.1.3 The Monitoring and Data Acquisition System

The monitoring equipment obtained and recorded data on the following parameters for approximately three months of the heating season.

- thermal comfort

  » dry-bulb temperature
  » operative temperature
  » vertical air temperature difference

- energy

  » metered electric consumption
  » outdoor temperature

The monitoring and data acquisition system used for the field study consisted of a Measured Performance Rating controller and Metrabyte DAS8 system.[8]

Thermal comfort stations were located in three of the most frequently used rooms in the house: the family room, the dining room/kitchen, and the master bedroom.[9] The locations of the stations within the three rooms are shown in Appendix B. Although the stations should be located to reflect occupancy patterns, the actual rather than simulated occupancy of this test house forced the stations more to the perimeter of the rooms. The stations consisted of three double-shielded, air temperature sensors located at 4, 43, and 93 inches from the floor, and a 6-inch hollow copper globe located at 43 inches with a temperature sensor sealed at its center. The sensors heights were determined in accordance with ASHRAE Standard 55-1992.

The 6-inch hollow copper globes were originally intended to estimate the mean radiant temperature, as prescribed in chapter 13 of ASHRAE 1993 Fundamentals. When, as is the case in the evaluation of most convective systems, the air temperature and globe temperature are very similar, the globe is a good approximation of the mean radiant temperature. If the 43-inch air temperature is significantly different than the globe temperature, as was the case during the radiant system operation for this field study, the globe is a much better estimation of the operative temperature, not the mean radiant.[10] Using the globe thermometer as an estimation

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[8] A full description of the MPR and DAS8 system used to obtain and record data is available: "Volume IV: Hardware Specifications, Measured Performance Rating System", a report prepared for the New York State Research and Development Authority by the NAHB Research Center, August 1991.

[9] Minute-averaged temperature data from three thermal comfort stations and two outdoor temperature sensors were recorded on a twenty channel data acquisition system.

[10] Berglund, L., R. Rascati, and M. L. Markel, "Radiant Heating and Control for Comfort During Transient Conditions," *ASHRAE Transactions*, Part 2: 765-775, 1982. The air and mean radiant temperatures effects on thermal comfort can be numerically combined into the operative temperature. An approximation of the operative temperature can be obtained by adding the air and mean radiant temperatures together and dividing by two; generally the air and mean radiant temperatures make equivalent contributions to thermal comfort.

of the operative temperature simplified evaluation of thermal comfort--this approach was used in this study.[11]

The sensitivity of the operative temperature globes to their location in a room during radiant heating system operation became apparent over the course of the research project. The globes were subsequently relocated to the indicated positions (directly underneath the largest panel in the three monitored rooms), approximately halfway through the testing period.

Relative humidity sensors were not available as part of the three comfort stations and, as a result, relative humidity was spot-checked with a hand-held Solomat over the course of the data acquisition period. Air speeds were also checked with the Solomat on two occasions to assess air movement during operation of the forced-air heating system.

Energy consumption for the heat pumps and the radiant panels was all electric. Two calibrated, pulse-initiating watt-hour meters monitored, separately, incidental and home-heating electric consumption. Electric service to both heating systems were wired so that current by the operating heating system was monitored by the meter dedicated to heating. Counts by both meters were summed hourly and recorded on a separate data acquisition system. The status of radiant panels in the three monitored rooms was recorded on a minute-by-minute basis on channels of the MPR system.

4.1.4 Methods of Evaluation

The relative performance of the Enerjoy and conventional heating system was evaluated according to the following methodology:

1. *Air infiltration* - Two blower door tests were performed on the *AFSD* House. In the first test, the registers and cold air returns of the ducted heating system were left open as they would be during normal operation of the forced-air heating system. For the second test, all registers and the two cold air returns were sealed to effectively eliminate the ducting from the house. This simulated the configuration of the *AFSD* House if the ductless non-mechanically radiant heating system was the primary, permanent system. In this way, the induced air infiltration losses associated with a ducted and non-ducted heating system could be quantitatively compared.

2. *Installed BTU capacity* - The installed Btu capacity of the heat pump, electric baseboard, and radiant panels are known and can be compared. A critical element of this comparison is the ability of the heating system to deliver thermal comfort during design conditions. Outdoor temperatures down to and below design conditions were encountered during the data acquisition period so that the sufficiency of installed capacity for the two systems could be assessed.

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[11] This simplification, however, should not obscure the fact that an elevated operative temperature with respect to the air temperature necessarily implies a mean radiant temperature elevated above the operative temperature by an amount roughly equal to the difference between the air and operative temperature.

3. *Energy savings under transient conditions* - The asserted energy savings with the Enerjoy radiant heating system are the result of the combined effect of reduced parasitic losses, room-by-room zoning, quick recovery from setback, and reduced air temperature. The total effect of these phenomena should be significantly reduced building heat loss without sacrifice of occupant thermal comfort.

Although it was beyond the scope of this field study to quantify that portion of any energy savings attributable to the individual phenomena of the four effects listed above, their total effect can be estimated. The energy consumption data obtained during alternate operation of the two heating systems permitted the determination of house load at different outdoor temperatures. During periods of radiant heating, thermostats were setback to 60°F when rooms were unoccupied and setup to 68°F when occupied.[12] This represented optimal operation of the radiant system under transient conditions. During periods of heat pump, forced-air heating, the two programmable thermostats had a setback of 60°F and setup of 68°F. The weekday and weekend schedules of the *AFSD* House occupants were used to program day and night setbacks of the heat pump thermostats. The state-of-the-art programmable thermostats are designed to allow flexible timed recovery from setback based on previous day power requirements. This represented optimal operation of the two heat pumps under transient conditions. The comparison of daily electric energy consumption as it relates to outdoor temperature permitted an energy efficiency comparison of the two alternately operated heating systems.

Previous research at the *AFSD* House involved installation of baseboard electric heat throughout the house. Room-by-room day and night setback schedules were employed during this study. Energy consumption as it relates to outdoor temperature was quantified for the baseboard heating system. This allowed comparison of the energy consumption of the radiant and baseboard heating systems for the same residential structure.

4. *Delivery of thermal comfort under transient conditions* - An inextricable element of any comparison of heating system efficiencies is the delivery of thermal comfort to the occupants. Reduction in either the installed BTU capacity or seasonal energy consumption of any heating system is only relevant if thermal comfort can be maintained. Thermal comfort is defined in *ANSI\ASHRAE Standard 55-1992* as "the condition of mind that expresses satisfaction with the thermal environment; it requires subjective evaluation." The environmental factors affecting thermal comfort have been determined: ambient air and mean radiant temperature, relative humidity, and air speed.[13] In this field study, data on air and operative temperature were recorded in three rooms on a minute by minute basis, the relative humidity was spot checked, and the air speed was not monitored.

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[12] Bathrooms, because of their frequent, short-term use and the occupant's potentially lower clo value (the thermal contribution of clothing is expressed in a unit called a clo), were setback on manufacturer's recommendation to 62 to 63°F. Additionally, the master bedroom was night setback to 61 or 62°F instead of 60°F, as the only occupied bedroom.

[13] Operative temperature is the primary environmental determinant of thermal comfort; relative humidity and air speed, unless extreme, are secondary effects.

The two heating systems were operated before data collection began in order to allow determination by the occupants of comfortable setback and set-forward temperature settings. Each heating system was operated in this manner for at least one week. The radiant and heat pump temperature strategies established as a result of the trial operations of the two systems were a setback of 60°F and set-forward of 68°F.

Thermal comfort was evaluated by review of thermal discomfort surveys (see Appendix C). Whenever an occupant of the research home experienced thermal discomfort in one of the three monitored rooms, the individual completed a short survey. The environmental conditions corresponding to the time of discomfort as recorded by the monitoring system were later linked to each survey for evaluation. Patterns or generalizations regarding the operation and thermal comfort delivery of the two heating systems could in this manner be established.

5. *Assessment of specific issues* - The minute-by-minute recording of environmental conditions in the three most used rooms of the AFSD House permitted evaluation of certain issues raised in literature discussions on the expected performance of the surface-mounted, ceiling radiant heating panels. The issues addressed were:

- time required for comfort conditions during recovery from setback
- localized versus room-wide comfort conditions during recovery from setback
- vertical air temperature difference
- effects on thermal comfort of panel cycling
- time duration of lower air temperature with respect to operative temperature (transient and steady-state conditions)

5.0 TASK 2 FIELD TEST RESULTS

5.1 Air Infiltration

Air infiltration is one of the primary determinants of heat loss in buildings. Air infiltration accounts for somewhere between 25 percent and 45 percent of the total heat loss in a typical home.[14] As conditioned air moves out of the building envelope, the energy required to heat or cool that air is lost. Research has shown that homes with forced-air heating systems can have air infiltration rates up to 36 percent greater than homes with non-ducted heating systems.[15]

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[14] Goldschmidt, V. W., "Average Infiltration Rates in Residences: Comparison of Electric and Combustion Heating Systems," *Measured Air Leakage of Buildings, ASTM STP 904*, H. R. Trechsel and P. L. Lagus, Eds., American Society for Testing and Materials, Philadelphia, 1986, pp. 70-98.

[15] Palmiter, L. S., I. A. Brown, and T. C. Bond, "Measured Infiltration and Ventilation in 472 All-electric Homes," *ASHRAE Transactions*, 91.15.3.

Determination of the difference in air infiltration at the *AFSD* House with and without heating and return ducts aided the researchers in determining the importance of sealing off all ducts during radiant system operation.

The blower door test is a common method of estimating air infiltration. It is particularly useful in assessing relative building tightness.[16] The air infiltration tests on the *AFSD* House were performed on November 29, 1993 in accordance with guidelines set forth in the ASTM Standard E779-87: *Method for Determining Air Leakage by Fan Pressurization.* The results are presented in Table 1 below. A copy of the full test report is included as Appendix D. The first test was performed with all floor and ceiling registers and cold air returns covered with foil-faced, bubble wrap insulation and air-sealed with duct tape. In the second test, all registers and returns were open as they would be during normal operation of the forced-air heating system.

Table 1
Blower Door Test Results

	Ducts Sealed - Radiant System	Ducts Open - Heat Pump System
Airflow @ 50 Pascals (Air changes per hour - ACH)	13.97	15.84
Estimated natural infiltration in ACH	.88	.99
% Reduction in ACH	12.5	Base

It is customary to estimate the natural air infiltration rate by dividing the calculated ACH at 50 pascals by either 16 or 20.[17] This places the natural air infiltration rate during radiant system operation between .7 and .88. While efforts to establish an average U.S. residential ACH show wide variation, an ACH in the range of .7 to .88 qualifies the *AFSD* House as an "average" U.S. home.[18] Regardless of the estimating procedure, the reduction in air infiltration with all elements of the forced-air distribution system effectively eliminated from the building envelope was approximately 12.5 percent. Clearly, significant air leakage is attributable to the forced-air system ducting. These results fall within the range of air leakage attributed to ducting by other researchers and Enerjoy claims.

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[16] Nantka, M. B., "Comparison of Different Methods of Airtightness and Air Change Rate Determination," *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 267-282.

[17] Persily, A.K. "Measurements of Air Infiltration and Airtightness in Passive Solar Homes," *Measured Air Leakage of Buildings, ASTM STP 904,* H.R. Trechsel and P.L. Lagus, Eds., American Society for Testing and Materials, Philadelphia, 1986, pp. 46-60. The natural air infiltration rate can vary widely over the course of the year with changes in inside/outside temperature differential and other factors. This aspect of the blower door assessment of air infiltration is one of the reasons that the test is most useful for relative building tightness, as it is being used in this report.

[18] Goldschmidt, V. W. "Average Infiltration Rates in Residences: Comparison of Electric and Combustion Heating Systems," *Measured Air Leakage of Buildings, ASTM STP 904,* H. R. Trechsel and P. L. Lagus, Eds., American Society for Testing and Materials, Philadelphia, 1986, pp. 70-98.

The results of the blower door tests are even more significant in light of research performed by Gammage and Modera.[19] Studies performed by Gammage and other work reviewed by Modera estimate that duct air leakage during blower operation can result in a doubling of the ACH of the structure. The air leakage attributable to duct losses is a function of the quality of the system installation and the location of the ducts inside or outside the heated space. These are issues of forced-air system installation that are currently being addressed by the industry. The effect of increased air leakage during blower operation of the ducted heat pump system will show up in this case study as an integral part of the energy consumption comparison of the two heating systems. The Enerjoy radiant system does not suffer from delivery losses in efficiency.

5.2 Installed System Capacity

The installed capacity of any heating system is a function of the estimated building heat loss, the winter design conditions, and the setback strategies, if any, to be implemented in the building. Table 2 presents a summary of the installed system capacities for the radiant, electric baseboard, and heat pump systems.

Table 2
Comparison of Heating System Installed Capacities - *AFSD* House

Parameter	Calculated Building Heat Loss (Right-J)	Heating System			
		Electric Baseboard	Heat Pump	Radiant Panel (Enerjoy)	Radiant Panel (Kansas State)
Indoor/outdoor Δt at design conditions °F	57° (70° - 13°)	57° (70° - 13°)	57° (70° - 13°)	55° (65° - 10°)	63° (72° - 9°)
Assumed ACH	.7	.7	-	.4	.7
Day and night setback strategies?	No	Yes	Yes	Yes	Yes
Installed capacity - Btu/h (watts)	45,442 (13,314)	69,967 (20,500)	57,100 (16,700)	27,645 (8,100)	29,864 (8,750)
% System Oversizing (at design conditions)	NA	+54	+26	-40	-34

The first column contains information on building heat loss for the *AFSD* House as calculated using the Right-J method. The Right-J computer output is certified by the Associated Conditioning Contractors of America (ACCA) to meet all requirements of the Manual Form J, a widely accepted standard design procedure for heating and cooling systems. Although the Right-J calculation utilizes substantial actual information on the building's construction and design, some important assumptions must be made. For example, the air change rate (ACH) is an input to the Right-J calculation that has significant impact on the building heat loss

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[19] Saunders, D. H., T. M. Kenney, and W. W. Bassett, "Evaluation of the Forced-Air Distribution Effectiveness in Two Research Homes," *ASHRAE Transactions* 99:1, 1993.

calculation, air infiltration accounting for fully a third of the total heat loss in typical houses. Yet this value was assumed in this analysis. Despite limitations, the Right-J building heat loss calculation provides a basis for comparing the installed capacities of the three different heating systems. Note that the units for heat loss and resulting installed system capacity are either btu/h's or watts. It is customary for heating and cooling contractors to work in btu/h's and electric utilities to work in watts or kilowatts--both are provided here for convenience.

The second column presents the installed capacity of the electric baseboard heating system from a previous research project. Note that the installed capacity is approximately 50 percent greater than the calculated design load of the building. System oversizing of up to 60 percent is standard practice when both day and night setback strategies are anticipated.[20] Setback strategies and room-by-room thermostatic control were used in previous research involving the electric baseboard system, making comparison of energy consumption between the electric baseboard and radiant panel systems meaningful.

The third column contains information on the heat pumps installed at the *AFSD* House. The air-to-air heat pumps were a 1 ton unit for the second floor and a two ton unit supplying the first floor. Conventional heat pumps are often not operated on setback strategies. The predictive nature of the state-of-the-art programmable thermostats, however, allowed efficient operation of the heat pumps with setback strategies. The combined installed capacity of just the two heat pumps is actually approximately 41,000 btu/h's. At design conditions, however, the installed capacity is most accurately estimated by adding the output of the backup strip heat (15 kilowatts) to the output of the heat pump at that particular temperature. This calculation is appropriate because the capacity of the heat pump depends on outdoor temperature and, at design conditions, the forced-air system is delivering heat primarily from the electric strip heat. Adding the output of the heat pumps at design temperatures to the strip heat results in the total installed capacity that is 26 percent greater than the calculated Right-J capacity. This extra capacity is the capacity required to meet the demands of day and night setbacks with the heat pump system.

The fourth column shows the installed capacity of the Enerjoy radiant heating system in the *AFSD* House. The installed capacity of the Enerjoy system is 40 percent less than the installed capacity recommended by the Right-J analysis.[21] Recall that the rapid response time and lower air temperatures possible with the radiant system permit significant reduction in installed capacity, even with day and night setback strategies. The installed capacity of the Enerjoy system is 2.5 times less than the electric baseboard system and 2 times less than the heat pump system. This is an important characteristic of the radiant system as it pertains to the demand an electric utility must plan to meet when design conditions occur or are exceeded.[22]

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[20] ASHRAE, *1993 ASHRAE Handbook: Fundamentals*, 1993, pp. 25-14.

[21] Although the indoor/outdoor temperature differential used for the Right-J calculation is 2°F less than the differential used to calculate the Enerjoy installed capacity, this difference is only around 4 percent.

[22] The winter of 1993-1994 was severe and power outages at the test house did occur as the result of insufficient electric utility capacity.

In the last column, the installed capacity recommended by analysis at Kansas State University's Department of Mechanical Engineering and Environmental Research Institute is presented. This calculation is based on a model developed by Drs. Jones and Chapman that has the following capabilities:

- Predict the combined effect of radiative, convective, and conductive heat transfer in a radiantly heated enclosure.
- Map the predicted comfort level distribution of occupants in the room.
- Model the effects of objects, such as furniture and partitions, on the comfort level distribution.
- Predict optimum placement of radiant heaters inside the room.

Although the Kansas State model simulates steady-state conditions, their assessment of installed capacity as it relates to Enerjoy's calculations is important verification of Enerjoy's current standard installation procedures and protocols. Note that the Kansas State calculations are higher than the actual installed capacity following the manufacturer's analysis. However, both the temperature differential and ACH assumed by Kansas State are significantly higher than those assumed for the Enerjoy calculation. These two factors alone may account for most of the difference in the two figures. The blower door tests performed on the *AFSD* House after the radiant system was installed suggest that the Kansas State assumption regarding ACH was closer to the actual rate than the value assumed for the manufacturer's analysis. This information will be relevant when performance of the radiant heating system at and below design conditions encountered during the testing period is discussed later in this report.

5.3 Energy Consumption Comparison

For approximately one-half of the 1993-1994 heating season, electric consumption at the occupied *AFSD* House was monitored. The heating systems were wired so that their electric consumption was dedicated to one meter, and all incidental household electric consumption was monitored by the second meter. The radiant and heat pump systems were operated alternately in two week blocks when possible and for one week blocks otherwise. This was done to minimize the impact of intermittent operation on the heat pump predictive thermostats during heat pump operation and maximize the routine of room-by-room thermostat use during radiant panel operation. All window coverings on the south and west sides of the house were kept closed for the test period to minimize the effects of solar gain on energy consumption and to prevent direct solar radiation from having any impact on the operative temperature globes. The precision of the pulse tabulations were checked against manual readings on at least three occasions--on all occasions the pulse counts were within 2 percent of manual readings.

Incidental electric household use contributes indirectly to home-heating and large variances in its consumption could have a significant impact on heating system energy requirements if the variances were to coincide with system operation. With two occupants, both fully employed outside the home, little variation was anticipated. Review of incidental electric consumption revealed significantly greater consumption on weekend days than weekdays but no other patterns or large variances. Because heating system operation changes were performed at approximately midnight on Saturdays, weekend variances in incidental electric consumption should have had very little impact on heating energy analysis of the two heating systems.

Gas consumption at the *AFSD* House was limited to operation of one driveway post light, the hot water heater, and the clothes dryer. The dryer's operation, generally on each Saturday, was felt to have little to no impact on the heating energy analysis. The two other uses of gas were virtually unaffected by the operation of two heating systems on an alternating basis.

5.3.1 Regression Analysis of Energy Consumption

Total daily heating electric consumption was plotted against corresponding daily average outdoor temperature (Electric consumption was compiled on an hourly basis, outdoor temperature on a minute basis). The data were regressed on a linear basis with the results presented in Table 3.

Table 3
Regression Analysis on Energy Consumption and Outdoor Temperature for Three Heating Systems

Parameter	Heating System		
	Heat Pump	Radiant Panel	Baseboard
Constant	250.9472	188.1726	256.2494
Standard error of Y estimate	20.82946	9.845121	13.9711
R^2	0.897179	0.913999	0.85182
No. of observations	32	31	44
Degrees of freedom	30	29	42
X coefficient	-4.37728	-3.36296	-3.72808
Standard error of coefficient	0.270549	0.191558	0.239928

The standard errors of both the y-intercept and the slope coefficient for all three regressions are statistically significant. The R^2 values, which can be interpreted as the percent of variation in the values of X explained by variation in Y, are quite high, varying between 85 and 91 percent. Inspection of the distribution of data points about the regression lines revealed no evidence of patterns in the residuals, patterns that might suggest problems in the interpretation of the regression statistics. Linear forms appeared to be the most appropriate functional forms for all three regressions.[23] A streak of very cold weather during the test period resulted in outlying

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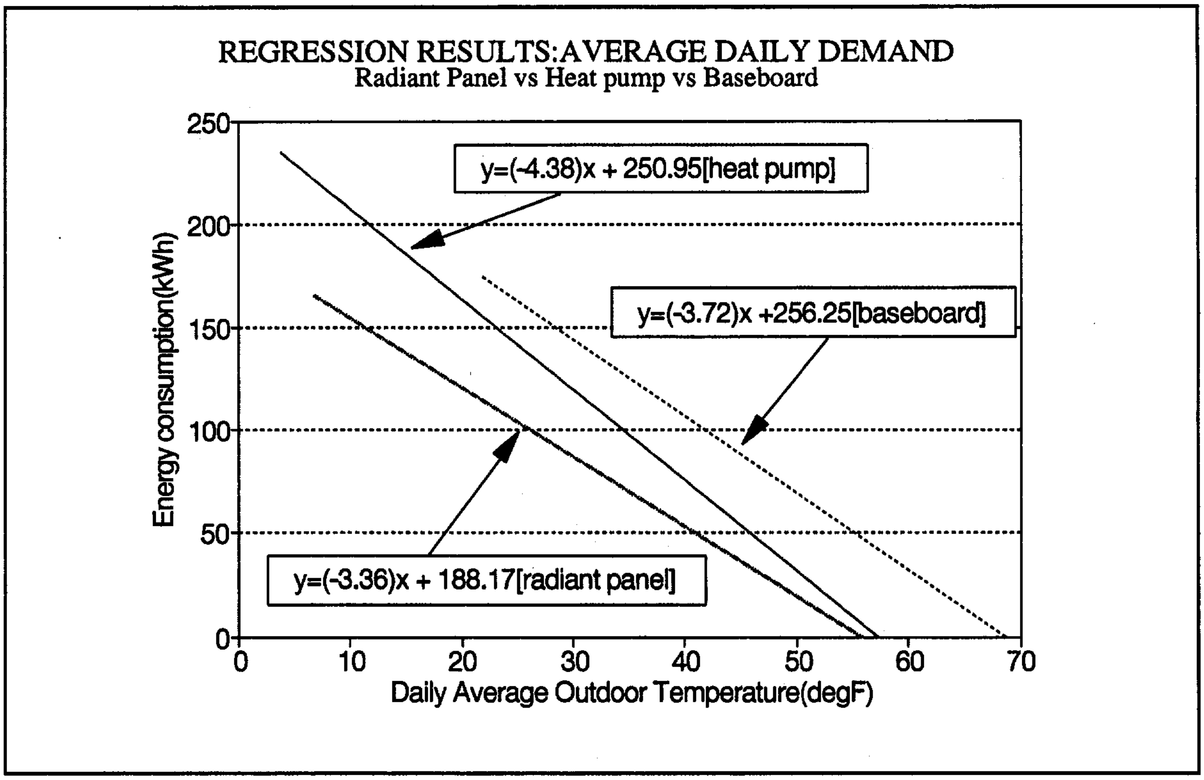
[23] Because the efficiency of heat pump operation is a function of outdoor temperature, a non-linear relationship above the heat pumps' balance points might be expected. The linear form, however, was the best fit over the entire range of data points. Since the data points are not a measure of the heat pumps' efficiencies but rather the efficiency of the entire heating system, other factors such as delivery and parasitic losses, defrosting cycles, etc. may have overwhelmed efficiency gains with higher outdoor temperatures.

data points for both the heat pump and the radiant panels. None of the outliers were found to be influential. The regression results suggest that the estimated linear relationships between energy consumption and daily average outdoor temperature for the three heating systems are credible representations of the true relationships and can be used with acceptable levels of confidence.

The three regression lines are shown in Figure 1. The negative slopes portray decreasing energy consumption with increasing outdoor temperature, as would be expected. The positions of the three regression lines indicate that the radiant panel heating system outperformed both the air-to-air heat pump and electric baseboard systems, regardless of the outdoor temperature.

The balance point of a structure is the outdoor temperature at which the structure requires no heating energy. The x-intercepts of the three regression lines are of interest as they estimate the balance point of the *AFSD* House. All else being equal for the same structure, the outdoor temperature at which no dedicated heating energy is required should be the same and so, the x-intercepts of all three regression lines should be approximately the same. The x-intercepts for the radiant, heat pump, and baseboard systems were 56, 57, and 68.7°F, respectively. The proximity of the heat pump and radiant panel x-intercepts is credible because the indoor temperature setpoints and setbacks, incidental energy gains, and operation of the house were quite similar during operation of each system. The one major difference was sealing of the forced-air delivery registers and cold air returns when the radiant system was being operated. This may explain the slightly higher balance point of the heat pump regression line.

Figure 1



The balance point for the baseboard system is significantly different than either the radiant panel or heat pump regression line. There are several factors that could account for the difference:

1. The *AFSD* House was unoccupied during the electric baseboard study. Incidental gains and losses from occupants' activities (cooking, domestic hot water use, exhaust fan use, entering and exiting, etc.) are not reflected in the baseboard data. Additionally, the interior conditions of the house during the baseboard study (curtain and blind positions, furniture contents, etc.) are not known and could effect the thermal performance of the house.

2. The thermostat setforward temperature for the electric baseboard study as 4°F higher than in the Enerjoy study. The actual indoor temperature was approximately 2°F higher (averaging 70.5°F).

3. The room-by-room setback schedules for the baseboard study were designed to simulate occupancy. How well they actually reflected the routines of the *AFSD* House occupants in the Enerjoy study cannot be determined.

It was not possible to factor these differences out of the present comparison. Accounting for the higher setpoints would serve to decrease the difference in comparison to the other two regression lines. The extent and direction of the impact of the other factors cannot be determined with the information available. For the current comparison, it can only be noted that differences exist and the comparison of the baseboard energy consumption to the other systems is limited by these differences.

It is interesting to note that the slopes of the radiant and baseboard system regression lines are similar, suggesting similar relationships between energy consumption and outdoor temperature. It is not possible to determine the reason for the slope similarity but the room-by-room thermostat control and lack of delivery losses for both systems may be at least part of the explanation.

5.3.2 Translation of Regression Relationships into Expected Energy Savings

The estimated relationships between energy consumption and outdoor temperature can be used to calculate the expected annual heating energy required for the Washington, DC area. Typical record year (TRY) data from nearby Andrews Air force Base allows translation of the regression lines into the expected average energy consumption for the heating system. Typical record year calculation is a method of weighting the individual relationships by outdoor temperatures typically encountered during a heating season. Table 4 gives the results of the typical record year calculations.

Table 4
Typical Record Year Heating Energy Estimations for the Three Heating Systems

Typical Record Year Information: Heating	Heating System		
	Heat Pump	Radiant Panel	Electric Baseboard
Estimated annual electric consumption (kWh)	10,764.1	7,229.4	15,107.5[24]
Estimated annual heating electric costs (@ $.055/kwh)	$592.03	$397.62	$830.91
Estimated annual % savings with radiant	33%	Base	52%

The radiant panel heating system demonstrates a projected 33 percent savings in comparison to the heat pump for the typical record year. Note should be made here that the different slopes of the two regression lines translate into varying savings with varying heating season climate. The fact that the radiant regression line is below the heat pump regression line over the entire range of outdoor temperatures suggests that the panels would outperform the heat pump, regardless of the record year or region in which the house is located. Greater savings would be expected in colder climates, less in warmer climates. The 52 percent energy savings estimated with the radiant heating system in comparison to the baseboard system must be presented with some caution. Different test conditions existed for the radiant panel and baseboard studies and the impact of these differences may have an impact on the relative energy savings. The primary reason the information on the baseboard system was included was to help demonstrate that any efficiency gains with the radiant system are not simply the result of room-by-room zoning. The regression results suggest that the efficiency gains with the radiant system result from more than just zoning gains alone.

5.3.3 Qualifying the Energy Savings Demonstrated by the Radiant System

The seasonal heating cost estimates pertain to the *AFSD* House occupied by a working couple. Significant impact on the operation and consequently the energy consumption of either or both heating systems could result from additional occupants. Because the setting forward of thermostats is occupant-dependent with the radiant system, more occupants would presumably significantly increase energy use. In other words, the energy consumption of an occupant-dependent heating system may be more sensitive than the floor-zoned conventional system to increases in the number of occupants. On the other hand, the impact of one occupant home during daytime hours could have a greater impact on the conventional forced-air system than the radiant. With the conventional, forced-air system, an entire zone or zones would be removed from daytime setback whereas with the radiant system, an occupant home during the daytime may only require the setting forward of certain rooms. While occupation of a 2,200 square foot

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[24] This figure does not include any adjustments for differences as discussed in the text.

house by one working couple does not represent the median living situation in the United States, these circumstances are by no means unusual and the savings demonstrated here are relevant. Actual savings in homes with varying numbers of occupants and schedules will result in different savings.

Furthermore, the relevancy of the projected savings with the radiant system is dependent on the delivery of acceptable levels of thermal comfort. The overall evaluation of the heating systems comparison hinges upon analysis of thermal comfort delivery with the two heating systems.

5.4 Delivery of Thermal Comfort Comparison

5.4.1 Assessment of Thermal Comfort Delivery

Assessment of thermal comfort involved a review of the thermal comfort surveys completed by the occupants (see Appendix C). The occupants of the *AFSD* House were asked to complete a short survey whenever they experienced thermal discomfort. By including the exact time of survey completion, the responses could be linked to environmental conditions recorded for the occupied room. A summary of the survey results are contained in Appendix E.

It should be noted that the occupants of the *AFSD* House were new to the region and had little experience with radiant panels, heat pumps, or forced-air systems in general. Both occupants were accustomed to hydronic baseboard and wood stove heat.

The following generalizations were made based on review of the surveys and the environmental conditions as recorded by the monitoring system.

1. *The set-forward temperature of 68°F for both heating systems was probably at the lower margin of thermal comfort for the female occupant of the research home.* During the trial operation period of both heating systems, the male occupant determined the setback and set-forward thermostat settings. Twenty of the 25 surveys completed for some level of cold discomfort were completed by the female occupant. Studies have shown that there appears to be no relationship between thermal comfort requirements and gender; however, substantial variation among individual requirements does exist.

   ASHRAE Standard 55-1992, the thermal comfort standard, includes a graph showing the relationship between optimum operative temperature and clothing insulation for typical metabolic activity, relative humidity, and air speed. Based on thousands of observations, the graph gives the optimum operative temperature range that would satisfy 80 percent of all individuals for a given level of clothing insulation. Given the 1.1 clo value of the *AFSD* House occupants, the optimum operative temperature was 69.5 and the lower and upper limits satisfying 80 percent of all individuals were 66.5 and 72.5, respectively.[25] While the set-forward temperature of 68°F is quite reasonable for a clo value of 1.1,

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[25] ASHRAE Standard 55-1992, p. 5. These temperatures are for individuals during light, sedentary activity, a relative humidity of 50 percent and an air speed less than 0.15 m/s.

individual variation certainly allows for the responses of both occupants to the temperature setting.

2. *For both occupants, an equal number of comfort surveys indicating insufficient thermal delivery were completed for each heating system.* If the setforward temperature of 68°F was a bit low for the female occupant, at least the reaction to this setpoint was roughly equivalent for both heating systems. Appendix F contains graphs of temperature profiles during the operation of each system on a typical winter day. Note the marked differences in temperature profiles even as each system provided thermal comfort. These differences embody many of the individual issues discussed in this section.

3. *Half of the comfort surveys indicating insufficient thermal delivery were completed for the family room alone.* This fact is a combination of the total amount of waking hours spent in this room and the fact that the heat loss from this room may have been greater than calculated for either heating system. For the forced air system, the distance of the room from the first floor thermostat and the room's relative isolation from the remainder of the first floor were most likely important factors. For the radiant system, insufficient panel density and/or panel location may have combined responsibility.[26] Related to this, the temperatures in the family room at the ceiling and floor were, regardless of the operating heating system, well below measured floor and ceiling temperatures for the master bedroom and dining room. The fact that five of the six surfaces in this room were exterior would make any errors in the estimation of the conductive and/or air infiltration load in this room critical in the delivery of thermally acceptable conditions.

4. *Occupants found more opportunity to locate for comfort with the radiant system.* Although occupant location was not information included on the comfort survey, the occupants noted that they found themselves locating in a room according to panel location. The generally higher thermal requirements of the female occupant could be accommodated by locating more directly beneath a panel and the lower thermal requirements of the male occupant were accommodated by locating less directly beneath the panel. This pattern was also demonstrated by *AFSD* House visitors on several occasions. One visitor remarked that it was similar to how people might gather around a wood stove, except that the location of the panel on the ceiling meant that no one's "view" of the heat source was obstructed. This location-dependency of thermal comfort delivery can be interpreted as either an advantage or a disadvantage of the radiant system depending upon whether occupants can or must locate for comfort in a room during recovery from setback. This point will be further discussed in the conclusions and recommendations of this report.

5. *On five occasions, comfort surveys indicating insufficient thermal delivery corresponded to periods of radiant panel cycling.* On all five occasions, inspection of the recorded radiant panel status for the occupied room indicated that a survey was completed just at the tail end of an off cycle. On the one hand, this phenomenon suggests that the radiant

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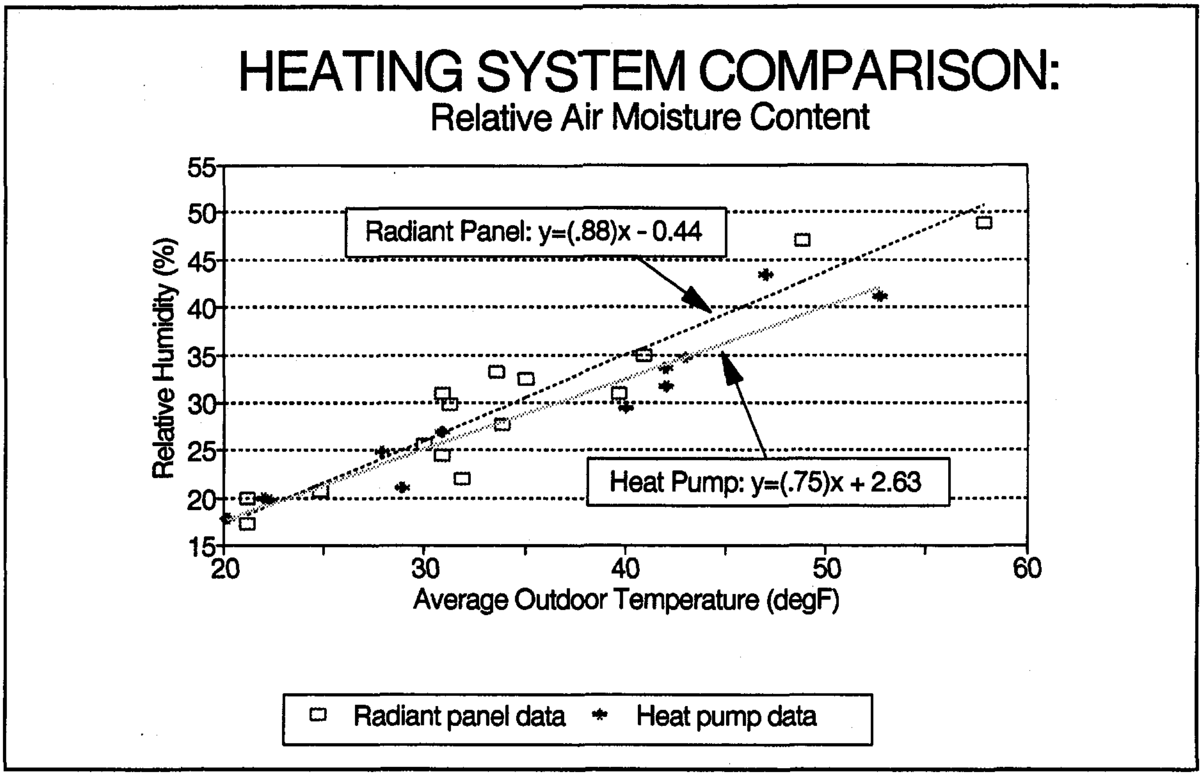
[26] Recall that the manufacturer's calculations included an assumed .4 ACH for the *AFSD* House, substantially lower than the measured .7 ACH.

thermostat is sensing thermal comfort requirements in the proximity of the panel quite efficiently. On the other hand, this phenomenon suggests that if thermally acceptable conditions are dependent on panel status, cycling as the panels near or achieve set forward conditions may be problematic for individuals requiring direct radiation for thermal comfort. All five of these surveys were completed by the female occupant of the *AFSD* House, the occupant whose comfort requirements have already been noted as more sensitive to the set-forward temperature.

6. *Four of the five comfort surveys indicating excessive thermal delivery were for the forced air system, all four of these for the master bedroom.* The only monitored room that had doors to isolate the room from the rest of the house was the master bedroom. The occupants generally slept with this door closed. With the master bedroom entrance door closed, the heat pump thermostat in the upstairs hallway was not receiving feedback from the single largest area on the second floor. Subsequently, overshoot in the master bedroom was quite common. Forty-three-inch air temperatures could go as high as 78°F in the early morning hours as the heat pump was ramping up to meet the morning set forward temperature. With occupants dressed and blanketed for overnight setback of 60°F, 78°F was quite uncomfortable. The problem of interior door position as it relates to delivery ducts, returns, and zone thermostats is not an unusual one for conventional forced-air systems.

7. *Overshoot occurrences were often coupled with occupant complaints of dry throats and headaches that they attributed to the dryness of the air.* It was anticipated that occupants' sinus problems would be associated with lower relative humidities with the forced-air system than the radiant system, particularly at lower outdoor air temperatures. The infiltration of cold, relatively dry air would be greater with the higher infiltration rate associated with the ducted forced-air system than the non-ducted radiant. This would be particularly true during very cold periods when longer periods of blower operation would increase the air infiltration rate associated with the ducted system. In fact, the graph in Figure 2 shows little difference in relative humidities for the two systems and unexpectedly less difference at colder outside temperatures. More continuous and consistent relative humidity measurement may be required to resolve this apparent anomaly. Regardless of the numerical results on relative humidity, sinus complaints were clearly common with forced-air system operation at cold temperatures and non-existent during radiant system operation. It is possible that sinus and respiratory irritation was related to some other phenomena, such as air-borne dust or room pressurization, that are also correlated to forced-air operation.

Figure 2



8. *The clo value of both occupants' standard dress may have had an impact on thermal comfort assessment of both heating systems.* The occupants made an effort to standardize the total clo value of day and night time dress. Day attire for both occupants was approximated at 1.1.[27] This clo value is, however, significantly higher than the clo value used in most thermal comfort studies with perhaps the most important difference being the percent exposed skin surface. The total clo value and relatively low percent exposed skin surface may have made occupants less sensitive to air temperature reduction with the radiant system and localized drafts near forced-air delivery registers. The occupants commented that on isolated occasions when substantial skin surface was exposed, walking from room to room during radiant system operation felt quite cool. The reduced air temperature associated with the cooling effect of apparent air speed when walking may have created the equivalent of a draft. Similar instances were described for the forced-air system operation, particularly in the bathrooms, where the location of delivery registers near the showers made lower total clo values sometimes unavoidable. Although the occupants' dress may have reduced their sensitivity to certain aspects of both heating systems operation, the fact that dress was standardized for both systems reduced the impact of this phenomenon.

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[27] Typical dress for both occupants included: heavy trousers or sweatpants, turtleneck, sweater, wool socks or leather-bottomed and lined slippers, and undergarments. The female occupant generally wore thin long underwear bottoms, as well. As recent arrivals to the area from rural New England, the occupants dressed as they have been accustomed.

At the end of the testing period, the two occupants of the *AFSD* House were asked which heating system they preferred and why. Their preferences were solicited before any information on the comparative energy consumption of the two systems was available. Both occupants stated their preference for the radiant heating system, for the following reasons:

1. *Room-by-room control and flexibility*: Both occupants liked being able to control the temperature in the room rather than have a hallway thermostat dictate the conditions. An activity such as exercising by one occupant in one room did not require changing the environmental conditions of an entire floor. The radiant system accommodated occupants' varying thermal requirements better than did the conventional, forced-air system.

2. *Silent and still operation*: Both occupants preferred the lack of air movement and fan operation noise.

3. *Sinus comfort*: Particularly during sleeping hours, the occupants preferred the conditions of radiant panel operation to those of forced-air operation.

The primary inconvenience cited in the operation of the radiant system was the need to anticipate the setting forward of room thermostats to achieve general room comfort as opposed to more local thermal comfort conditions. While the occupants felt that acceptable thermal conditions could be achieved in approximately 10 to 15 minutes if activity was restricted to panel proximity, total room comfort required approximately 30 to 45 minutes. For example, the master bedroom thermostat was set forward by the earlier riser in the morning so that thermally acceptable, whole-room, conditions would exist for the other occupant upon rising.

The occupants also felt that it was more difficult to remember to setback the thermostat upon exiting then it was to set forward upon entering a room. There was no "prompt" to set back the thermostat as there is for lighting when exiting a room.

The input from actual occupants was invaluable in assessing the operation and delivery of thermal comfort by the two heating systems. Their input goes beyond the capabilities of measured environmental factors. Their experiences are by nature, however, individual and subjective. Their specific thermal requirements and preferences are important but must be viewed as limited. The recorded environmental parameters from the three thermal comfort stations can be used to broaden the discussion of thermal comfort delivery.

5.4.2 Sufficiency of Installed Capacity

Assessment of thermal comfort delivery is in part determined by the ability of each heating system to meet heating needs down to design conditions. The installed capacity of a heating system must be sufficient to meet the whole-house requirements for maintenance of acceptable thermal conditions down to an outdoor temperature extreme typical of the region. Design condition for the area where the *AFSD* House is 13°F.

The 1993-94 heating season for the mid-Atlantic region of the United States was unseasonably cold, particularly in mid-January and early February. Outdoor temperatures approaching and exceeding design conditions were common during parts of January and February. Data for two full days of outdoor daily average temperatures below 10°F were available for comparing the performance of the radiant and forced-air heating systems. Of the three monitored rooms, the family room was selected for discussion because the heat loss from this room placed the greatest load on both heating systems.

Figure 3 shows the operative temperature recorded in the family room during radiant system operation for the entire 24-hour period on January 15, 1994. Outdoor temperatures were at or below design conditions for the entire 24-hour period. The temperature started at 12°F and worked its way down to 0°F as the day progressed. This means that the *AFSD* House was experiencing outdoor conditions primarily below design conditions for the entire 24-hour period.

The pattern of family room operative temperatures suggested that the installed capacity was sufficient to at least maintain the setback temperature of 60°F, even at temperatures approaching 0°F. The indoor/outdoor temperature differential at 0°F was 60°F, 5°F greater than the differential used for the manufacturer's installed capacity calculations.

It is more difficult to determine if the installed capacity was sufficient for recovery from setback. The setpoint of the family room thermostat is known only for the early morning and late night hours for this 24-hour period. These periods corresponded to night time setbacks of 60°F. On most days, inspection of the status channel for a monitored room in conjunction with the pattern of the operative temperature provided the information necessary to determine when monitored rooms were occupied. For this day, however, inspection of the status channel revealed that the panels in the family room were energized without interruption for the entire 24-hour period. Little can be determined regarding family room occupancy and day time thermostat setting from the database. Although the operative temperature peaks of 65°F suggest some intermittent occupancy, the fact that this day was a weekend day meant that nothing could be determined regarding occupancy.[28]

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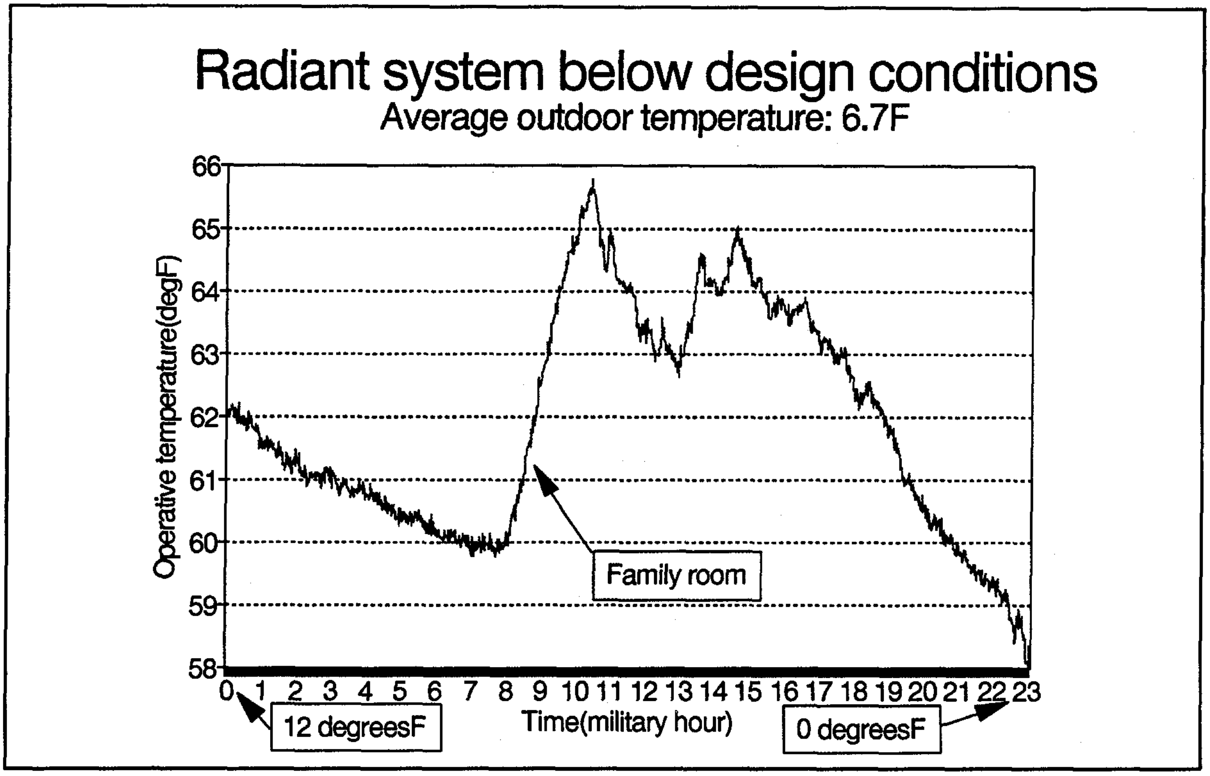
[28] The location of the operative globe near the room perimeter at this point in the study made interpretation of this data more difficult. Tests performed on the effect of globe location discussed later in this report suggest that perimeter operative temperatures of 65°F could correspond to operative temperatures closer to 68°F in the central portion of the room.

Figure 3



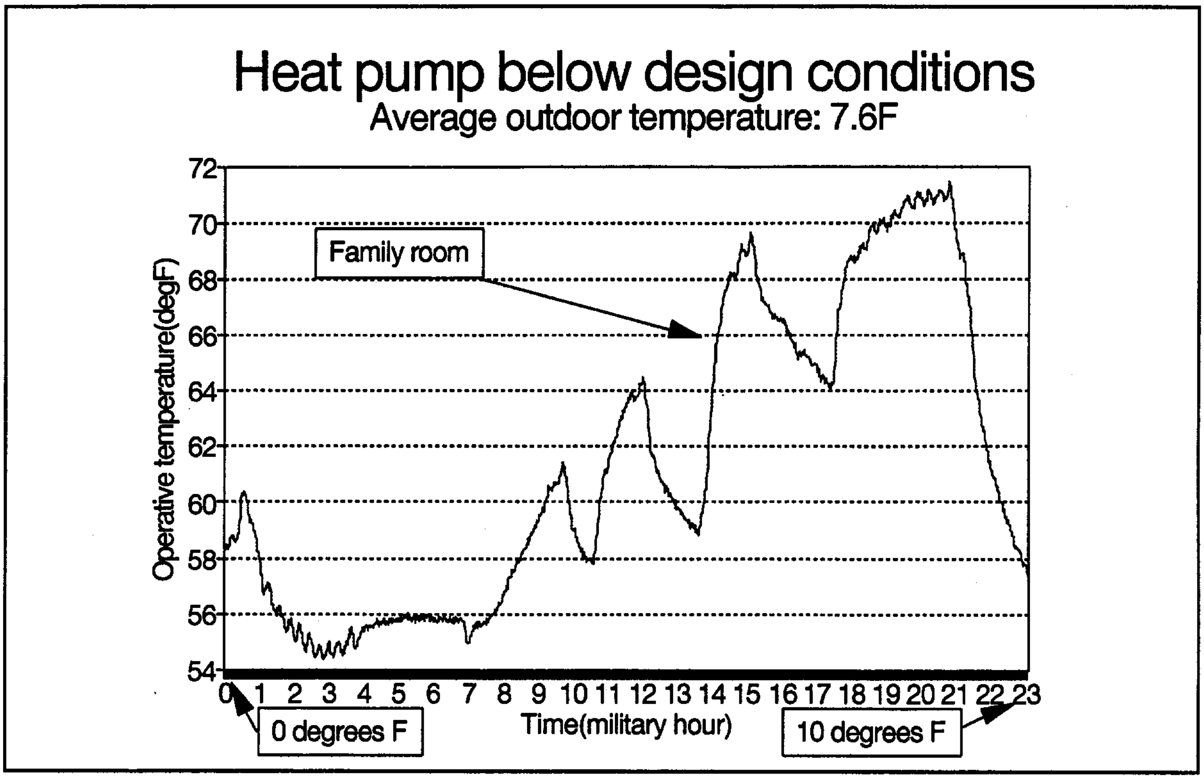
Inspection of data for this 24-hour period for the other two monitored rooms indicated frequent panel cycling, even late in the evening when outdoor temperatures were well below design conditions. This suggested that the installed panel capacity in these rooms was more than sufficient to meet design conditions under steady state conditions. Review of cold days above design conditions (average daily outdoor temperatures in the 20's) revealed no difficulties in any of the monitored rooms' abilities to recover from setback. Although the information available does not prove the sufficiency of installed capacity, there are strong indications to suggest that the installed capacity was adequate for design conditions and day and night setbacks.

Figure 4 shows the graph of operative temperature patterns for the family room during forced-air system operation for a day with an average outdoor temperature below design conditions and very similar to the average outdoor temperature in Figure 2. Because the forced-air system followed a schedule and it was known that this 24-hour period represents a weekend day, the thermostat settings were known. The night time setback was 60°F and the day time setting was 68°F.

The night setback of 60°F was not maintained in the family room. This period did, however, correspond to outdoor temperatures well below the design condition of 13°F. The temperature pattern of peaks and valleys from 9 a.m. to 5 p.m. suggests problems with maintenance of the 68°F set forward temperature. The cycling associated with the pattern may be more a problem of thermostatic control than sufficiency of installed capacity. On both floors, the forced-air thermostats were located approximately halfway down the hallways. Temperature feedback from a room isolated and distant from the thermostat can be a problem with floor-zoned heating systems.

Inspection of the other two monitored rooms for this 24-hour period revealed better maintenance of setback and setforward temperatures. The patterns of operative temperature in the dining room and master bedroom suggest that the installed capacity of the forced-air system was sufficient.

Figure 4



Proving the sufficiency of the installed capacity for the forced-air system was not the point of this comparison--the sizing criteria for conventional heating systems are well established. Fast-acting, radiant panel sizing criteria are an issue because the undersizing of the radiant system is so dramatic compared to the sizing of conventional systems. The radiant system's performance down to and below design conditions supports the methodology for sizing that the manufacturer and Kansas State modeling employed for this installation, at least for steady-state conditions. The information available suggested that the installed capacity was adequate for recovery, as well, but more specific investigation of this phenomenon may be required.

Calculating the heat loss of rooms and entire structures and subsequently establishing installed capacity is based on assumptions and often judgments by HVAC contractors. Sizing a heating system to meet the most severe possible weather for a location is clearly not economical.[29] The calculations and methodology of either the manufacturer's or the Kansas State are certainly

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[29] ASHRAE, *1993 ASHRAE Handbook: Fundamentals*, 1993.

within the proper range. The significantly reduced installed capacity of the radiant system by either method of calculation appears appropriate to meet assumed design conditions given the evidence from this field study. The manufacturer's significant reduction in installed capacity with non-mechanical radiant panels operating at lower average indoor air temperatures is credible.

5.5 Issues Discussed by the Literature Review

Six issues regarding the performance of ceiling radiant heat were prominent in the literature review for this case study that can be at least partially addressed with results from the field research.

5.5.1 Localized versus Room-Wide Comfort Conditions During Recovery from Setback

It has been mentioned earlier in this report that the original location of the operative temperature globes was relatively near the room perimeter. While location of the air temperature sensors near the room's perimeter appeared to have little impact on their readings, there was clearly significant impact on the globe readings depending on their location with respect to the radiant panels.

Figure 5 demonstrates the impact of globe location on operative sensor readings. In Figure 5, the four curves correspond to the readings from four operative globes located directly underneath, 2 feet, 4 feet, and 6 feet to the side of a 2-foot by 8-foot radiant panel, all globes hanging 43 inches from the floor. The location of the four globe thermometers in 2-foot increments away from the 2-foot by 8-foot ceiling radiant panel was a method of estimating the effects of viewing angle between the radiant heat source and occupants. All of the globe sensors started at approximately the same temperature of 60.5°F. This is equivalent to the recorded ambient air temperature at the start of the test, a condition to be expected when the room has been at a steady-state setback of 60°F.

As soon as the panel was energized, the recorded temperatures of the operative-estimating globes began to diverge. The increase in operative temperature is clearly proportional to the viewing angle with respect to the energized panel. This divergence is an indication of the impact that location of occupants with respect to the panel could have on thermal comfort conditions during panel recovery. Care must be taken in interpreting the rate of rise of all four sensors because of the problem regarding the lagged response time of 6-inch copper globes, to be discussed in the following section. After operation of the panels for 1 hour 24 minutes, however, the operative temperature difference between the globe directly underneath the panel and the globe located 6 feet away was almost 5°F. And, although the globe temperature readings had not quite leveled off after 1 hour 24 minutes, the curves appear to be very close to leveling off. This significant differential can be speculated to only decrease as the ambient air temperature continues to rise and the room begins to approach steady-state conditions, conditions under which the 43-inch globe and air temperature sensor would become roughly equivalent. During the 1 hour 24 minute test period, the 43-inch ambient air temperature rose from 60.2°F to 61.0°F.

The specific conditions existing in the dining room where the globe location test was performed are important to consider in interpreting Figure 5. Refer to the *AFSD* House first floor schematic in Appendix B for the following discussion:

1. Only a ½-height, ¾-length partition defines the living and dining room spaces.
2. Only a ¾-length counter and kitchen cabinet wall defines the dining room and kitchen spaces.
3. Although the 2-foot by 8-foot dining room panel is located within the specifications outlined by the panel manufacturer, the 2-foot by 8-foot living room panel is located on the end of the living room away from the dining room and 90° rotated from the manufacturer's recommended location. A ceiling fan and sprinkler head prevented location of the living room panel in the specified location.
4. The living room 2-foot by 8-foot panel was operated by a separate thermostat whereas the kitchen and dining room panels were on the same thermostat.

These conditions are important because the orientation of panels and thermostatic control affected the globe readings in this test and therefore are indications of the impact panel location and room geometry have on thermal comfort, particularly during setback recovery. First, the globes with increasing distance from the dining room panel did not have the benefit of reflectivity of full height walls between the kitchen and living room. In a sense, the lack of containing full height walls between the kitchen and dining room and living room and dining room allowed radiant heat from the dining room panel to "escape" beyond the dining room's dimensions. Second, the globes did not "see" the living room panel as they would have if the living room panel was located in the center of the living room as the manufacturer prescribed. Third, the open nature of the kitchen, dining, and living room spaces probably resulted in a slower rise in the air temperature during recovery, and therefore delayed its contribution to operative temperature rise. Fourth, because the dining and living rooms were on separate thermostats, the living room panel was not energized during the globe location test. (A better design may have been for the living room and dining room panels to be on the same thermostat and the living room panel centrally located because the open nature of the living/dining room spaces makes them more a common space than individual rooms).

The globe location test and the above discussion on room geometry indicate the importance of panel location and thermostatic control with fast-acting, ceiling radiant panels. Because provision of thermal comfort during recovery is so dependent on panel location and distribution, panel location and thermostatic control must be carefully determined, particularly if the system is going to be used under setback conditions.

5.5.2 Time Required for Comfort Conditions During Recovery from Setback

Research by Berglund of the Pierce Foundation has shown that occupants of a radiantly heated enclosure accept cool spaces upon entry as long as the radiant system can quickly raise the operative temperature.[30] "Quickly" in the case of radiant panels in the Berglund study meant acceptance at the 92 percent level after 15 minutes. This information corresponds to the

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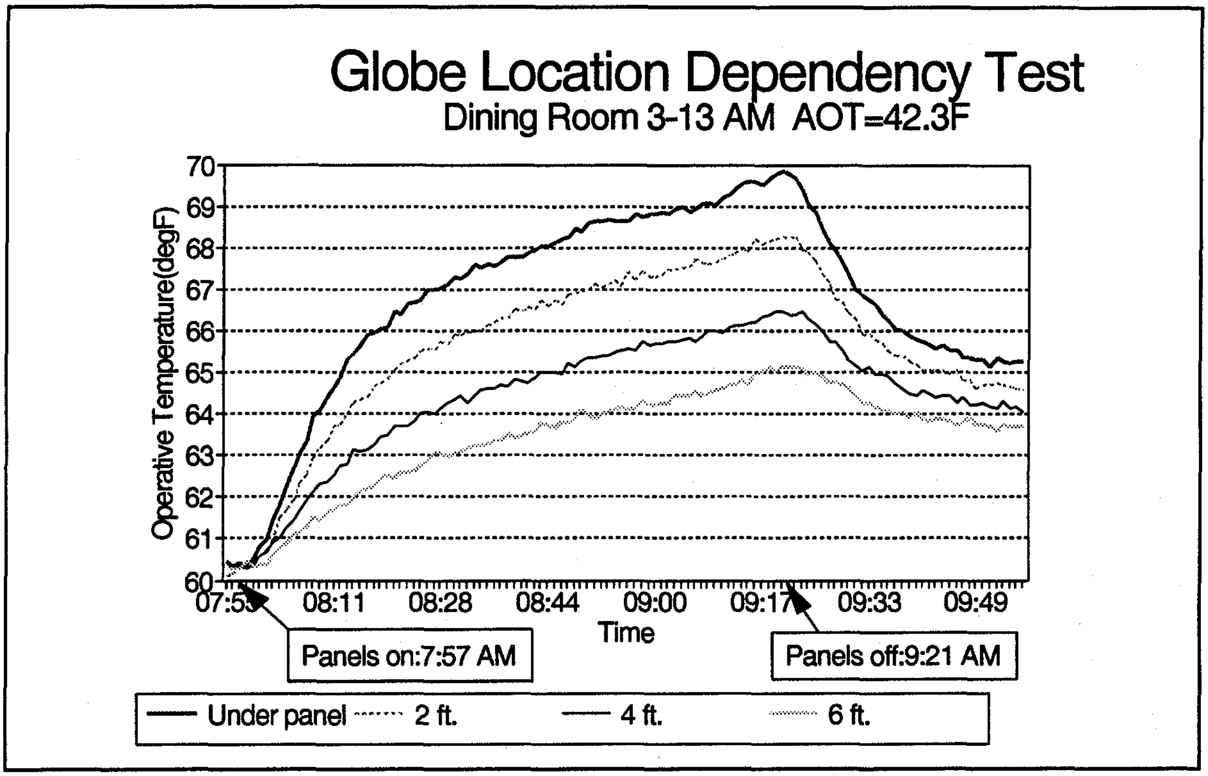
[30] Berglund, L., R. Rascati, and M. L. Markel, "Radiant Heating and Control for Comfort During Transient Conditions," *ASHRAE Transactions*, Part 2: 765-775, 1982.

experiences of the *AFSD* House occupants but does not correspond to the data presented in Figure 5.

Figure 5



Note that even the globe directly underneath the panel does not reach an operative temperature of 68°F from a setback of approximately 60°F until approximately 45 minutes after the panel was energized. This is a factor of three greater than the rate demonstrated in the Berglund study. There are several possible explanations for this discrepancy.

First, the enclosure for the Berglund test was a room only 8 feet by 8 feet and supplied with four 4-foot by 4-foot radiant ceiling panels. The *AFSD* House dining room had ¼ of the area of radiant panel installed (one 2 foot by 8 foot), and the dining room was 12 feet 4 inches by 13 feet 4 inches, an area over 2.5 times greater than the test chamber in the Berglund study. Room dimensions and aspects of radiant and reflective surfaces can have a significant impact on the delivery of thermal comfort.

Second, in the Berglund test, the ambient air temperature was raised by a separate convective heating system at a rate of 6.3°F an hour. In the test shown in Figure 4, the estimated ambient air temperature rise was at a rate of approximately 1°F per hour. Because the ambient air temperature is one of the primary determinants of the operative temperature, differential rates of ambient air temperature rise would have a significant impact on the rate of operative temperature rise, and hence, thermal comfort.

Third, the 6-inch copper globe is known to have an "undesirable [sic] high time constant."[31] In most monitoring situations, the lag time in 6-inch copper globe response is not critical because the operative temperature rise when testing convective heating systems is not rapid. With fast-acting radiant panels, however, a 15 minute thermal lag in the response of the operative globe can have substantial impact on the assessment of thermal comfort delivery, particularly in periods of temperature recovery. Although experts in the field of heat transfer agree that the 6-inch copper globe does demonstrate lag in estimating operative temperature, only estimates of the lag time exist and no specific references quantifying lag time could be obtained. It is clear that development of a more efficient and rapidly responding operative temperature sensor will be required to quantitatively assess thermal comfort delivery with fast-acting radiant systems, particularly during the early stages of temperature setback recovery.

Quantitative assessment of thermal comfort delivery during periods of radiant panel setback recovery was not possible with the monitoring equipment currently available. Occupants of the *AFSD* House generally felt that thermal comfort was acceptable in close panel proximity in approximately 15 minutes.

5.5.3 Time Duration of Lower Air Temperature with Respect to Operative Temperature

Lower air temperature in conjunction with an elevated mean radiant temperature is central to the Enerjoy claims of energy savings and maintained thermal comfort. Under steady-state conditions and radiant panel operation, the operative and air temperature are approximately equal. Under transient conditions, as the setpoint of the thermostat is changed from the setback to setforward temperature, for some period of time the air temperature remains at a lower temperature than the newly elevated operative temperature. Energy savings from lower air temperature are dependent on the length of time it takes for the portion of the total heat transfer that is convective in the room to reach an equilibrium with radiant heat transfer. An heating element that is radiating a high portion of its total heat output to a room filled with building materials that have high emissivities and low convective coefficients provides the environment for a sustained lower air temperature. The following factors also influence the length of time a lower air temperature will endure after the thermostat is set forward:

1. *Outdoor temperature* - As illustrated in Figure 6, the duration of a lower air temperature was longer at lower outdoor temperatures. A 43-inch air temperature of 68°F was achieved after approximately 2 hours at an average outdoor temperature of 37.7°F. At an average outdoor temperature of 27.4°F, ten degrees colder, the air temperature reduction was maintained for more than three hours. The rate of air infiltration is dependent in large part on the indoor/outdoor temperature differential. The larger the differential, the higher the air infiltration rate. The higher the air infiltration rate, the greater the entry of cold air into the room, and the longer the air temperature reduction period.

2. *Natural air infiltration rate* - At the same outdoor temperature, rooms or structures with higher natural air infiltration rates will take longer to reach equilibrium or steady-state.

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[31] ASHRAE, *1993 ASHRAE Handbook: Fundamentals*, 1993.

Because air is the medium of convective heat transfer, higher rates of replacement of the space's air content will slow the air temperature rise and the time required to reach steady-state conditions.

3. *Room geometry* - As discussed in a previous section, the degree to which any room is isolated from free air exchange with other parts of the house will have an impact on the rate of ambient air temperature rise in the room.

Figure 6

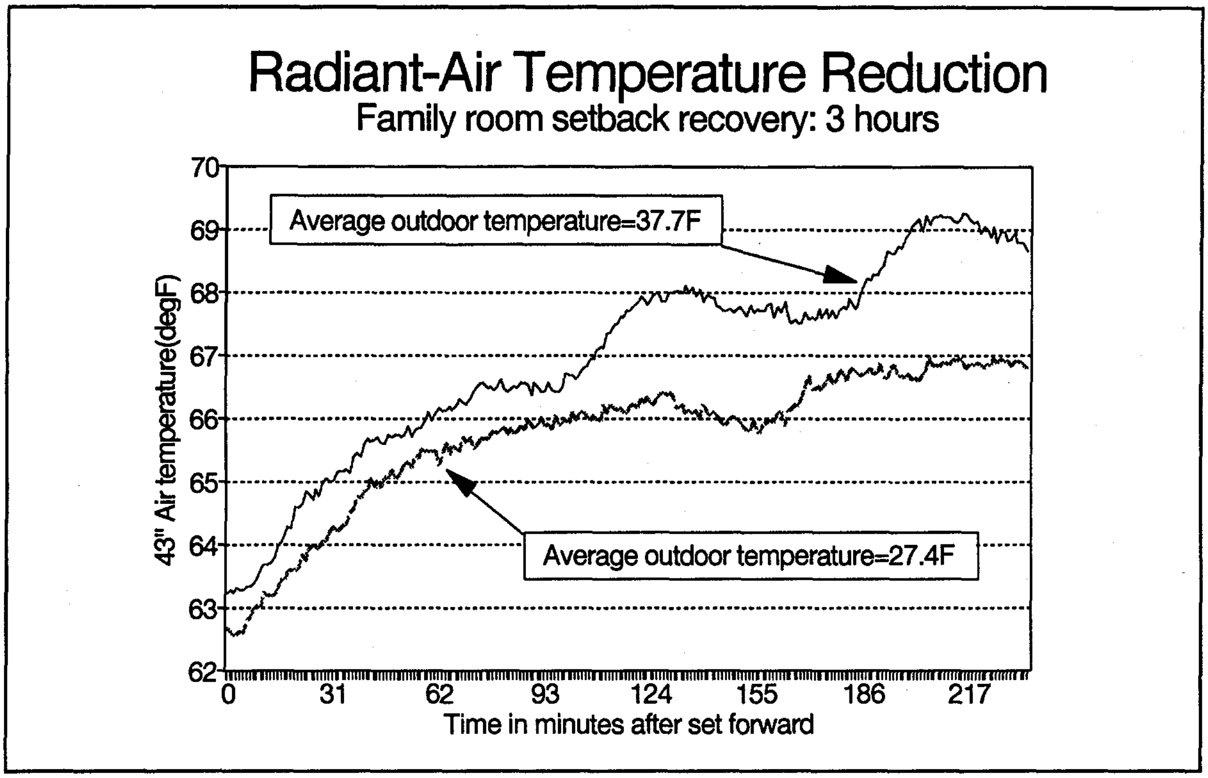


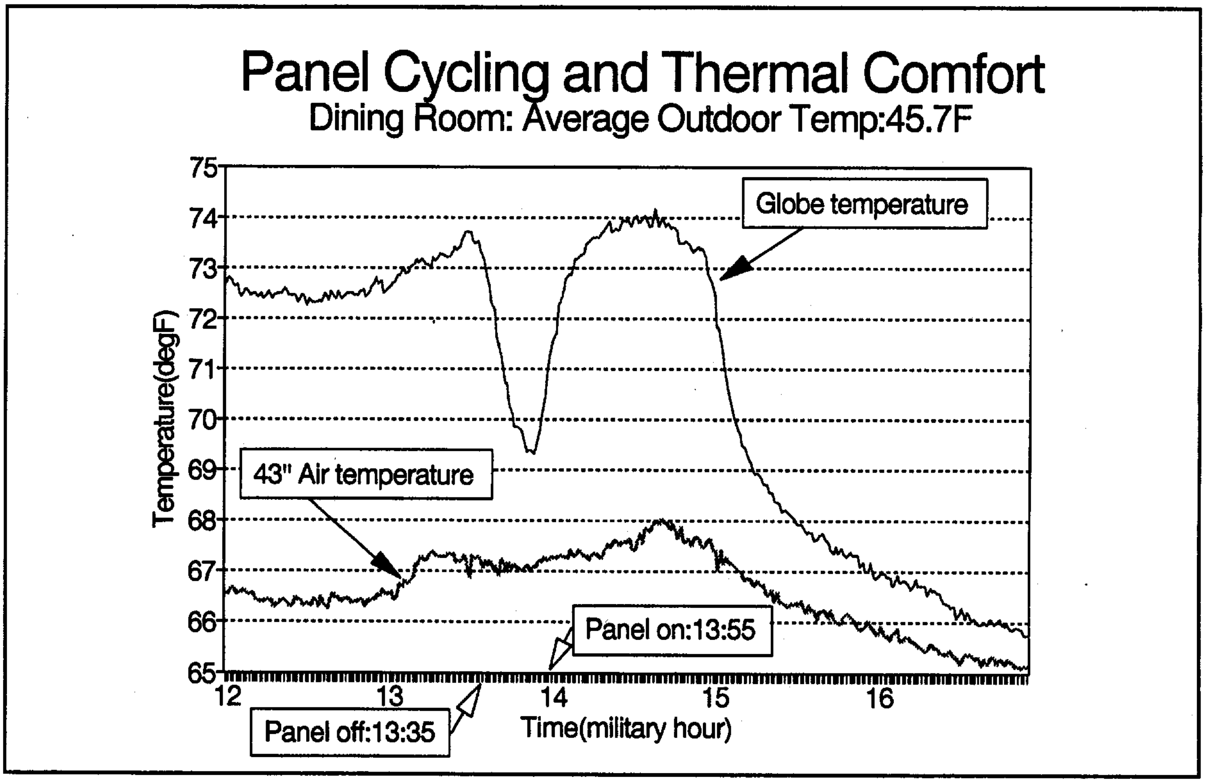
Figure 6 shows the effects of outdoor temperature for a room with five exterior surfaces. The natural air infiltration rate of this particular room is relatively high and must be considered in an evaluation of the duration of lower air temperature under transient conditions. Review of 43-inch air temperature rise to steady-state conditions for other monitored rooms revealed that air temperature rise under transient conditions was related to outdoor temperature but durations of 2 to 4 hours were not unusual. Time periods of this length provide a significant opportunity for any subsequent energy savings. Consideration must also be given to the fact that recovery from setback (transient conditions) occurs during occupied periods. Occupants' activities (opening of exterior doors, exhaust fan operation, etc.) raise the air change rate and can serve to increase the duration of lower air temperatures.

5.5.4 Sustained thermal comfort and radiant panel cycling

Panel cycling and thermal comfort were discussed as part of the review of thermal comfort surveys completed by *AFSD* House occupants. For a number of thermal comfort surveys, discomfort was associated with a period of panel cycling. In general, panel cycling occurred during or just prior to steady-state conditions. This situation is graphically portrayed in Figure 7. This graph represents a time period of continued occupation of the dining room on a weekend day. The thermostat had been set forward for several hours prior to the time period portrayed. Note that the 43-inch air temperature, while lower than the operative temperature, was approaching 68°F. The globe operative temperature was significantly above the standard set forward temperature of 68°F but acceptable thermal conditions were occurring until the time corresponding to the sharp drop in the operative temperature. The sharp drop in operative temperature corresponds to a period of panel cycling, as indicated by review of the panel status records. While the operative temperature never dropped below 69°F, two individuals indicated thermal discomfort during the time period corresponding to the sharp drop in operative temperature. Both individuals registering thermal discomfort were located directly beneath the 2-foot by 8-foot radiant panel. Two other room occupants not located directly beneath the panel did not register thermal discomfort.

The thermal comfort surveys completed that corresponded to periods of panel cycling and the graph in Figure 7 illustrate that panel cycling can be a source of thermal discomfort for occupants whom are located in close proximity to the radiant panel(s). If the occupant directly beneath the panel found the thermal environment acceptable prior to the panel cycling off, the sharp drop in operative temperature while the panel cycle off resulted in thermal discomfort. Occupants not directly underneath the radiant panel experienced less of a drop in operative temperature and consequently were less likely to find the panel cycling thermally unacceptable.

Figure 7



It is interesting to note that panel cycling during setback can be quite frequent and be accompanied by rapid changes in the operative temperature directly underneath a radiant panel. This situation was a common occurrence in the master bedroom--occupants were located directly beneath the 2-foot by 8-foot panel during setback periods, periods for which inspection of the database revealed frequent panel cycling, on for approximately 8 minutes, off for approximately 12 minutes. Inspection of air and operative temperatures during setback revealed air temperatures around 62°F with the operative temperature rising and falling from approximately 65°F to 63.5°F. Thermal discomfort complaints, however, did not correspond to panel cycling during setback periods. Thermal discomfort may have been less likely under these circumstances for one or a combination of the following reasons:

- The difference between air and both operative and mean radiant temperatures was significantly less during setback.
- Substantially elevated clo values associated with bedding reduced sensitivity to rising and falling operative temperatures.
- Sleeping reduced the sensitivity of individuals to temperature swings or the likelihood of completion of a survey.

5.5.5 Vertical Air Temperature Difference

Vertical air temperature difference can result from less dense, warmer air rising to the ceiling and more dense, cooler air falling to floor level. Vertical air temperature difference can be important in terms of its effect on thermal comfort and increased heat loss.[32] ASHRAE Standard 55-92 sets a maximum vertical air temperature difference for thermal comfort of 5°F differential from 4 inches to 67 inches off the floor.[33]

Figure 8 shows three examples of vertical air temperature difference, two corresponding to periods of heat pump operation and one corresponding to a period of radiant panel operation. The vertical axis represents the difference between air temperatures measured at 4 inches off the floor and 4 inches off the ceiling. The three lines are all generated from data for the dining room and were selected because they represented close to the maximum stratification generated by either heating system. (With unconditioned space above both the master bedroom and family room, vertical air temperature difference was less pronounced in these two rooms than in the dining room.)

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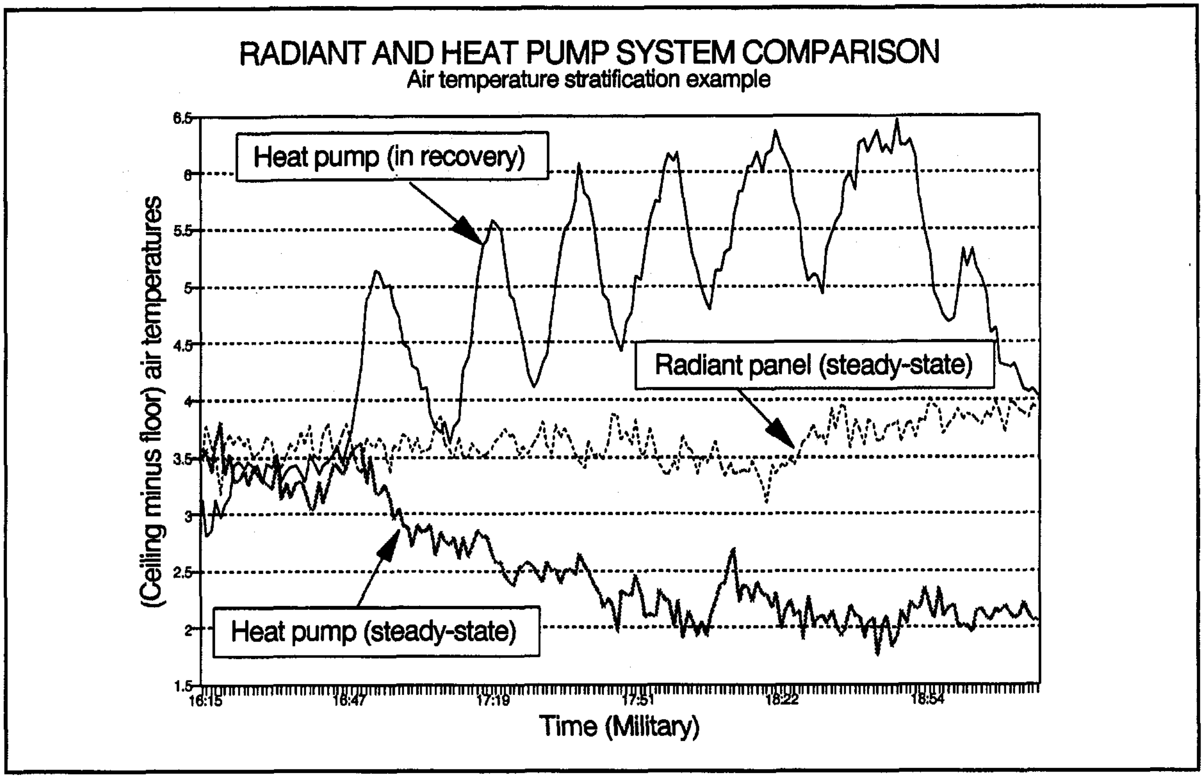
[32] Higher temperatures at the ceiling can result in a higher indoor/outdoor temperature differential at the ceiling, increasing conductive losses. Additionally, higher air infiltration can result from stack effect, even within a single-story.

[33] The ceiling air temperature measurement is significantly different than a 67-inch off-the-floor measurement specified in the ASHRAE standard and so quantitative evaluation of compliance with this standard was, strictly speaking, not possible.

Figure 8



The large peaks in the "heat-pump-in-recovery" line were thought to coincide with cycling of the auxiliary strip heat as the predictive, programmable thermostat brings the first floor temperature up to the setpoint of 68°F for occupancy on a very cold day. During ramping up periods on very cold days, the blower ran continuously and the air temperature of the heated air as it left the floor registers varied significantly as the auxiliary strip heat cycled off and on. It is customary for the delivery temperature at registers to be significantly higher when the backup strip heat is on and supplementing heat pump capacity. Note that the vertical air temperature difference from floor to ceiling approaches 6.5°F during recovery. In steady-state, the forced-air system demonstrates much less stratification and the trend over time is less rather than more stratification, just the opposite of the stratification demonstrated during the recovery period. The radiant system, on the other hand, behaved in an opposite manner. The vertical air temperature difference was greater during steady-state conditions than during recovery.[34] In comparing the two heating systems, the vertical air temperature difference for the radiant system in steady-state was less than the vertical air temperature difference of the heat pump in recovery.

The large differences in vertical air temperature difference for the two heating systems was probably the result of different phenomena. With the forced-air system blower on continuously during recovery, periods of elevated delivery temperatures as the strip heat cycled on caused the peaks and the mixing of this warmer air as the strip heat cycled off represents the valleys. With the radiant system, sustained periods of energized panels and little active air movement resulted

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[34] The vertical air temperature difference during recovery was not included in Figure 8 because the difference was negligible.

in some natural or passive vertical air temperature difference. It is possible as well that the convective coefficient of the panel while at operating temperatures of 150 to 170°F creates a thin layer of warmer ceiling air that remains stratified since the heating system involves no active movement of air. Regardless of the exact mechanism the radiant heating system demonstrated less vertical air temperature difference than the operating forced-air system and did not exceed limits of vertical air temperature difference as set forth in ASHRAE Standard 55-92. The greater vertical air temperature difference with the forced-air system supports the fact that hot air, not heat, rises. A system heating air is more prone to vertical air temperature difference than a radiant system which only heats the air indirectly and over extended periods of time.

5.5.6 Computer Modeling Analysis of Thermal Comfort Delivery with Radiant Heating

Research is ongoing in the development of computer models capable of more accurately representing the actual heat transfer dynamics in complex structures such as homes. One such model has been developed with support from ASHRAE by Drs. Jones and Chapman of the Kansas State University's Institute for Environmental Research. Their model has the capability to predict local thermal comfort conditions for residential structures heated with a ceiling radiant system. It is only recently that computer modeling has gained the capability of incorporating all three forms of heat transfer. This new capability allows comparison of empirical field results on thermal comfort delivery by radiant heating systems to computer modelling results.

Comparison of the field data from the AHTP Enerjoy case study to computer modeling results from the Kansas State Comfort and Building Analysis Program would provide important information on the modeling validity and field testing protocols for radiant heating. Time and budget constraints prevented inclusion of any comparison in this report. A database exists, however, should resources be available for this comparison.

6.0 SUMMARY OF FINDINGS

The objectives of Task 2 were to assess the comparative airtightness, installed capacity, energy consumption, and delivery of thermal comfort by the fast-acting, ceiling radiant and forced-air heat pump heating systems. Comparison to an electric baseboard system was to be included where possible. In addition, specific unresolved issues regarding performance of the ceiling radiant heat in residential structures were to be discussed.

6.1 Air Infiltration

The literature review provided consistent evidence of the reduced air infiltration rates with non-ducted heating systems in comparison to forced-air, ducted systems. The results of the two blower door tests performed on the *AFSD* House were in accordance with this evidence. The *AFSD* House demonstrated a 12.5 percent reduction in the natural air infiltration rate when in the radiant mode as compared to the forced-air mode. Previous research has shown that air infiltration during blower operation of a ducted system can double the air infiltration rate. The blower door tests performed at the *AFSD* House emphasized the validity and importance of effectively eliminating the duct system during operation of the radiant system. The sealing of all ducts and returns during radiant system operation served to increase the validity of the two-system comparison.

6.2 Energy Consumption

The radiant heating system demonstrated significantly better energy performance than either the heat pump or baseboard systems. Translation of the three energy consumption/outdoor temperature relationships into expected energy savings for a given locale was accomplished with typical record year data from Andrews Air Force Base. Thirty-three percent savings could be expected in the *AFSD* House by operating the radiant system instead of the heat pump and 52 percent savings could be expected by radiant system operation in place of the electric baseboard system. The significantly better performance of the radiant system in comparison to the baseboard system suggests that savings with the radiant system are not solely due to efficiency gains associated with room-by-room zoning and the absence of delivery losses associated with centralized, forced-air systems.

It is important to note that the comparative energy performance of the three systems is specific to the *AFSD* House and its occupancy by a working couple. Savings in other homes with varying numbers of occupants and their daily routines could have significant impact on the comparative energy performance of the three heating systems.

6.3 Installed Capacity

The installed capacities of the radiant, heat pump, and electric baseboard systems support the radiant panel manufacturer's claim of significantly reduced installed capacity for the radiant system. The actual installed capacity of the radiant system was 40 percent less than Right-J recommendations for steady-state system operation, 50 percent less than the installed capacity of the heat pump system, and 60 percent less than the electric baseboard installation.[35] Review of data for outdoor conditions to and below design conditions (13°F) revealed that the installed capacity of the radiant system was adequate to maintain set indoor temperatures. There was insufficient information to determine definitively if the installed capacity of the radiant system was sufficient in the family room. Accurate information on the specific heat loss characteristics of a structure at the room-by-room level may be required to reduce the installed capacity of the radiant system to the extent presented in the *AFSD* House.

6.4 Thermal Comfort

Review of the thermal comfort surveys completed by the two *AFSD* House occupants suggested that comparable levels of thermal comfort were provided by the radiant and heat pump systems. Occupants found that their location in relation to the panels influenced thermal comfort. During recovery form setback, location for thermal comfort may be required. During steady-state conditions, the effect that viewing angle had on thermal comfort permitted individuals with varying thermal requirements to locate in relation to the panel for comfort. Localized thermal comfort was found to be provided by the radiant system within 10 to 15 minutes during recovery

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[35] Both the heat pump and electric baseboard installed capacities were designed for day and night setback.

and room-wide comfort in approximately 45 minutes. Both occupants found these delivery times acceptable, although the room-wide provision of comfort during recovery required anticipation of this room's use. The occupants, prior to any knowledge of the two systems' energy performance, indicated their preference for the radiant system because of greater flexibility and control on a room to room basis, silent operation, and fewer problems with sinus discomfort. Their preferences were based less on thermal comfort criteria than on features associated with system operation.

The comfort analysis in this report is limited to the evaluation of subjective input from two occupants of the *AFSD* House. While the evaluation of completed thermal comfort surveys provided valuable information on thermal comfort, their specific thermal requirements, standards of dress, and backgrounds cannot be ignored as limiting factors in the thermal comfort analysis.

Quantitative analysis, such as PMV analysis or comparison to computer modeling results, would provide an additional basis for thermal comfort evaluation. Quantitative analysis would be complicated by the lagged response time of currently available operative or mean radiant sensors and the present inability of computer models to analyze thermal comfort delivery with radiant heating systems under transient conditions.

6.5 Specific Performance Characteristics of Radiant Heating as Discussed in the Literature

Research by Berglund has demonstrated that occupants can find it thermally acceptable for a room to be cool upon entry as long as the operative temperature is rapidly raised; "rapidly" being defined as approximately 15 minutes. This corresponds to the experience of the *AFSD* House occupants in the Enerjoy case study so long as the occupant's activity permits location in close proximity to a radiant panel. Room-wide thermal acceptability may require as long as 45 minutes. During recovery periods, the operative temperature varied depending on occupant location with respect to the radiant panel.

Lower air temperatures as the operative temperature rises rapidly is central to energy savings claims with fast-acting radiant heat. The rate of rise in ambient air temperature in the monitored rooms of the *AFSD* House suggested reduced ambient air temperatures for two to four hours, with prevailing outdoor conditions having a significant impact on the duration of reduced air temperatures. The specific geometry and heat loss characteristics of the room also had a significant impact on duration.

During some periods of extended panel operation, individuals located directly beneath a radiant panel registered thermal discomfort when a panel cycled off. Although the individual found the environmental conditions acceptable while the panels was energized, the rapid and sharp drop in operative temperature associated with the panel cycling off caused thermal discomfort. Thermal discomfort due to panel cycling was only registered by individuals located beneath a radiant panel.

The degree of vertical air temperature difference associated with any heating system is important in terms of thermal comfort and conductive heat loss. The ASHRAE thermal comfort standard sets a maximum difference between floor and head-high air temperatures. Stratification can create a stack effect associated with increased heat loss. Under recovery or steady-state the vertical air temperature difference associated with radiant heating system operation in the *AFSD* House was found not to exceed 4°F. This degree of vertical air temperature difference is within the limits set by the ASHRAE 55-92 thermal comfort standard and less than the degree of vertical air temperature difference identified during some periods of forced-air system operation.

7.0 CONCLUSIONS AND RECOMMENDATIONS

In a head-to-head comparison with a conventional forced-air system, the surface-mounted, ceiling radiant heat system delivered generally comparable levels of thermal comfort and substantial energy savings. The sources of energy savings as described by the manufacturer--reduced parasitic losses, room zoning, quick recovery from setback, and lower ambient air temperature during recovery--combined to yield the energy savings. The specific number of occupants and their routines in the *AFSD* House were important elements in the evaluation of thermal comfort and the magnitude of the energy savings associated with the radiant system.

All-electric heating systems cannot be automatically dismissed as energy-inefficient. Electricity is simply a power source. Comparison of heating systems' energy performance should focus on the efficiency with which acceptable levels of heating comfort are delivered within actual structures, not ratings given to mechanical power plants in laboratory tests. The efficiency of any heating plant is a function of its mechanical and delivery system. The room-by-room controls, rapid recovery from setback, and lower ambient air temperature associated with radiant, surface-mounted ceiling panels provided the opportunity for substantial energy savings.

Because operation of this radiant system depended so much on occupancy, energy savings and receptivity of households to radiant system operation can be expected to vary. The response of the average household, including children, to thermostats that require operation each time a room is entered or exited, ten to fifteen minute lags in the development of localized thermal comfort, and 45 minute lags in room-wide thermally acceptable conditions may be quite different than the response of the occupants in this study. On the other hand, the magnitude of the energy savings, experienced at the *AFSD* House indicates that savings are obtainable for a wide range of households. The flexibility and degree of control with the radiant system will be attractive to many households. Also, both the dramatically reduced installed capacity and zoning setback has implications for many capacity-stressed utilities.

This case study provided insight on several thermal comfort issues specific to surface-mounted radiant ceiling systems. The results of this study indicate that ambient air temperatures can remain lower for significant periods of time while thermal comfort is achieved by elevated mean radiant temperatures. Localized thermal comfort can be achieved in an acceptable period of time during recovery from setback while room-wide thermal comfort requires some anticipation of occupation. Vertical air temperature differences were not a problem for the Enerjoy panels in the *AFSD* House. Panel cycling can be a source of thermal discomfort, depending on the occupants relationship to panel location. Significant variation in comfort conditions can result from occupant location with respect to panel location.

The potential for thermal discomfort associated with panel cycling, unacceptable lead times for room occupation, and panel location can be readily mitigated or eliminated by more sophisticated thermostatic control and careful panel placement and distribution. These local thermal comfort issues were considered to be minor, requiring only adjustments to the current Enerjoy radiant system. Specific recommendations regarding panel cycling, location, and distribution are made at the end of this section.

Although this comparative assessment of the radiant and a conventional, forced-air system focused on heating energy consumption, thermal comfort, and system operation, there are certainly other valid measures to be included in a broader assessment. Energy consumption efficiency can be considered a necessary but not sufficient element in overall system efficiency. Other measures of system efficiency not included in this analysis are:

- installed cost
- maintenance costs
- life cycle

The fact that the radiant panels do not involve a mechanical or delivery system would certainly have significant impact on both the maintenance and life cycle cost of the radiant system.

The substantial energy savings potential demonstrated by the Enerjoy radiant heating system suggest further study is warranted to assist Enerjoy in commercialization as an energy-efficient technology.

- *Develop total installed and life-cycle cost analysis* - Total installed and life-cycle cost comparisons of the Enerjoy radiant system and other heating strategies would provide a broader perspective for the home owner on the long-term benefits of various heating strategies.

- *Explore specific markets* - Three specific features of the Enerjoy system give it a distinct advantage over other heating strategies--sinus comfort, quick recovery with reduced installed capacity, and non-ducted operation. Hospitals, nursing homes, and housing for the growing number of individuals who are hypersensitive to air-borne allergens are markets inclined to highly value greater sinus comfort and reduced air movement. Vacation homes or homes heated by wood stoves that require a backup system should value the quick recovery from setback of the Enerjoy system. Areas of the U.S. and Canada where central air-conditioning is not prevalent forfeit nothing in year round comfort with a non-ducted heating system.

- *Identify Enerjoy-compatible ductless and ducted air-conditioning systems* - One advantage to centralized, forced-air systems is their utility in terms of both heating and cooling. The nationwide trend, regardless of region, is an increase in the installation of central air-conditioning systems in new homes.[36] Over 78 percent of new homes in 1993 had central air-conditioning and this included 54 percent for the Northeast. If thermal comfort is defined by households as including conditioned air during both the heating and cooling season, then this requirement dictates that provisions for cooling be an integral part of year-round evaluation of systems that condition interior spaces.

Ductless air-conditioning and systems with all air-handling and delivery runs inside the conditioned space are being developed and promoted because of the problems associated with duct losses and with locating delivery registers appropriately for both heating and cooling. The Enerjoy system would be well-suited for use with either of these systems.

- *Analyze hourly heating demand of Enerjoy and heat pump systems* - Utilities are interested in heating strategies that either reduce total demand or better distribute power demand. The significantly reduced installed capacity of the Enerjoy system, if coupled with more evenly distributed power demand would make promotion of the fast-acting radiant panel systems an attractive option for electric utilities.

The results of the Task 2 field test led to the following additional recommendations:

1. The sensitivity of the radiant system's under-sizing to the exact extent and distribution of heat losses in a structure indicates that reasonably accurate characterization of the building's heat loss is required prior to installation.

2. The sensitivity of thermal comfort conditions to the location of both occupants and panels, particularly during periods of recovery, indicates that:

    - the square area of panels installed be held constant while increasing the number of panels in order to provide greater thermal comfort to a broader area of a room, particularly for periods of recovery. For example, four 2-foot by 2-foot panels distributed evenly across a ceiling may provide better comfort conditions than one 2-foot by 8-foot panel.

    - emphasis on panel location for comfort should be incorporated into installation instructions or part of instruction program for certified installers.

    - emphasis should be placed on the location of radiant-sensitive thermostats in clear view of the panels the thermostats control.

3. The experience of the *AFSD* House occupants with the need to anticipate setforward times in the master bedroom and the likelihood of forgetting to set a thermostat back upon exiting a room indicates that some programmable and light or motion sensitive thermostats are recommended for frequently used rooms. These thermostats are commercially available and marketed by the panel manufacturer and others.

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[36] Crist, Dean, "New Homes Are Larger, But Upper End Stalls," *Housing Economics*, National Association of Home Builders, Washington, DC, March 1994, pp. 9-11.

4. Discomfort associated with panel cycling may be alleviated with a thermostat more sensitive to operative temperature and located in better view of the panel or some type of modulating device to "micro-cycle" the panel as steady-state conditions are approached. The modulation would be designed to "smooth" the peaks and valleys in the operative temperature that are associated with panel cycling.

5. Follow-up on the Kansas State proposal to employ their Comfort and Building Analysis Program in analysis of the data from the *AFSD* House would provide important validation of the Kansas State model. Validation of a model that can be run on a personal computer and used to design radiant panel installations to comfort conditions is an important part of the radiant system commercialization process.

6. Home owners and HVAC contractors need a handbook that gives them access to the information on the principles of radiant heat transfer and the operation of fast-acting radiant panels. Although this information is readily available to a small group of researchers and engineers through the manufacturer's engineering manual, greater diffusion of innovative heating systems such as fast-acting radiant panels hinges upon home owners' and HVAC contractors' understanding and acceptance of radiant heat transfer, system design, and system function.[37]

7. Researchers are currently working on mean radiant and operative temperature sensors that do not have an undesirably high time constant. The results of this field study should be used to encourage and support the development and commercialization of operative sensing technologies.

8. Concern among home owners regarding the electro-magnetic fields (EMFs) associated with home appliances and installed equipment varies widely and is based on limited information. Electric, radiant systems vary widely in electro-magnetic field generation but could be tested for conformance to a "prudent avoidance" standard.[38] While informal review by Northeast Utilities found Enerjoy to be at the lower range of EMF generation among radiant systems, the manufacturer concurs with the recommendation to establish a "prudent avoidance" standard and procedures for its measurement.

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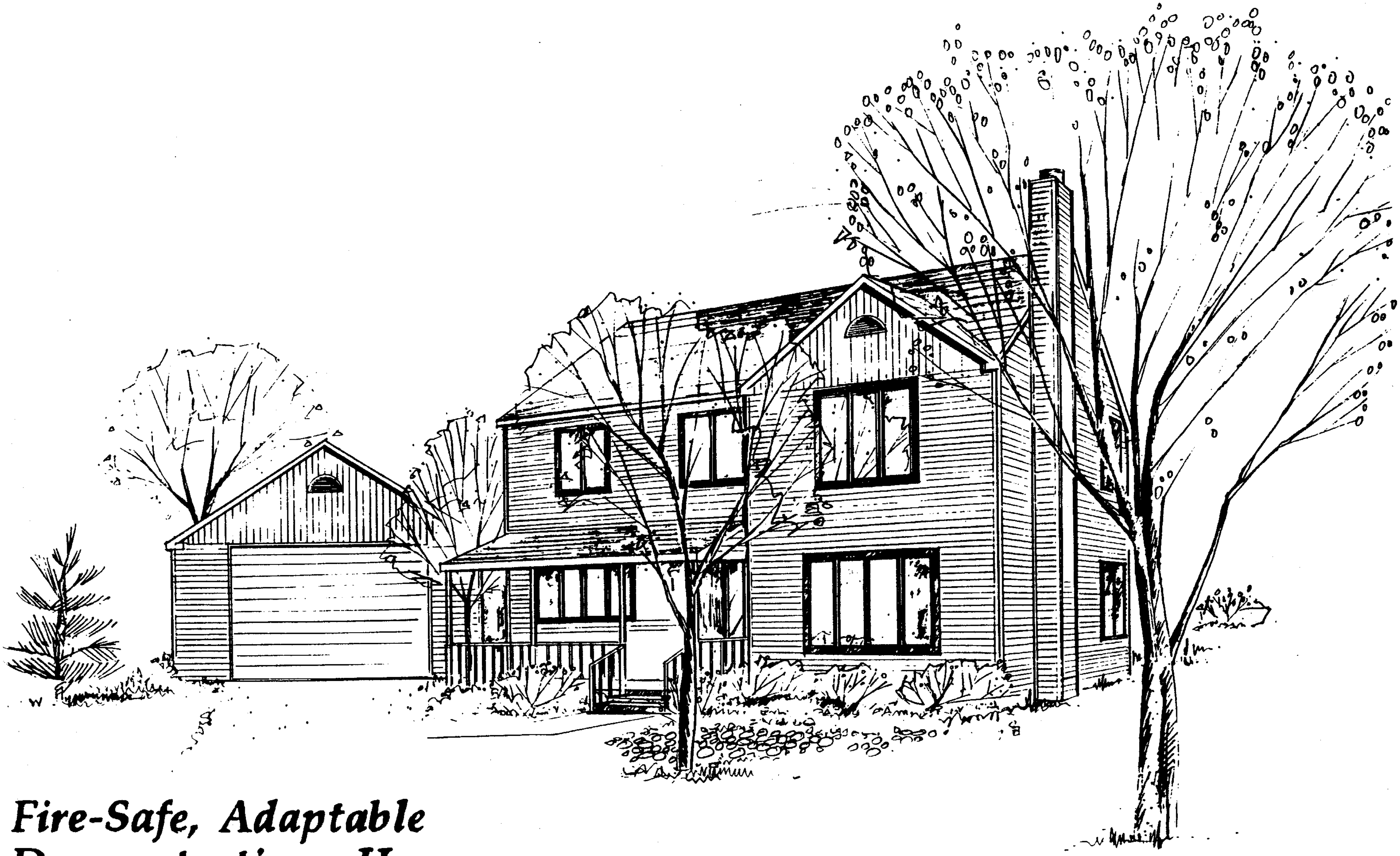
[37] The lack of available information on and reluctance to explore new innovative, energy-efficient technologies is nicely discussed by R. B. Hayter in "Comfort Education for Energy Conservation," *ASHRAE Transactions*, 1987, Volume 93, Part 1.

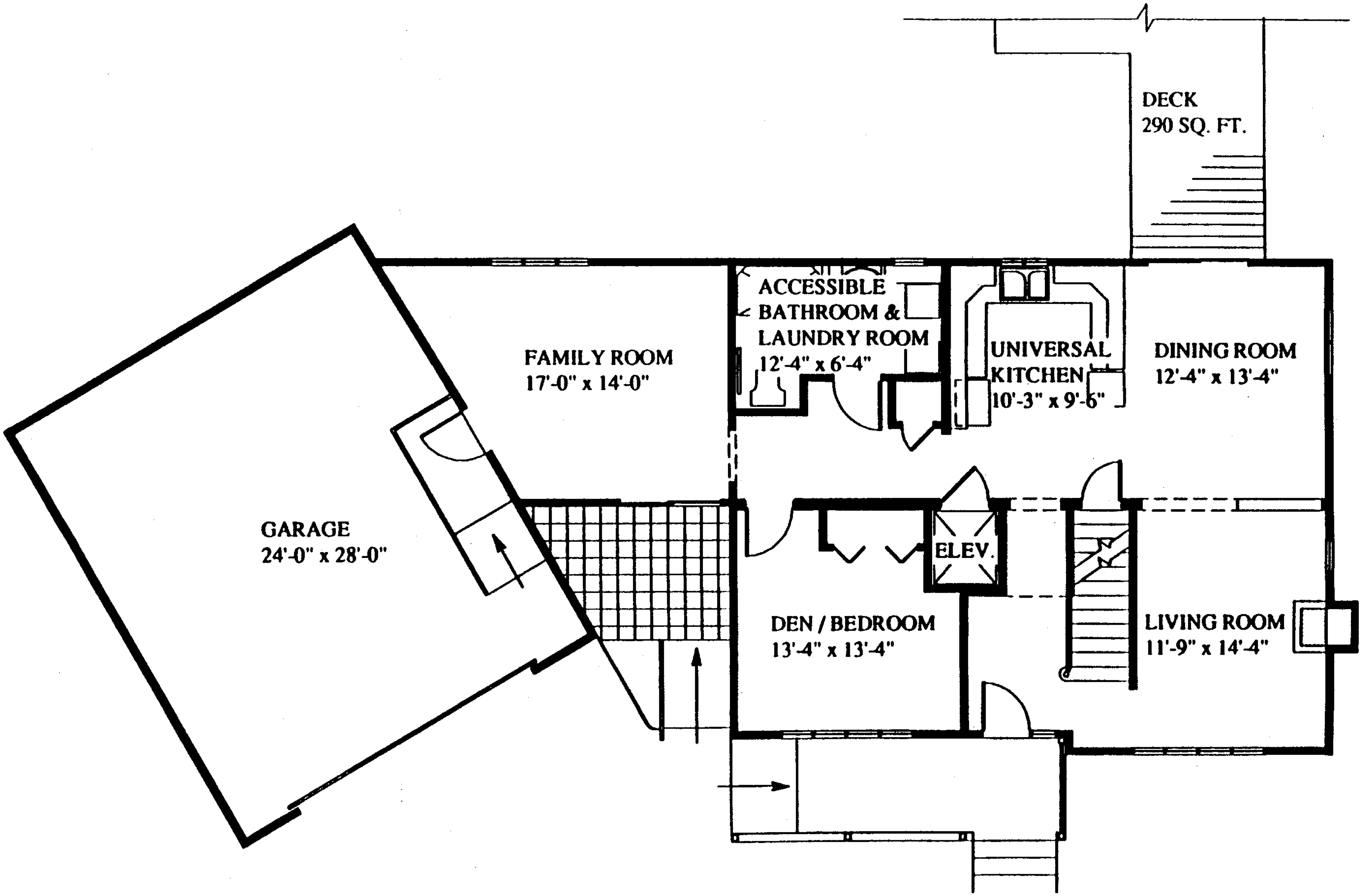
[38] Wilson, Alex, "Building Design and EMF," *Environmental Building News*, March/April 1994, pp. 8-11.

APPENDIX A

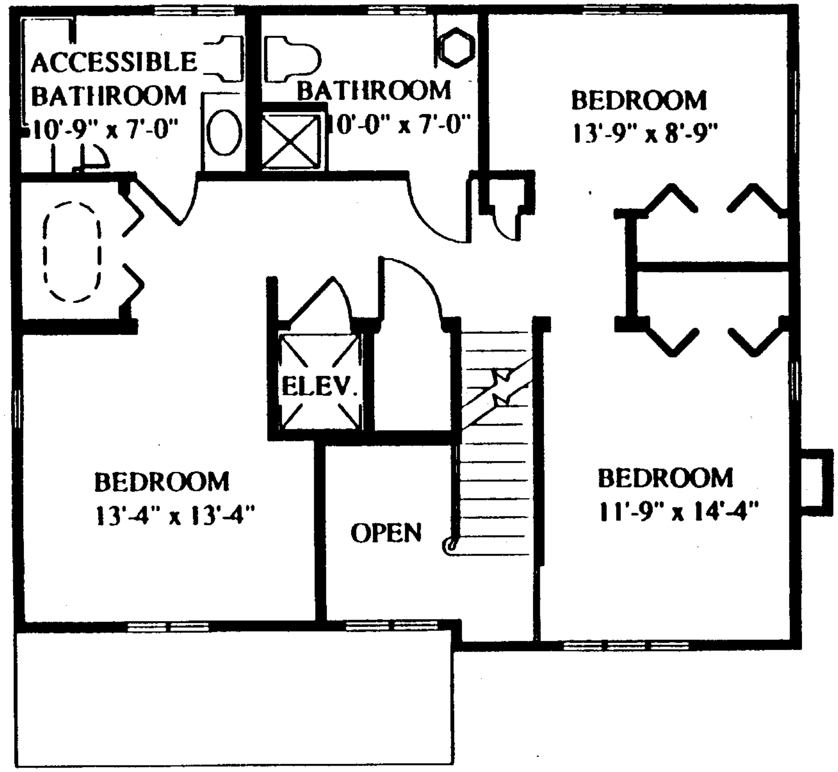
Research Home Floor Plans



Fire-Safe, Adaptable
Demonstration House


DECK
290 SQ. FT.
ACCESSIBLE
BATHROOM &
LAUNDRY ROOM
12'-4" x 6'-4"
UNIVERSAL
KITCHEN
10'-3" x 9'-6"
DINING ROOM
12'-4" x 13'-4"
FAMILY ROOM
17'-0" x 14'-0"
GARAGE
24'-0" x 28'-0"
ELEV.
DEN / BEDROOM
13'-4" x 13'-4"
LIVING ROOM
11'-9" x 14'-4"

FIRST FLOOR

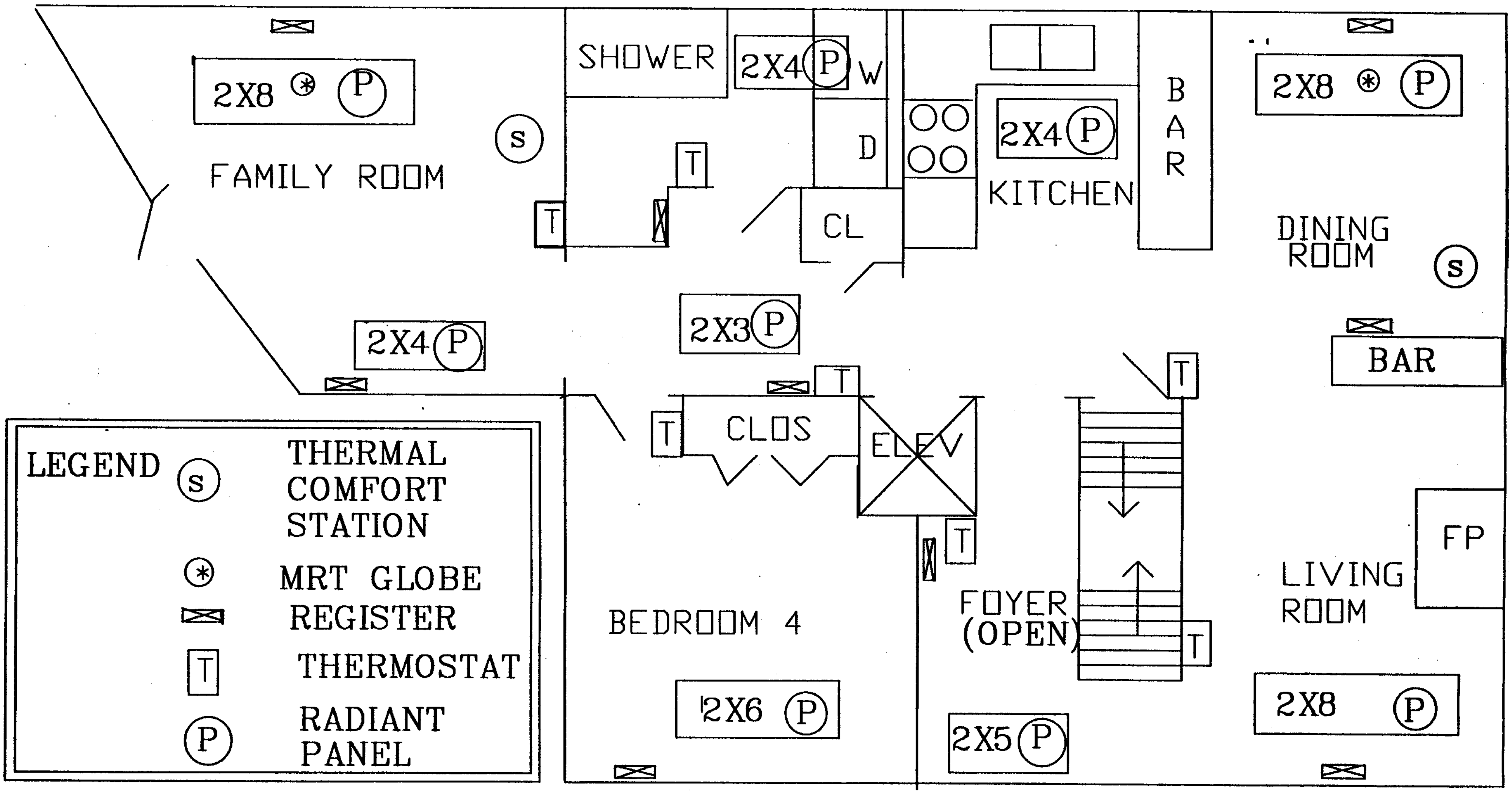


SECOND FLOOR

APPENDIX B

Radiant Panel and Monitoring Equipment

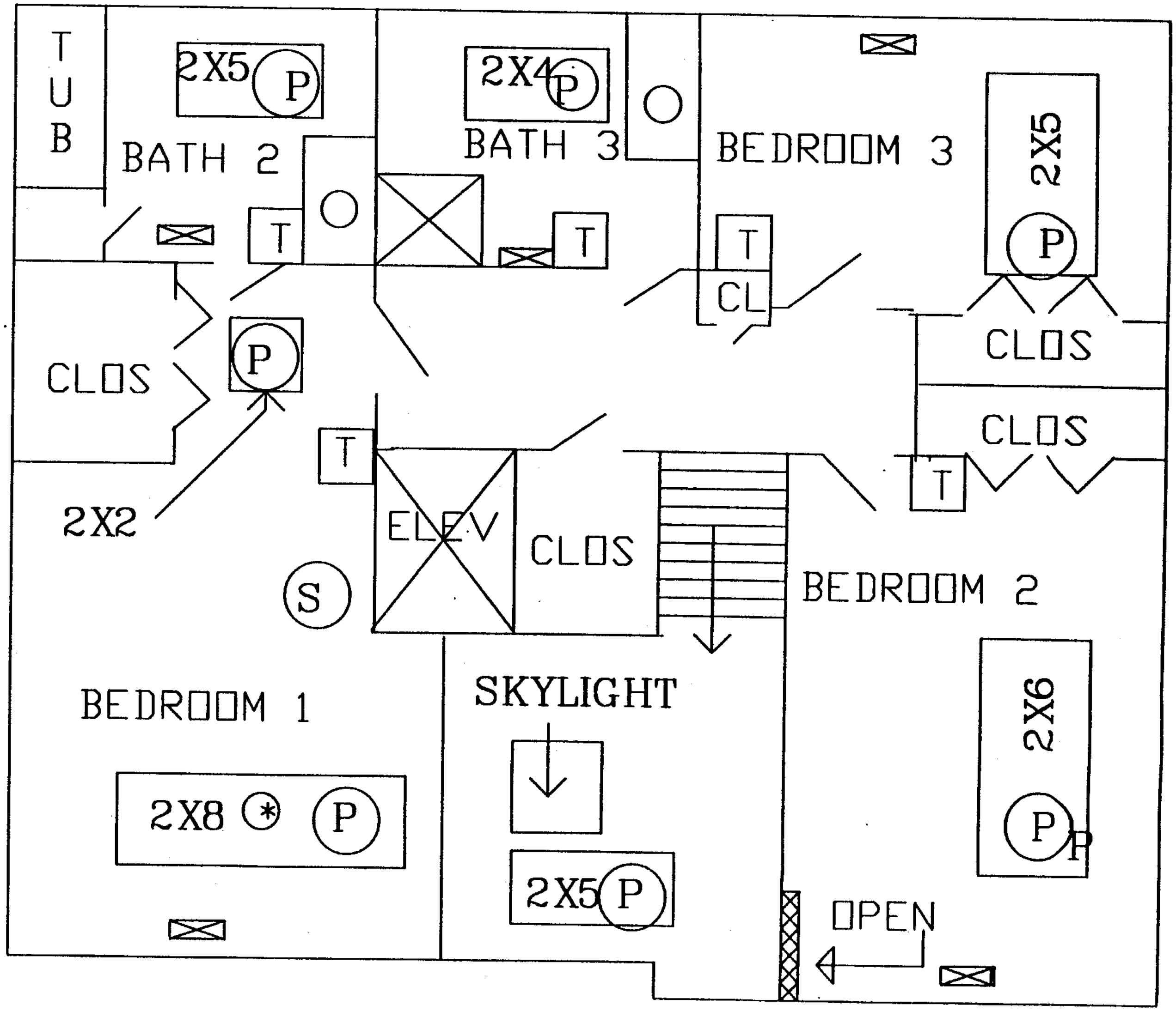
FIRST FLOOR OF MODULAR HOUSE



2ND FLOOR OF MODULAR HOUSE

LEGEND

⊠	REGISTER
⊛	MRT GLOBE
T	THERMOSTAT
Ⓟ	RADIANT PANEL
Ⓢ	THERMAL COMFORT STATION



APPENDIX C

Thermal Comfort Survey

THERMAL COMFORT SURVEY

A comparison of the thermal comfort provided by the two heating systems in this research home is being performed during this heating season. Your input is both confidential and greatly appreciated.

Date: ______________ **Heating System in operation:** Heat Pump Radiant Ceiling

Time: ______________ **System status:** On Off

Station : Family Room Master Bedroom Dining Area

Your health (simply note if your are experiencing any anything such as cold or flu symptoms):

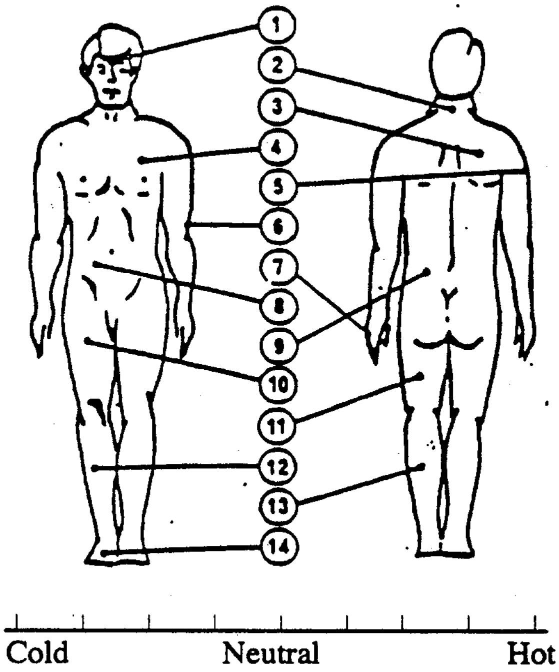
Your attire (briefly describe your clothes, except undergarments):

Below circle any general thermal discomfort, draft, or temperature asymmetry you may have experienced, the relative strength of this sensation on the given scale, and the affected areas of your body.

Thermal discomfort

Draft

Temperature Asymmetry



Comments:

APPENDIX D

Research Home Blower Door Test

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          NAHB National Research Center 301/249-4000
11-29-93
MODULAR HOUSE
16005 PENNSBURY DRIVE
TEST DONE BY B. DEWEY & P. YOST
All HVAC vents sealed shut.  All windows shut.  Garage door and basement door cl
osed.  All other interior doors open.  Wood stove in L.R. with damper shut.  Unv
ented range hood in kitchen.  Two bathrooms contain exhaust fans vented to the o
utdoors.
WIND FACTOR = 1.0    NUMBER OF STORIES = 2.0
VOLUME=   17065 CUBIC FEET
INTERIOR TEMP.=  65 DEGREES F   EXTERIOR TEMP.=  53 DEGREES F

   HOUSE PRESSURE    FAN PRESSURE     CFM      % Error
        50               145          4002       0.7
        45               125          3731       0.1
        40               115          3587       3.4
        35                90          3194       0.0
        30                75          2930       0.8
        25                57          2573      -1.0
        20                43          2252      -0.6
        15                28          1839      -3.3
        10                20          1568       5.5
        10                20          1568       5.5
        15                28          1839      -3.3
        20                43          2252      -0.6
        25                53          2486      -4.5
        30                72          2874      -1.1
        35                90          3194       0.0
        40               110          3512       1.3
        45               120          3660      -1.8
        50               140          3936      -1.0

CORRELATION COEFFICIENT (r) =0.9965
C=  361.04   n= .613

EFFECTIVE LEAKAGE AREA (LBL)=  239.47 SQUARE INCHES  +/-   2.8%
EQUIVALENT LEAKAGE AREA (CANADA) =  435.07 SQUARE INCHES  +/-   1.7%

AIRFLOW AT 50 PASCALS :
       =  3974 CFM  +/-   0.7%
       =  13.97 AC/H

ESTIMATED NATURAL INFILTRATION (50 PASCAL FLOW DIVIDED BY  16.0)
      =  249 CFM
      =  0.88 AIR CHANGES PER HOUR

% REDUCTION IN CFM AFTER RETROFIT:
  HOUSE PRESSURE      PRE            POST          % REDUCTION
     4 Pa             845            845              0
    10 Pa            1481           1481              0
    50 Pa            3974           3974              0
```

```
                 NAHB National Research Center 301/249-4000
11-29-93
MODULAR HOUSE
16005 PENNSBURY DRIVE
TEST DONE BY B. DEWEY & P. YOST

WIND FACTOR = 1.0    NUMBER OF STORIES = 2.0
VOLUME=   17065 CUBIC FEET
INTERIOR TEMP.=  65 DEGREES F   EXTERIOR TEMP.=  53 DEGREES F

   HOUSE PRESSURE    FAN PRESSURE     CFM      % Error
        50              180           4433      -1.6
        45              160           4193      -0.7
        40              140           3936       0.2
        35              122           3688       1.9
        30               95           3277      -0.4
        25               75           2930      -0.4
        20               62           2678       4.3
        15               37           2098      -2.4
        10               22           1640      -2.0
        10               25           1743       4.0
        15               33           1987      -8.1
        20               62           2678       4.3
        25               75           2930      -0.4
        30               93           3244      -1.4
        35              107           3466      -4.4
        40              140           3936       0.2
        45              170           4315       2.1
        50              190           4548       0.9

CORRELATION COEFFICIENT (r) =0.9953
C=  405.83    n= .615

EFFECTIVE LEAKAGE AREA (LBL)=  269.99 SQUARE INCHES  +/-   3.3%
EQUIVALENT LEAKAGE AREA (CANADA) =  491.51 SQUARE INCHES  +/-    1.9%

AIRFLOW AT 50 PASCALS :
        =  4506 CFM  +/-   0.8%
        =  15.84 AC/H

ESTIMATED NATURAL INFILTRATION (50 PASCAL FLOW DIVIDED BY  16.0)
       =  282 CFM
       =  0.99 AIR CHANGES PER HOUR

% REDUCTION IN CFM AFTER RETROFIT:
  HOUSE PRESSURE      PRE             POST             % REDUCTION
     4 Pa              952             952                0
    10 Pa             1674            1674                0
    50 Pa             4506            4506                0
```

APPENDIX E

Thermal Comfort Survey Results

Thermal Comfort Survey Results

Day	Date	Time	Avg. Outdoor temp	Heating System	Status	Room	Gender	43" Air	Operative	4" floor	Ceiling	Thermal discomfort
Wed	11/10	2:45 AM	25	Heat Pump	Off	Bedroom	M	64.4	62	60	60.8	Cool
Thurs	11/11	6:40 PM	47.5	Heat pump	Off	Dining	F	68.8	68.7	65.8	69.9	Cool
Sat	11/13	3:41 PM	61.1	Heat pump	Off	Family	F	67.9	67.9	66.8	68.7	Cool
Sat	11/13	9:20 PM	52.8	heat pump	Off	Family	F	67.3	67.8	66.9	70	Cool
Fri	11/19	9:08 PM	50.9	Radiant	On	Family	F	69.4	69.4	66.8	70.4	Cool
Sun	11/21	6:36 PM	40.3	Radiant	Cycling	Dining	F	65.8	66.7	64.2	68.9	Cool
Wed	11/24	4:35 AM	29	Radiant	Cycling	Bedroom	F	62.2	62.6	60.6	62.5	Cold
Thurs	11/25	10:38 AM	36.5	Radiant	Cycling	Dining	M	64.9	66	62.3	69.2	Warm
Thurs	11/25	7:05 PM	36.3	Radiant	Cycling	Family	F	67.4	67.9	64.7	68.5	Cool
Fri	11/26	7:00 PM	39.3	Radiant	On	Dining	F	64.1	64.5	62.9	69.4	Cool
Tues	11/30	6:04 AM	23.3	Heat pump	On	Bedroom	M	76.6	72.7	63.2	76.2	Slightly warm
Wed	12/1	6:15 AM	20.7	Heat pump	On	Bedroom	M	77.3	73.6	64.7	78.4	Warm
Fri	12/3	8:10 PM	44.9	Heat pump	Off	Family	F	67.5	68	65.8	68.4	Cool
Sat	12/4	8:28 PM	50.4	Heat pump	Off	Family	F	67.3	67.5	65.2	67.9	Cool
Sun	12/12	8:32 PM	27.1	Heat pump	On	Family	F	65.5	65.6	64.7	65.9	Slightly cool
Mon	12/13	2:30 AM	27.1	Heat Pump	Off	Bedroom	F	61.2	61.3	60.3	61.8	Cool
Wed	12/19	8:20 PM	32.7	Radiant	Cycling	Family	F	67.4	68.5	65.1	67.9	Cool
Tues	12/21	8:57 PM	31.9	Radiant	On	Family	F	65.9	66.9	63.6	65.7	Cool
Sun	1/1	8:30 AM	18.7	Heat pump	On	Bedroom	F/M	69.1	68.2	64.4	71.3	Warm
Thurs	1/6	4:18 AM	24.2	Radiant	Cycling	Bedroom	F	61.8	61.6	60.5	62	Cool
Sun	1/9	4:38 PM	25.1	Radiant	On	Family	M	63.4	64.4	61.1	62.8	Cool
Tues	1/11	7:39 AM	22.3	Radiant	On	Dining	F	61.8	62.5	62.9	64.3	Cool
Wed	1/26	6:50 AM	32.3	Heat Pump	On	Bedroom	F/M	67.2	66.9	64.8	70.7	Cool
********************OPERATIVE GLOBES RELOCATED 1/27/94 NOON********************												
Thurs	1/27	8:58 PM	20.7	Heat Pump	On	Family	M	62.1	61.6	63.3	65.9	Slightly cool
Sun	1/30	7:22 PM	27.5	Radiant	On	Family	F	66.1	71.3	63.3	65.9	Cool
Tues	2/22	7:54 PM	38.7	Heat Pump	Off	Dining	F	67.7	67.7	66.5	68.5	Cool
Wed	2/23	5:30 AM	30.8	Heat Pump	On	Bedroom	M	62.2	62.8	61.4	62.8	Cool

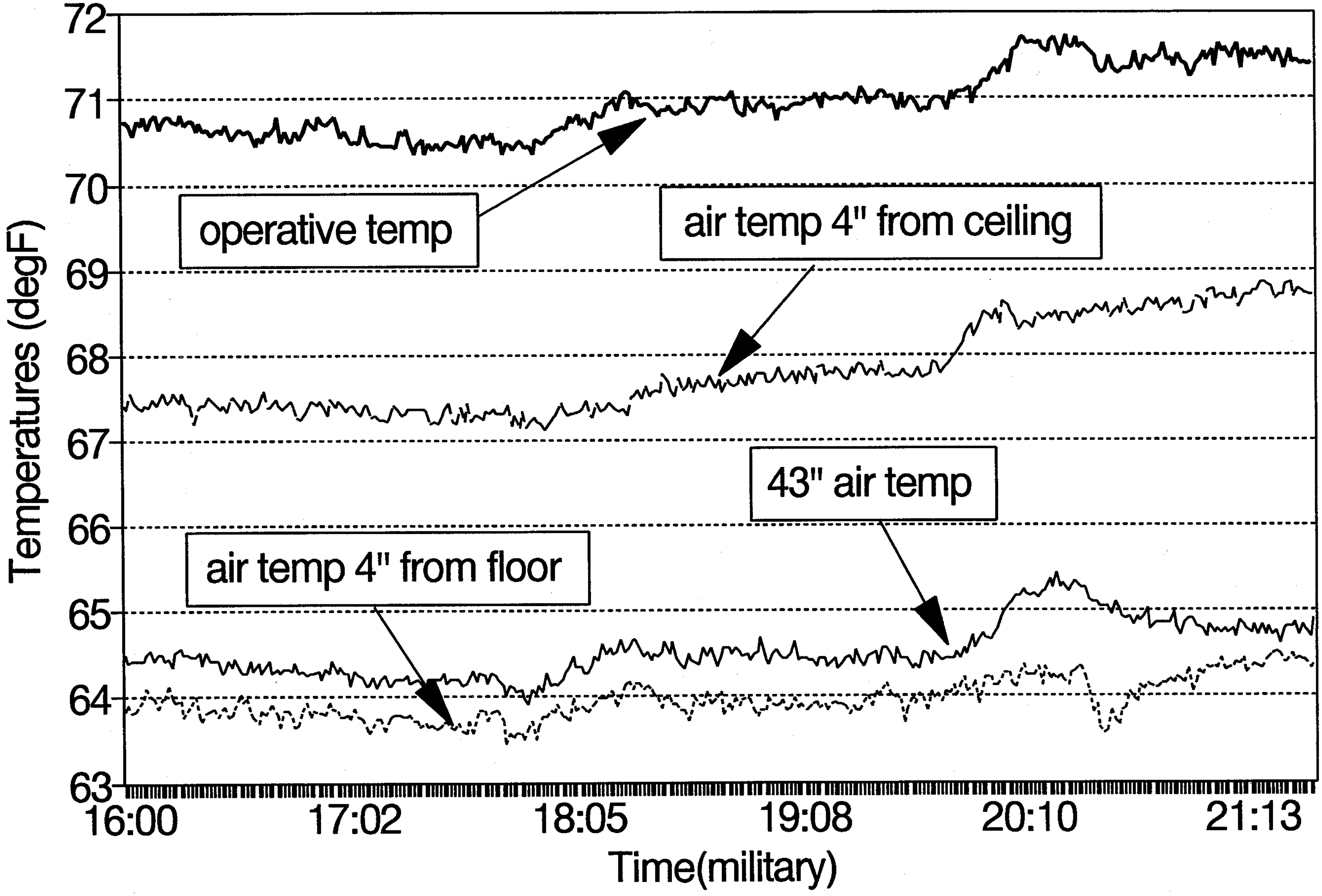
APPENDIX F

Temperature Characterization Graphs for Each Heating System

Temperature Characterization: Panels

Dining room AOT=28.0F

(Thermostat setting throughout = 68F)



Temperature Characterization:Heat Pump

Dining room AOT=28.6F

(Thermostat setting throughout = 68F)