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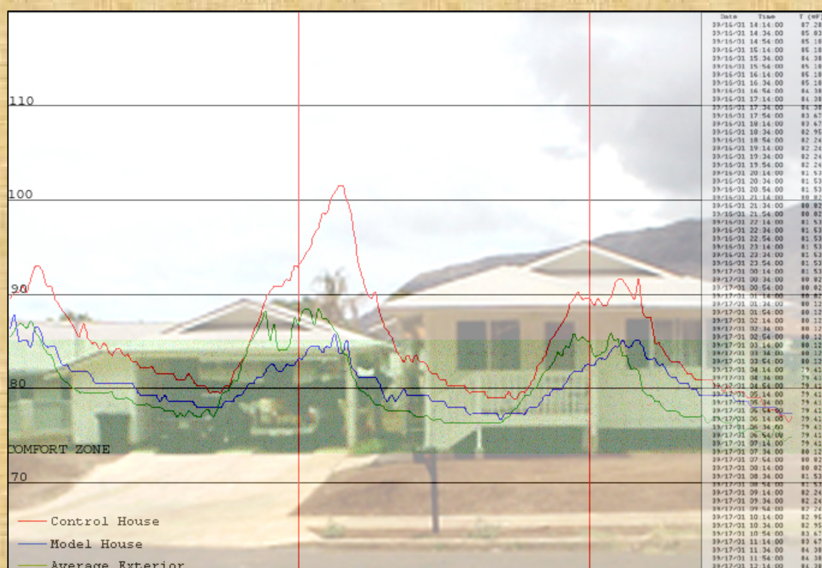
DATA COLLECTION AND ANALYSIS OF THE HEAT MITIGATING, PASSIVE DESIGN STRATEGIES AT THE WAIANAE MODEL DEMONSTRATION HOUSE



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DATA COLLECTION AND ANALYSIS OF THE HEAT MITIGATING, PASSIVE DESIGN STRATEGIES AT THE WAIANAE MODEL DEMONSTRATION HOUSE

Installation of Radiant Barrier on the Model House.

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TABLE OF CONTENT

INTRODUCTION

1.0 PROJECT SUMMARY

1.0.1 Background

The purpose of this project is to quantify the effectiveness of the design strategies that were incorporated into the demonstration house that was built on Hawaiian Homelands in the Waianae area of Honolulu, Hawaii. The "demonstration house" is referred to as the "model house" throughout this report. The model house was designed and built to demonstrate methods to increase comfort and reduce energy demand in Hawaii's homes. Some design strategies address the quality of life within the home and others target kilowatt and dollar savings and in many cases the benefits overlap.

On the energy cost savings strategies, the biggest difference between the two homes is the solar hot water system and the energy efficient appliances and lighting. Mitigating heat gain through the building's roof, walls and windows and natural ventilation were design features in the model home but not in the control home. These features save money by eliminating the need for air conditioning but they are more principally motivated by the need to make people comfortable in their home. This study measures the difference in comfort levels between the model house and a control house.

A monitoring study was conducted to quantify the physical comfort levels within the home. The recently completed model home was compared to a reasonably identical home one block away. The second home is referred to as the "control house". Temperatures were logged externally and at five interior locations in each of the homes over a three-month period in 2001. In addition to the temperature readings, relative humidity and instantaneous air movement readings were taken and illumination levels in the living room areas were also logged. The light level data are less of a human comfort influence and more representative of a quality of life, day lighting and reduction of electric lighting issue.

The heat mitigating and natural ventilation components that were designed into the model house, and absent from the control house, are generally passive technologies, relatively inexpensive and have shown, through this study, to be quite effective. Neither the model nor the control house has any insulation in the roof or the walls. The roof and the south, west and east walls of the model home include a layer of radiant barrier. The exterior surfaces of the roof and walls of the model unit are of lighter colors and are therefore less heat absorbing. Both homes ventilate the attics with venting in the blocking between the roof rafters just above the wall top plate, but the model home increases the ventilation with a continuous ridge vent that runs the length of the roof. Natural ventilation in the occupied areas is improved in the model home due to the increase of window openings and the availability of ventilation paths throughout the occupied spaces. A skylight has been installed at the end of the hallway in the model house. It has a fixed low-pressure evacuation-venting screen. The skylight is responsible for some direct heat gain but encourages the evacuation of collected hot air in the house and brightens what would otherwise be a darkened end to a hallway. The model home does also include ceiling fans. Reports from the owner indicate that the ceiling fans are used only during the hottest times. It was impossible to determine, through the analysis of the logged data, when the ceiling fans were in use.

1.0.2 Results:

The results of the testing indicated that the model home consistently outperformed the control house for providing a comfortable environment for the inhabitants. The exterior temperatures at any given time are the same for both homes. The exterior temperature was used as a constant against which the interior temperatures are compared.

The control house’s attic space consistently heated up and quickly exceeded the exterior temperatures on a diurnal basis. The attic temperatures in the control house were more than 26 ^{o}F above the outside temperatures where the model home’s attic never exceeded 6.03^{o}F increase over the outside. Therefore there was a 20^{o}F difference between the two attic spaces during the hottest times of the day. Without a thermal barrier, this built up heat will eventually be transmitted to the occupied spaces below. It is also interesting to note, more as an aspect of technical curiosity than having any bearing on the comfort of the residents, that during the coolest part of the day, between 10PM and 8 AM, the model home’s attic runs 2-3ºF warmer. This indicates to the research team that the radiant barrier that is placed in the upper attic space is not allowing the long-wave re-radiated heat to escape as quickly as it is able to in the absence of a radiant barrier, as is the case in the control house.

During the hottest times of the day, the temperatures in the model house’s living area were cooler than the outside temperature and as much as nearly 9ºF cooler than the living room of the control house. The graphs show that the control house’s living room temperatures are typically running 6-9 ºF above the high range of the bioclimatic comfort zone whereas the model home’s living room temperatures run in the middle and in the high range of the comfort zone and only slightly and infrequently do they exceed the comfort zone during the active hours of the daytime or evenings. The increased air movement in the model house expands the comfort zone for the inhabitants while the lack of ventilation in the control house leaves the residents feeling uncomfortable due to the increased temperatures.

The bedroom located in the west corner of each house yielded impressive data. Both bedrooms are the same size, configuration and location. The control house bedroom was consistently warmer than both the exterior temperatures and the model house’s bedroom temperatures. The greatest difference in both cases was that the control bedroom was about 17ºF hotter than the outside and the model bedroom temperature. Furthermore, the model bedroom consistently stayed cooler than the exterior temperatures when they increased above an equilibrium point of 82ºF. The difference is attributed to the higher reflective exterior surfaces, use of radiant barrier, increased ventilation and reduced attic heat gain in the model home.
These numbers supply quantitative evidence that the model home is providing a more comfortable environment due to the design approach. The building’s envelope is designed to mitigate heat gain and encourage natural ventilation, and it is also designed to allow more natural light to penetrate the interior. Light sensors were installed along with the temperature sensors in the living room of each house. There is

nearly, on average, five times more natural illumination in the living room of the model than there is in the control house. This is not glaring, direct, heat-gain daylight but very usable, indirect ambient light.

Overall the model house is an effective demonstration of passive design strategies. Temperature differences, for the sample period of 09/16/01 to 09/19/02, between the control and model house are as high as 21ºF in the attics, about 8ºF in the living room and as much as 17ºF in the bedroom.

Comprehensive comparative graphs for sample time period are available in **Appendix C**. The impression one gets upon entering the model home is that it is cool, bright and airy. Even when the temperature is higher than the comfort zone the airflow across the skin of the inhabitants cools them. The design strategies that the model home demonstrate are reducing this family’s monthly utility bill by about 40%, creating more comfortable interior spaces and improving their overall quality of life.

1.2 PROJECT BACKGROUND

The purpose of this project is to quantify the effectiveness of the human comfort design strategies that were incorporated into the model house. The methods employed at the house focused on the issues of human comfort and reduced residential energy use. Some design strategies address the quality of life within the home and others target kilowatt and dollar saving. In many cases the desire to improve the quality of life and design more efficient buildings are mutually supportive. The home’s solar hot water system and energy efficient lighting design are reducing the energy demand and the resident’s energy costs by about 40%. The daylighting design is reducing the daytime need for electric lighting. Daylighting along with cross-ventilation and envelope design diminish internal and external heat gains, thereby mitigating the need for mechanical cooling. These are very critical design considerations and integral influences on the quality of life and the energy savings in the home [Table 01].

Table 01 - Purpose and Benefits of Design Strategies

Strategy	Quality of Life	Energy / $ Savings	Benefits
Solar Hot Water System			E/$ savings only
Energy Efficient Lighting			E/$ savings, reduces internal heat gains, cooler interior, less need for AC
Building Orientation			Improves ventilation, & solar control, cooler interior reduces need for AC
Exterior Reflective surfaces			Reduces external heat gain. Cooler interior, reduces need for AC
Radiant Barrier			Reduces external heat gain. Cooler interior, reduces need for AC
Cross Ventilation			Cooler interior, increases human comfort, reduces need for AC
Day lighting			Reduces electric lighting need and its associated heat gains, connects occupants to outside, good quality of light, need not introduce external heat gain

The focus of this project is primarily on the comfort of the occupants. Two houses were monitored, the model house and the control house. The model house was built as part of this larger project. It was designed by Nick Huddleston AIA and constructed during 2001. It incorporates the passive design strategies that were described and illustrated in the FIELD GUIDE for Energy Performance, Comfort and Value in Hawaii Homes. The control house was built about ten years earlier and is more typical of the houses in the development, in that it does not incorporate energy efficiency and passive design strategies. They are both Department of Hawaiian Homeland homes in Waianae [Fig. 1.01]. It is one of the hottest areas on Oahu. In this area, temperatures typically range in the mid to upper eighties, relative humidity ranges from the mid-fifties to the mid-seventies, and precipitation is in the low 20 inch annual range. It is on the island’s lee side, which reduces the trade wind exposure. The solar radiation is steady at about a daily annual average of 5.5 peak sun hours.

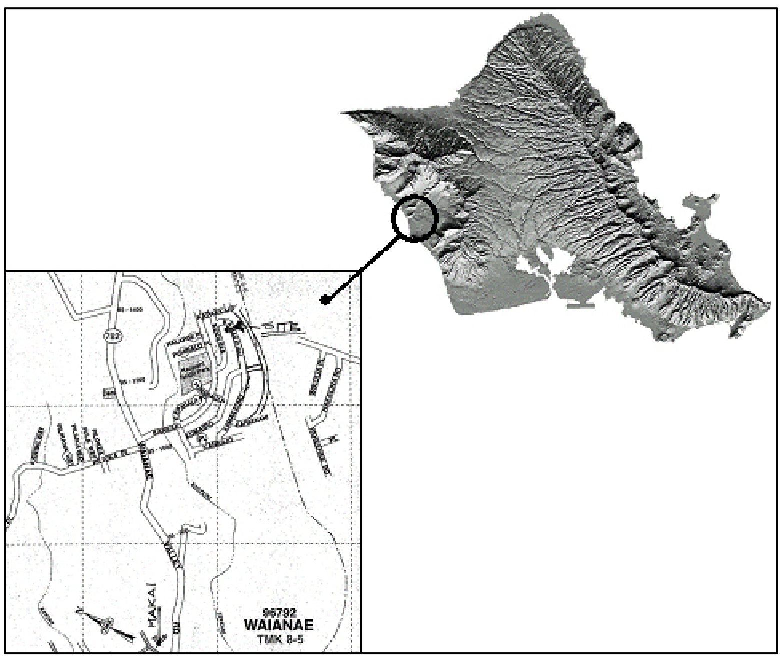


Fig. 1.01 – Area Map.

The homes are only one block apart [Fig. 1.02]. They are nearly identical in orientation, form and overall construction. There is about a 15^0 variation in the buildings’ orientations but this does not significantly impact the exposure to the sun or the trade winds.

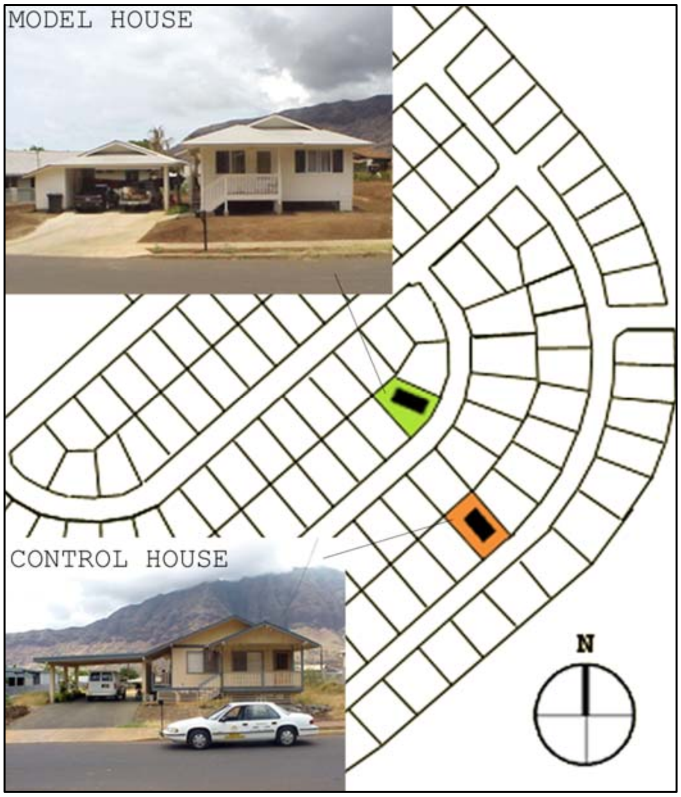


Fig. 1.02 – Proximity Map.

Each house is one story with 2″ X 4″ uninsulated wall framing. The first floor is elevated about 30″ off grade with the sides of the crawl spaces that are either open, as is the case with the model unit, or surrounded by 1″ X 3″ slats as in the control home. The horizontal slating provides an effective open area of about 50%.

Although the walls were not insulated, a two-ply radiant barrier with a 4mm air bubble center was used in the South, East and West walls and in the roof assembly of the model house. The exterior surfaces of the control house are slightly darker than the model home’s walls. The control house exterior surfaces have a solar reflectance of about 40% and the model home’s exterior surfaces are intentionally lighter with a reflectance of 60%.

The roof assemble of the model house is a white asphalt shingle with a solar reflectance of 35% on top of 15 pound felt that covers 1/2″ plywood decking. Between the underside of the decking and top of the 2″

X 6″ rafters is the air sandwich - 2 ply radiant barrier. It is draped from the top of rafters and hangs 1 1/2″ inches down into the rafter cavity [Fig. 1.03].

The control house is generally the same construction with the major difference being that it has no radiant barrier, the asphalt shingles are a darker, medium brown color with a solar reflectance of about 18% and the decking is a 5/8″ plywood. For attic ventilation, the control house has the typical cut and screened vents in the wall line rafter blocking with no gable ridge or skylighting venting. On the other hand the model house went beyond the radiant barrier to relief attic heat gain. It includes a continuous, baffled ridge vent and circular vents in the blocking between each rafter at the wall line.

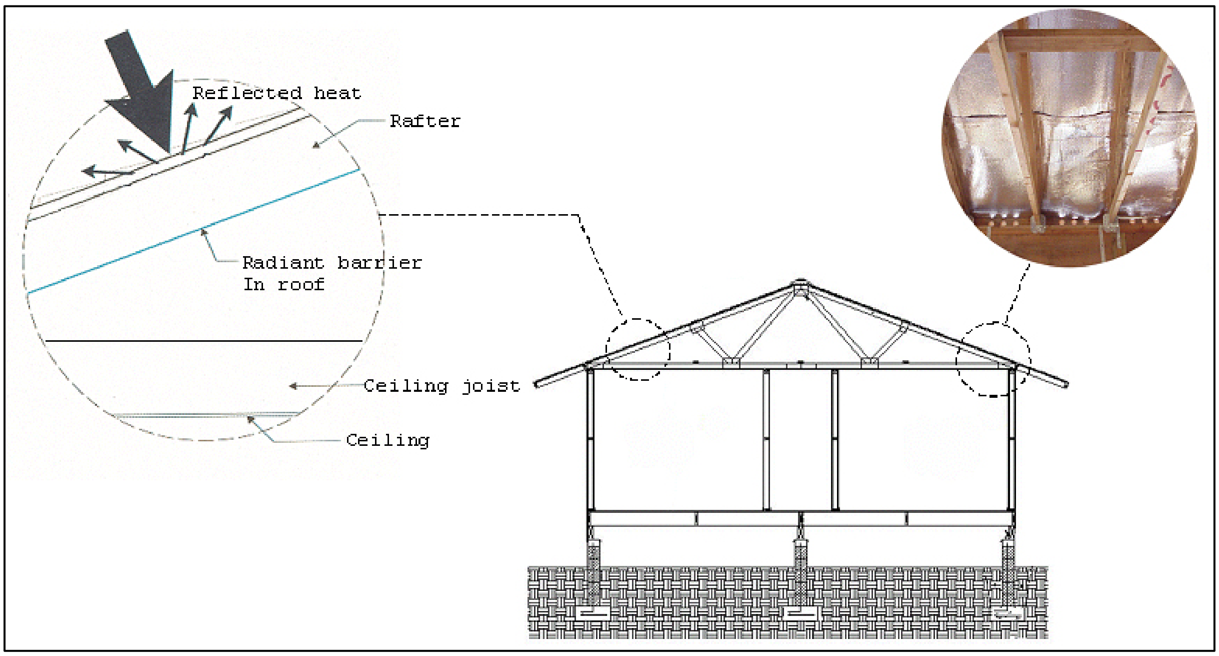


Fig. 1.03 – Radiant Barrier Installation.

1.3 METHOD OF ANALYSIS

The model and the control home are one block apart. They were monitored for three months in the last quarter of 2001. September was the hottest period during the monitoring. The duration of monitoring between September 16 to September 19 is representative of the larger testing period. For the purposes of this report, the data collected between September 16 to September 19 will supply the primary samples of comparative focus. For both the control house (Rapoza house) and the model house (Paling house), temperature sensors were placed in six locations. Another sensor to record the light levels was included with the temperature instruments in each of the respective living rooms. These sensors were coupled to data loggers. They recorded the readings in 20-minute intervals during the testing period for the following spaces [Fig. 1.04]:

- Exterior of the house.
- Attic space – 3 feet above attic floor [top-position].
- Attic space – floor level [bottom-position].
- Dining room.
- Living room.
- Bedroom.

The research team downloaded the data on the site. The data was organized and analyzed by the researchers. The methods and conclusions are described in the following sections of this report.

The field instruments used were sensors that recorded the temperature, relative humidity and light and are directly connected to data loggers [Appendix B]. The sensor and data logger manufacturer is Onset Computer Corporation from Massachusetts. The Onset data logger is the HOBO® model.

Each data logger can collect a maximum of 2000 pieces of information before being downloaded. The time between downloads is dependent upon the recording intervals that are set by the researchers. At regular intervals, logged data is downloaded into Onset Computer’s Boxcar® Pro data management software. The data from the loggers was furthered

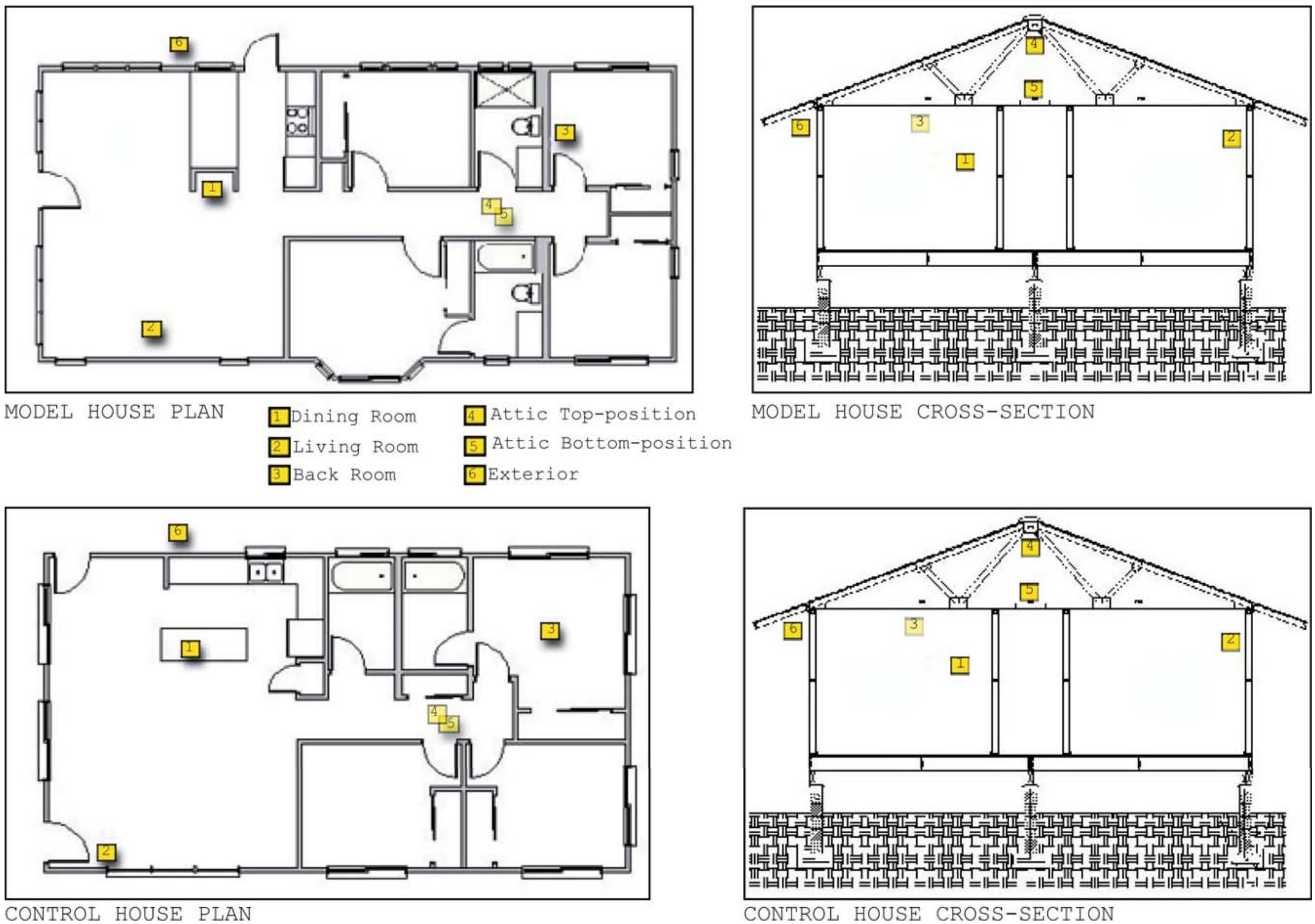


Fig. 1.04 – Data Loggers Locations.

managed and analyzed in Microsoft Excel® spreadsheets. The spreadsheets were categorized by the house (model or control) as well as by the space they were monitoring, the date and the time of the recording. The temperature is recorded in degrees Fahrenheit. Handheld instantaneous, air movement readings were taken using Solomat® anemometers [Appendix B]. The air movement readings were not recorded in data loggers. The air velocity is measured in feet per minute.

On a spreadsheet, the data were matched according to their recording locations and date and time of monitoring to allow the temperature recordings to be compared as simultaneous readings.

Following is a description of the plotted graphs, categorized by the space monitored.

1.3.1. Exterior:

- The exterior temperature data for each house was plotted against the time of day they were recorded – from midnight to midnight. A polynomial trend line was traced for the data to give a general idea of the pattern the data are following. The bioclimatic chart as developed by Victor Olgyay[1] was adjusted for Hawaii's latitude by the research team. See APPENDIX A. This bioclimatic comfort chart was superimposed with the data charts as seen in Fig. 1.05. This provides a comfort reference that can be seen against the data.

[1] From Olgyay. V. 1963. *Design with Climate*. Princeton: Princeton University Press.

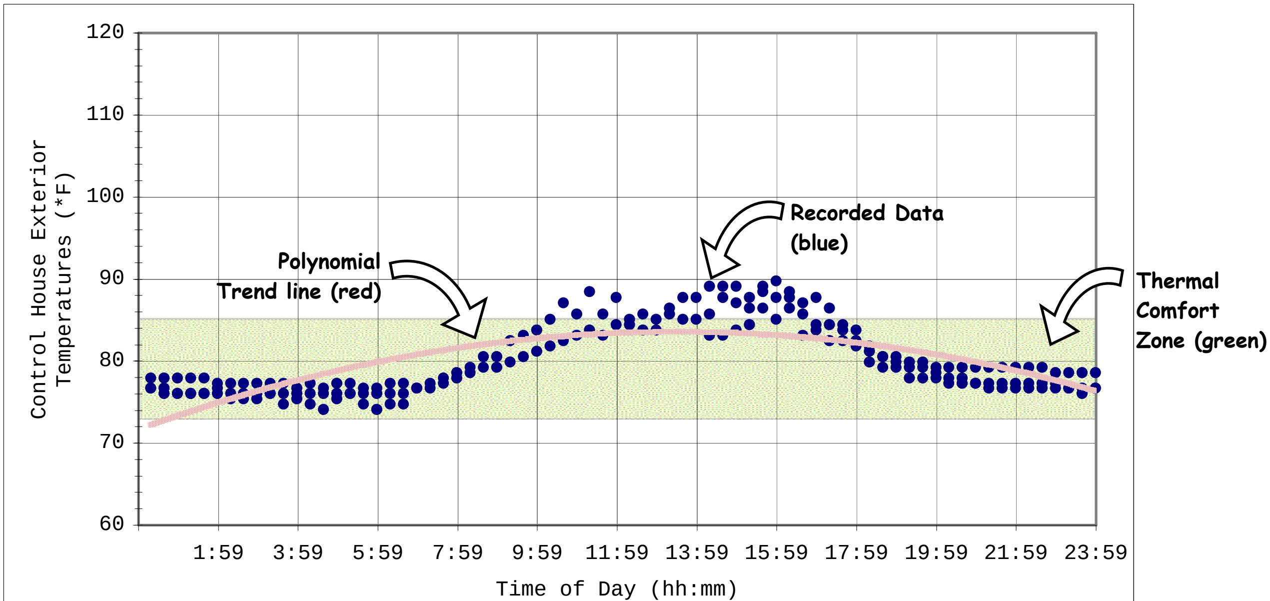


Fig. 1.05 - Control House Exterior Temperatures versus Time of the Day from 09/16/01 to 09/19/01

- The exterior temperatures of the control house were plotted against the temperatures of the model house. A line of slope =1 was inserted into the chart to compare the temperature difference between the exterior temperature of both houses.

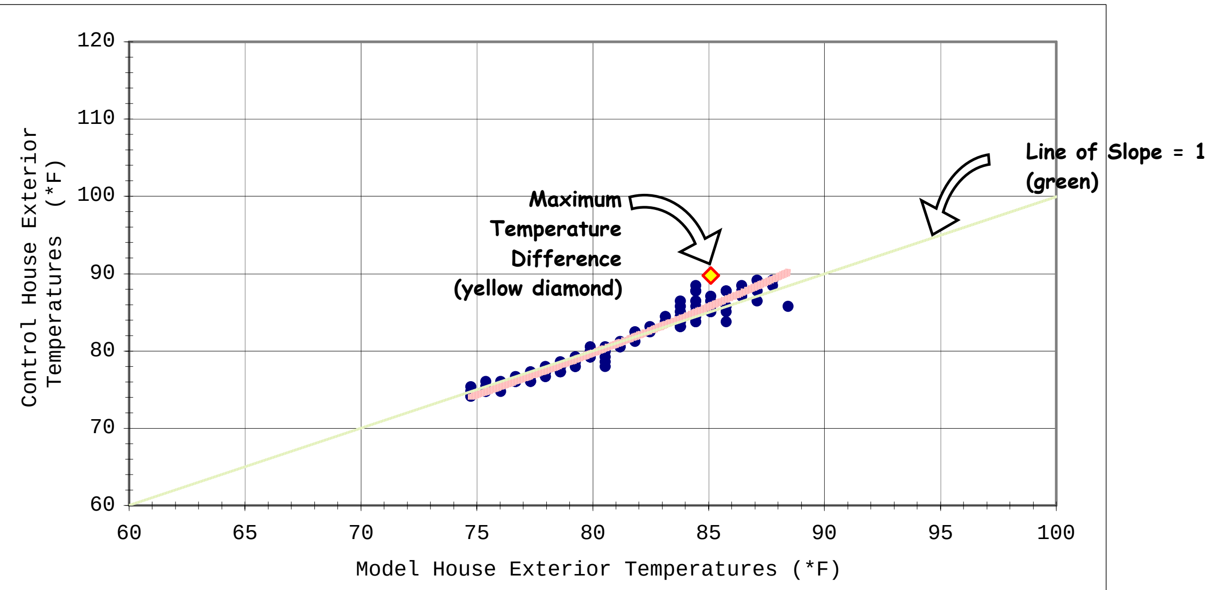


Fig. 1.06 - Control House Exterior Temperatures versus Model House Exterior Temperatures from 09/16/01 to 09/19/01

The more grouped around the line of slope =1 the data are, the more similar the exterior temperatures of the two houses are. A trend line was again traced for the data. The trend line also helps in comparing the data to the reference line of slope =1 [Fig. 1.06].

1.3.2. Indoor spaces – Attic, Living Room, Dining Room, Bedroom:

- The temperatures data from the indoor spaces of both houses were plotted against the exterior temperatures recorded at the same time. A line of slope =1 was again traced for each graphs, as well as a trend line for the data.

- The temperature data from each of the monitored indoor spaces of both houses were each plotted against the time of the day. A trend line for the data was added to each graph, as well as a bioclimatic comfort zone reference adjusted to a latitude of 20º [2] for the living space graphs.
- The simultaneous data of each individual indoor space of the control house was plotted against the data of each individual indoor space of the model house, to analyze the temperature differences between the two houses for each individual indoor space. A line of slope =1 and a trend line was added to each graphs.
- For each individual indoor space, a graph was plotted illustrating the temperatures of the control house, the temperatures of the model house, and the average exterior temperature, calculated by averaging the exterior temperatures of each house. The data were plotted against time [Fig 2.08, 2.14, 2.20, 2.26, 2.32].
- Bioclimatic evaluation charts were plotted for the control and model house's living rooms to assess their comfort levels. Living room temperatures were thus plotted against relative humidity [Fig. 3.01].

1.3.3. Attic Top-Position Versus Occupied Spaces

[2] ibid

- Each indoor living-space temperature data was plotted against the attic top-position temperature data for both the control house and the model house. A line of slope =1 was added, as well as a trend line for each of the graphs.

From the plotted graphs described above, the following analysis were made:

- Control and model houses exterior temperature differences.
- Control and model houses attic top-position temperature differences.
- Control and model houses attic bottom-position temperature differences.
- Control and model houses living room temperature differences.
- Control and model houses dining room temperature differences.
- Control and model houses bedroom temperature differences.
- Control house attic top-position and control house living spaces temperature differences.
- Model house attic top-position and model house living spaces temperature differences.

2.0. ANALYSIS OF DATA FROM 09/16/01 TO 09/19/01

2.1. CONTROL AND MODEL HOUSES EXTERIOR TEMPERATURE DIFFERENCES:

- Fig 2.01 shows a comparative graph of the control house and the model house exterior temperatures recorded from 09/16/01 to 09/19/01. It can be observed that the data tend to follow closely the line of slope one (green), illustrating a strong similarity between the control and the model house exterior temperatures at any given time during the monitored period. The red trend line reinforces the observation. A slight rise of the trend line above the green line shows slightly higher exterior temperatures (< 5ºF) at the control house during the warmest part of the day.

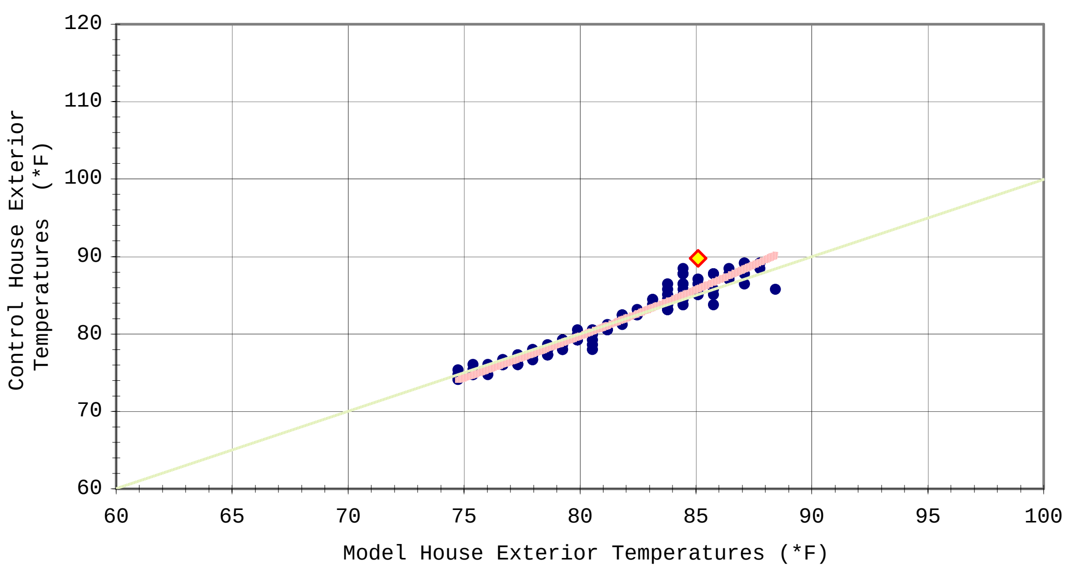


Fig. 2.01 - Control House Exterior Temperatures versus Model House Exterior Temperatures from 09/16/01 to 09/19/01

- A maximum exterior temperature difference (represented by a yellow diamond () of 4.69°F was recorded between the control house and the model house, although an average exterior temperature difference of 0.13°F between the two houses confirms very similar exterior temperatures. From 09/16/01 to 09/19/01, the maximum exterior temperature recorded was 89.79°F, while the minimum exterior temperature recorded during the same period was 74.10°F.

- Fig 2.02 and 2.03 show comparative graphs of respectively the control house and the model house exterior temperatures versus the time of the day. The green band across the graph represents the comfort zone range, adjusted to our tropical climate[3].

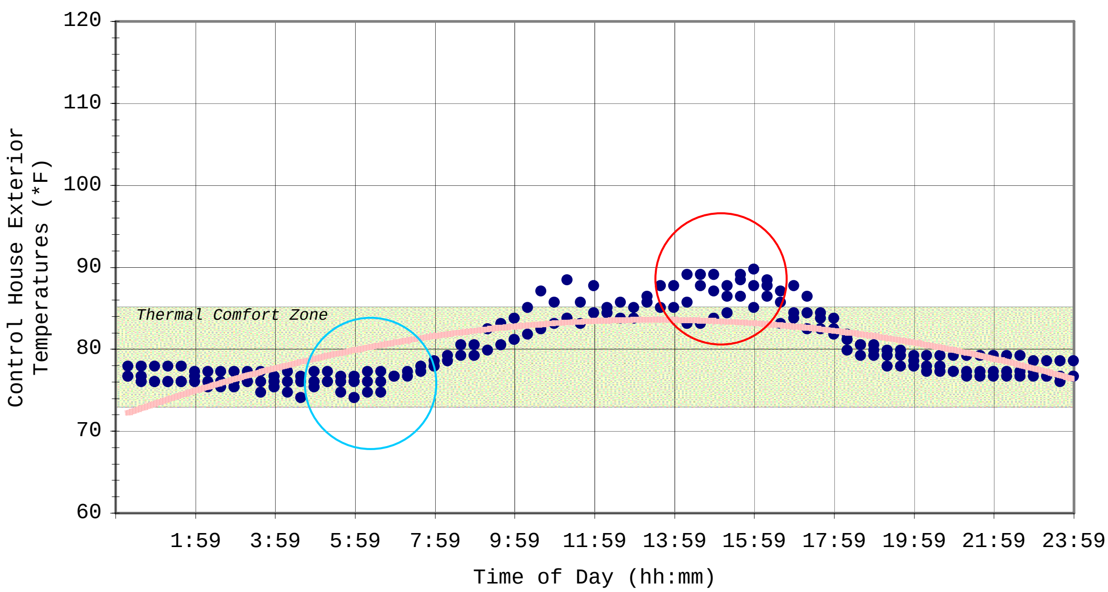


Fig. **2.02** - Control House Exterior Temperatures versus Time of the Day from 09/16/01 to 09/19/01

[3] ibid

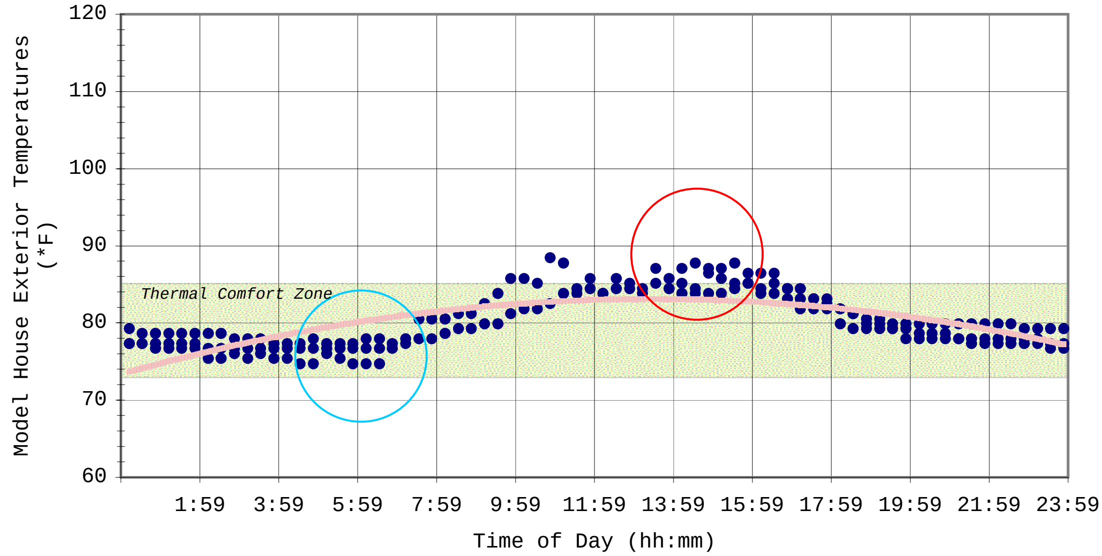


Fig. 2.03 - Model House Exterior Temperatures versus Time of the Day from 09/16/01 to 09/19/01

Both graphs show that the minimal exterior temperatures for both the control and the model house occurred around 0600 (circled in blue), while the warmest temperatures were reached between 1400 and 1600 (circled in red) at both houses.

2.2. CONTROL AND MODEL HOUSES ATTIC TOP-POSITION TEMPERATURE DIFFERENCES:

- Fig. 2.04 and 2.05 show the temperature differences between the attic top-position of the control house and the model house against the exterior temperature.

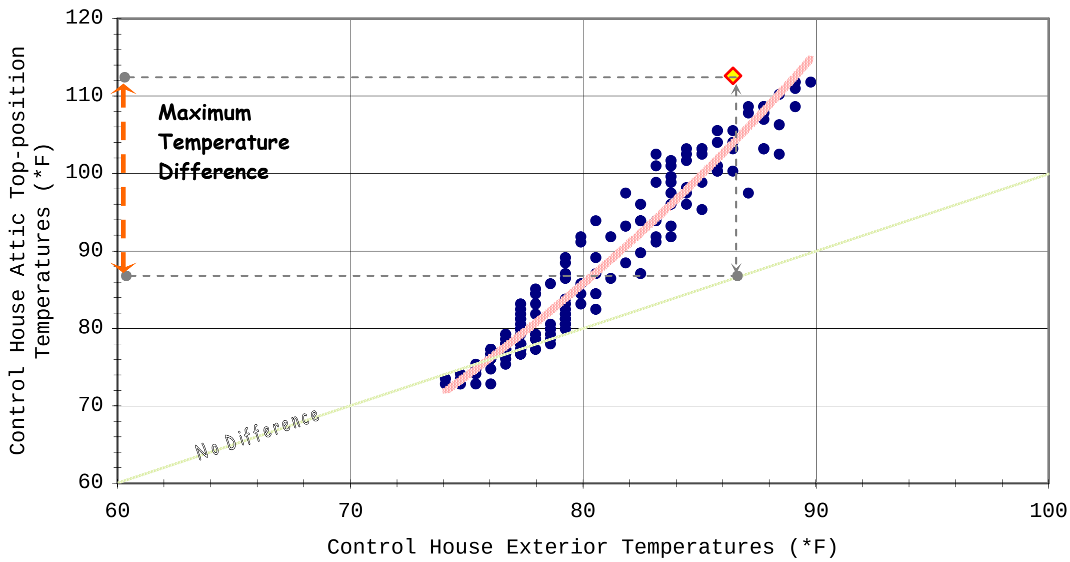


Fig. 2.04 - Control House Attic Top-position Temperatures versus Control House Exterior Temperatures from 09/10/01 to 09/19/01

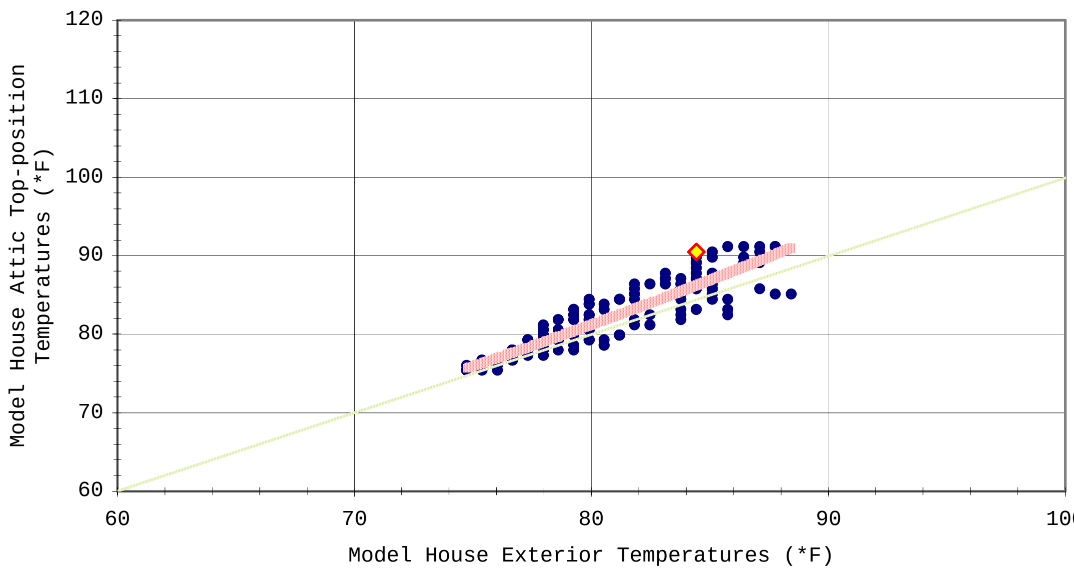


Fig. 2.05 - Model House Attic Top-position Temperatures versus Model House Exterior Temperatures from 09/10/01 to 09/19/01

The graphs clearly show that the highest reach of the control house's attic becomes much warmer that the outside temperatures during the hottest part of the day, with a recorded temperature difference reaching 26.17ºF (represented by a yellow diamond)
and an average of 6.54ºF above exterior temperatures [Fig. 2.04]. On the other hand, the model house's attic apex temperatures closely approach the exterior temperatures, with maximum differences never exceeding 6.03ºF ( ) and an average of 1.34ºF above exterior temperatures [Fig. 2.05].

- Fig. 2.06 and 2.07 represent the attic top-position temperatures versus the time of the day for the control house and the model house respectively. The graphs show that the attic top-position temperatures for both the control and the model house become warmest between 1400 and 1600 (circled in red), echoing the warmest time of the day for exterior temperatures.

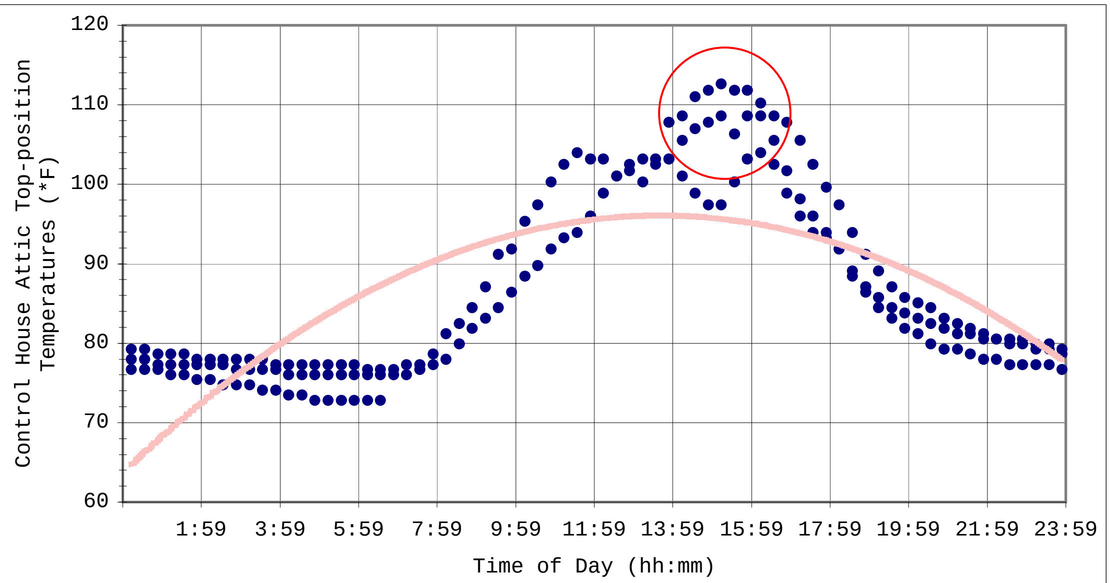


Fig. 2.06 - Control House Attic Top-position Temperatures versus Time of the Day from 09/16/01 to 09/19/01

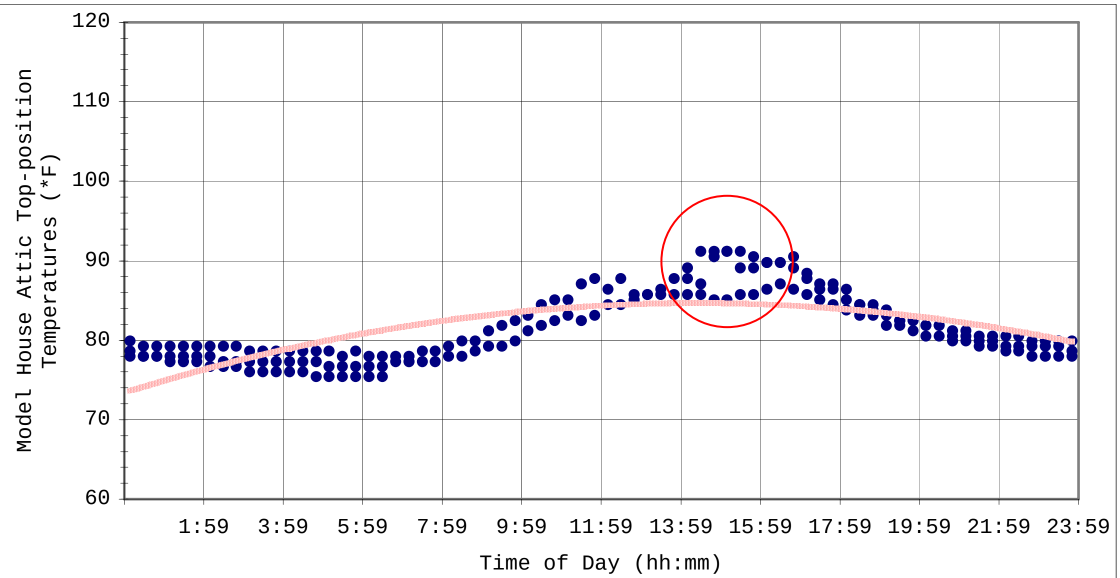


Fig. 2.07 - Model House Attic Top-position Temperatures versus Time of the Day from 09/16/01 to 09/19/01

- Fig. 2.08 illustrates the patterns of the attic top-position temperatures for the control and the model house, as well as the average exterior temperature recorded from 09/16/01 to 09/19/01. The graph shows that the upper reach of the control house's attic become much warmer than the model house's during the warmest part of the day. Loggers recorded a temperature difference reaching 21.44°F on 09/17/01 around 1515. An average temperature difference of 5.06°F between the control and the model's attic top-position was recorded.

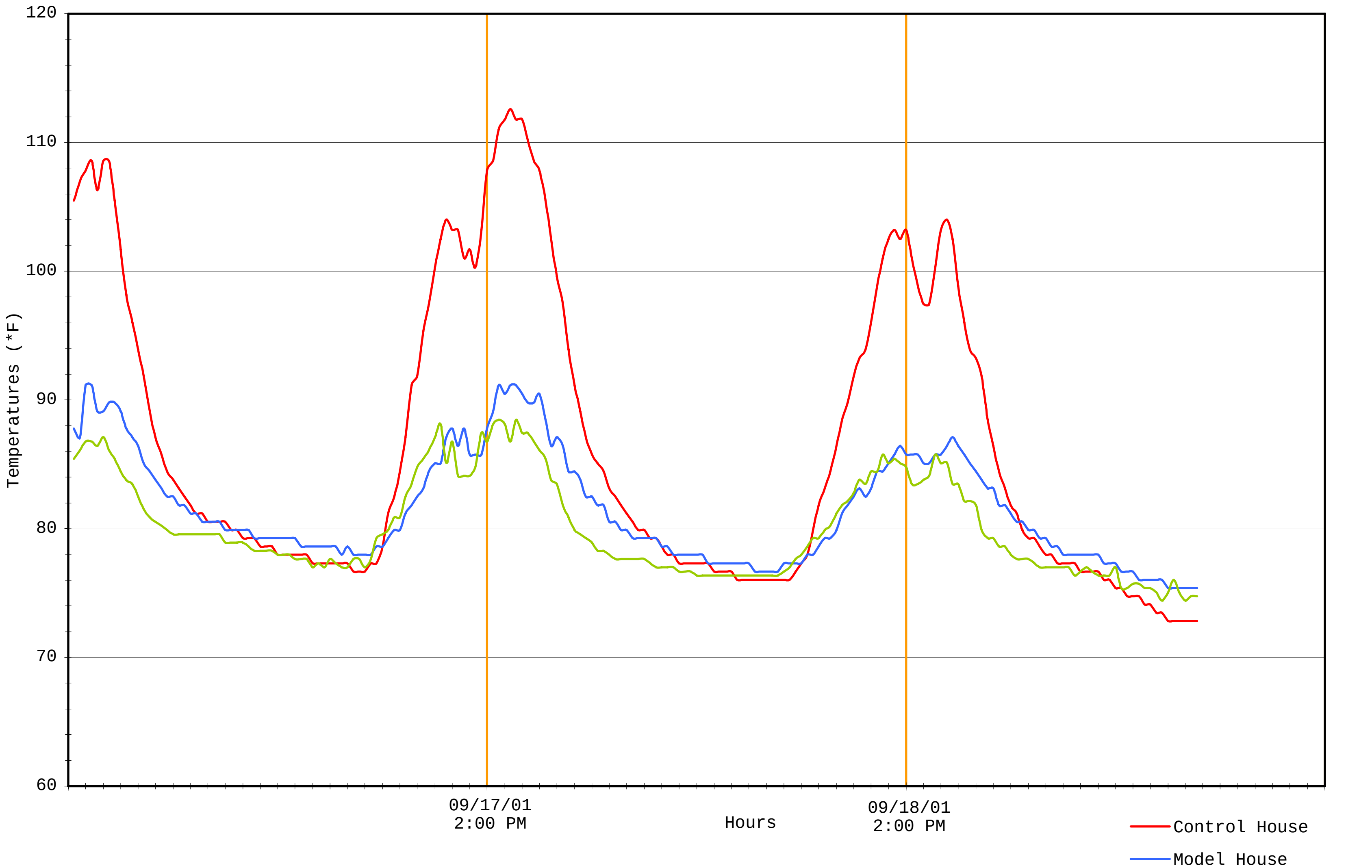


Fig. 2.08 - Control House and Model House Attic Top-position temperatures and Average Exterior Temperatures from 09/16/01 to 09/19/01

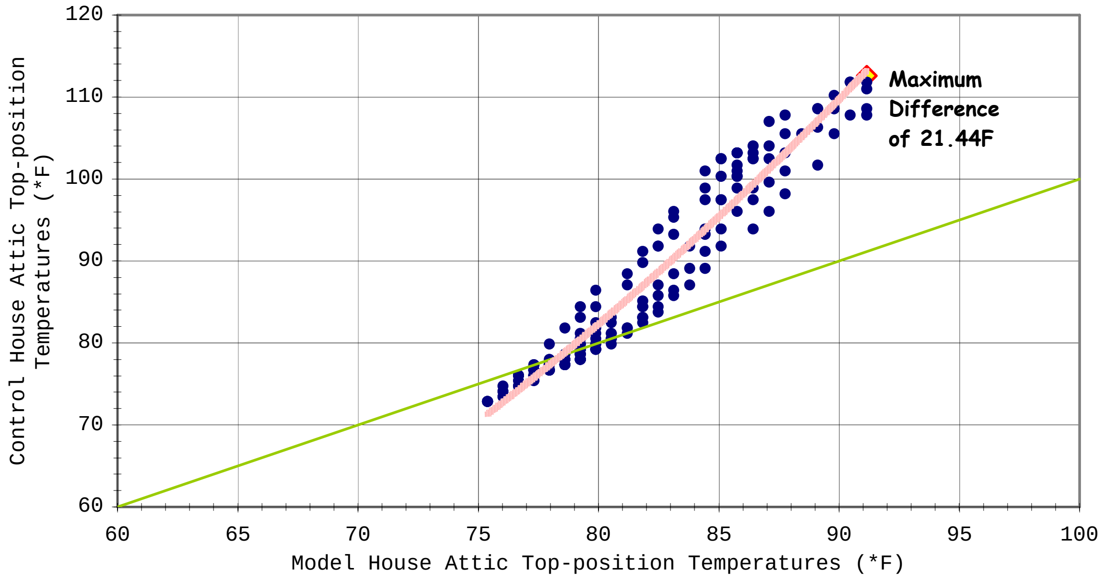


Fig. 2.09 - Control House Attic Top-position Temperatures versus Model House Attic Top-position Temperatures from 09/16/01 to 09/19/01

Fig. 2.09 explicitly reinforces the observation: the trend line rises sharply above the line of slope one as temperatures increase, illustrating an increasing difference of temperature between the control and the model house's attic top-position as the attic temperature rises. Only during the coolest part of the day (between 75ºF and 79ºF) does the control house's attic top-position temperatures become cooler than the model house's (generally between 2200 and 0800) with a maximum temperature difference of 2.67ºF. During the three months of testing the control house’s attic temperatures reached peaks in the 120-125ºF range. The maximum temperature recorded at the control house's attic top-position during the sample period of 9/16 to 9/19 was 112.6ºF, while its minimum recorded temperature was 72.83ºF, averaging 86.59ºF. The maximum temperature recorded at the model house's attic top-position was 91.16ºF, while its minimum recorded was 75.39ºF, averaging 81.53ºF

2.3. CONTROL AND MODEL HOUSES ATTIC BOTTOM-POSITION TEMPERATURE DIFFERENCES

- Fig. 2.10 and 2.11 show the temperature differences between the attic bottom-position and the exterior of the control house and the model house respectively.

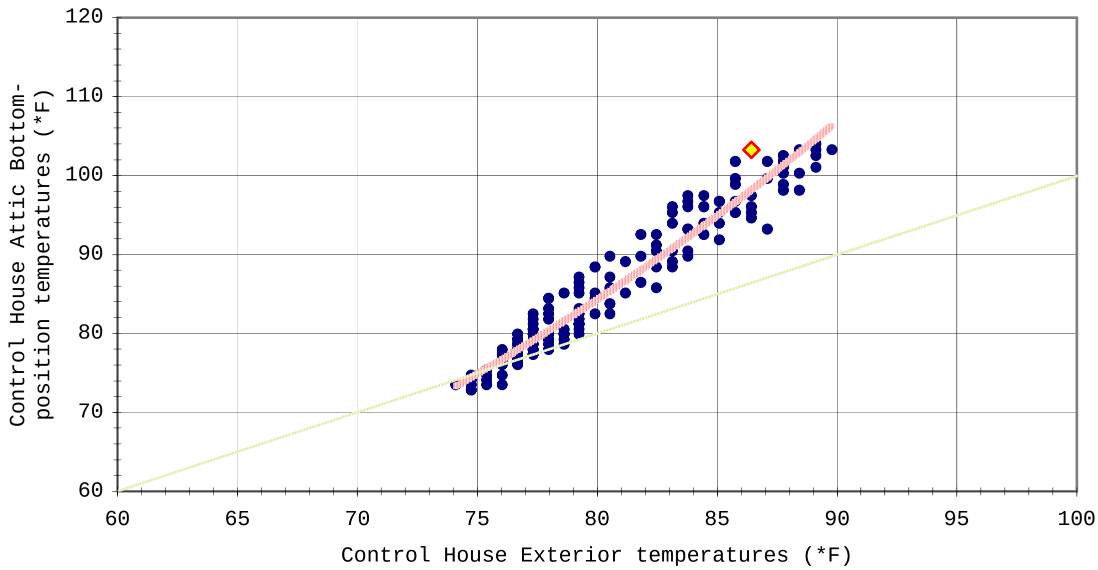


Fig. 2.10 - Control House Attic Bottom-position Temperatures versus Control House Exterior Temperatures from 09/16/01 to 09/19/01

Similarly with Fig. 2.04, Fig. 2.10 shows that the control house's bottom-position temperatures are considerably warmer than the exterior temperatures, with a maximum recorded temperature difference of 16.84°F (◇)and an average of 4.77°F above exterior temperatures. On the other hand, the temperatures of the model house's attic bottom-position very closely approach the exterior temperatures, never exceeding a difference of 5.35°F, averaging 0.55°F above exterior temperatures [Fig. 2.11].

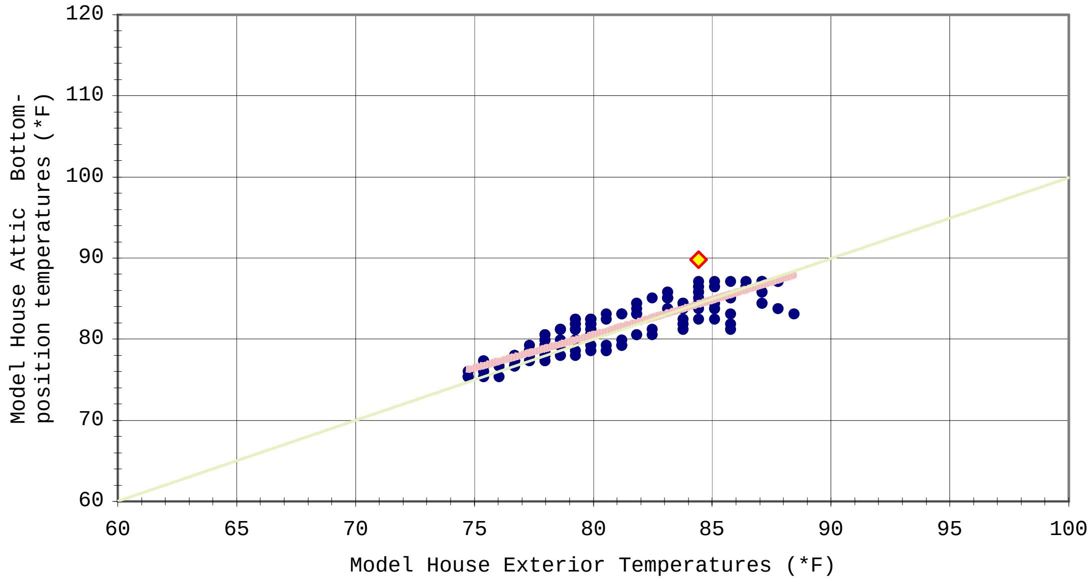


Fig. 2.11 - Model House Attic Bottom-position Temperatures versus Model House Exterior Temperatures from 09/16/01 to 09/19/01

- Fig. 2.12 and 2.13 represent the attic bottom-position temperatures versus the time of the day for the control house and the model house respectively. Once again, the graphs indicate that the warmest attic bottom-position temperatures occur between 1400 and 1600.

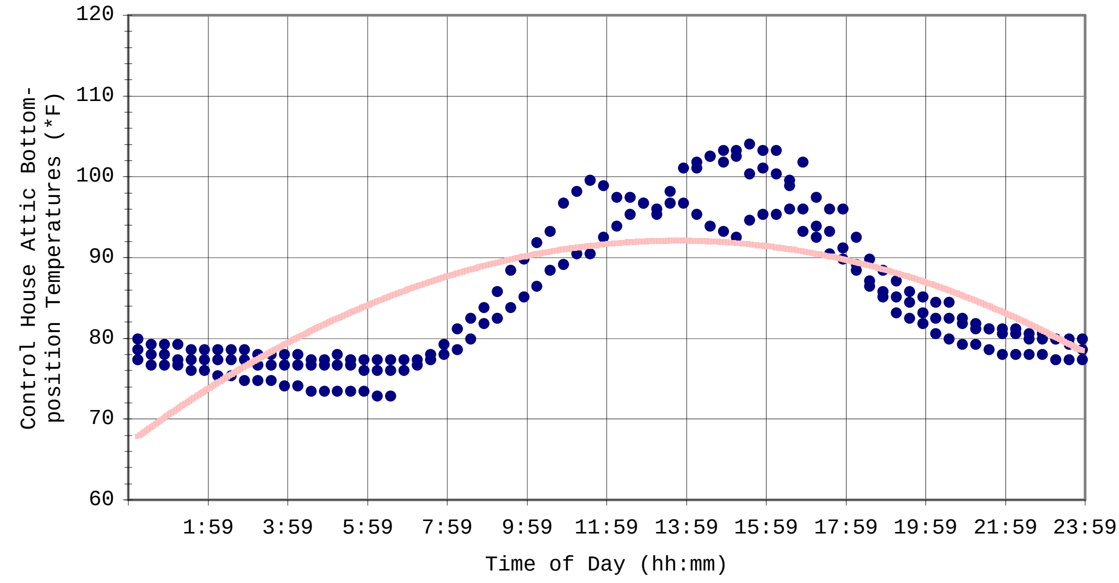


Fig. 2.12 - Control House Attic Bottom-position Temperatures versus Time of Day from 09/16/01 to 109/19/01

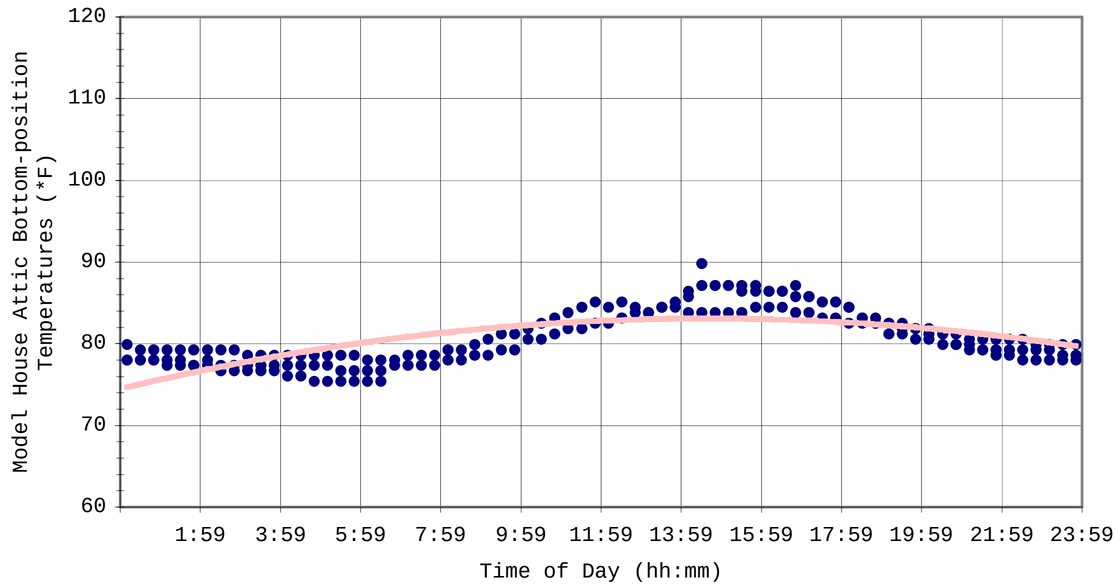


Fig. 2.13 - Model House Attic Bottom-position Temperatures versus Time of Day from 09/16/01 to 09/19/01

- Fig. 2.14 illustrates the patterns of the attic bottom-position temperatures for the control and the model house, as well as the average exterior temperature recorded from 09/16/01 to 09/19/01. The graph shows clearly the differences in temperature between the control and the model house's attic bottom-position.

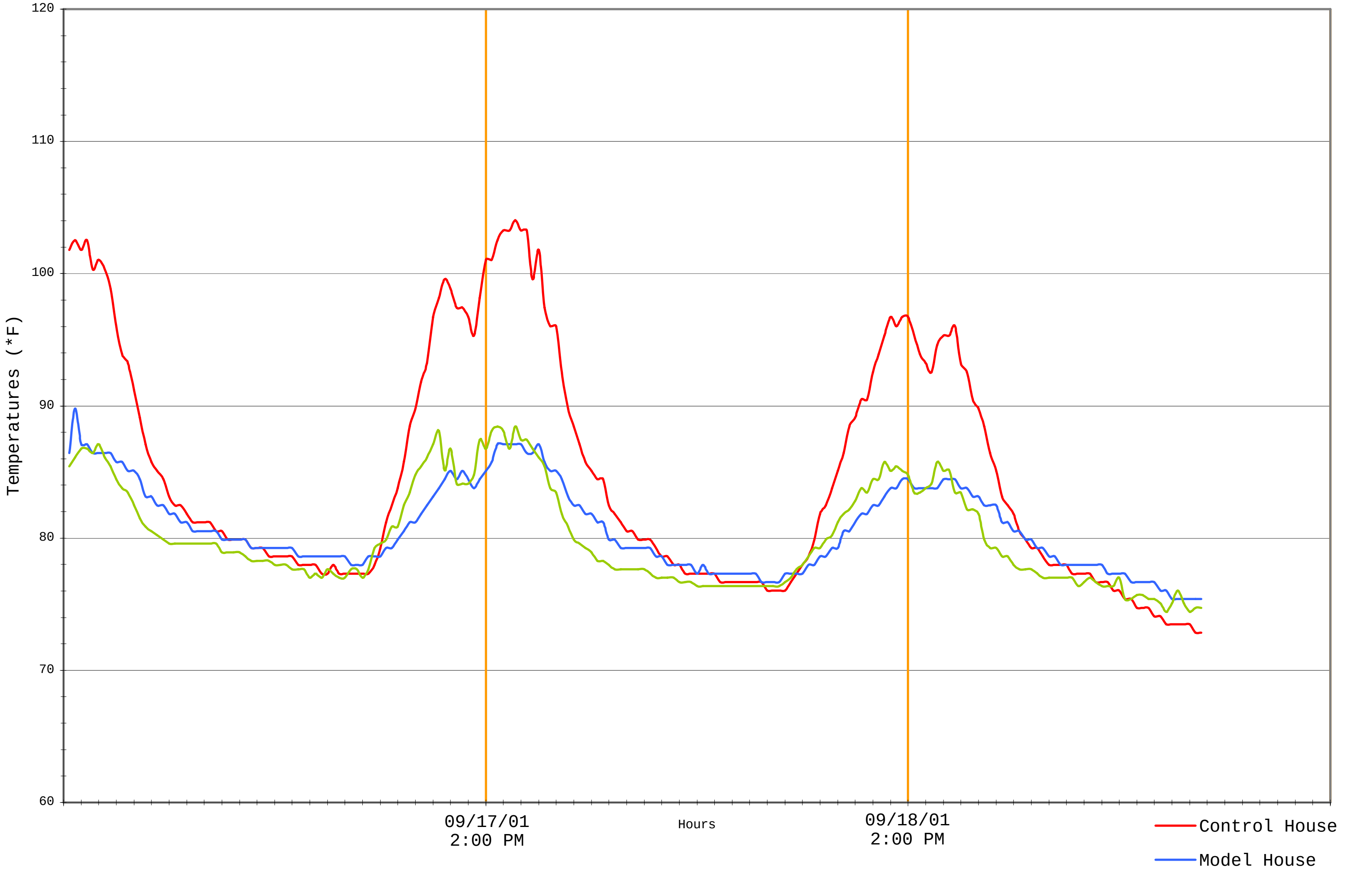


Fig. 2.14 - Control House and Model House Attic Bottom-position Temperatures and Average Exterior Temperatures from 09/16/01 to 09/19/01

- The lower reaches of the control house's attic are warmer than the model house's during the hottest part of the day, with a maximum temperature difference reaching 16.92°F on 09/17/01 around 1530. An average temperature difference of 4.08°F between the control and the model's attic bottom-position was recorded.

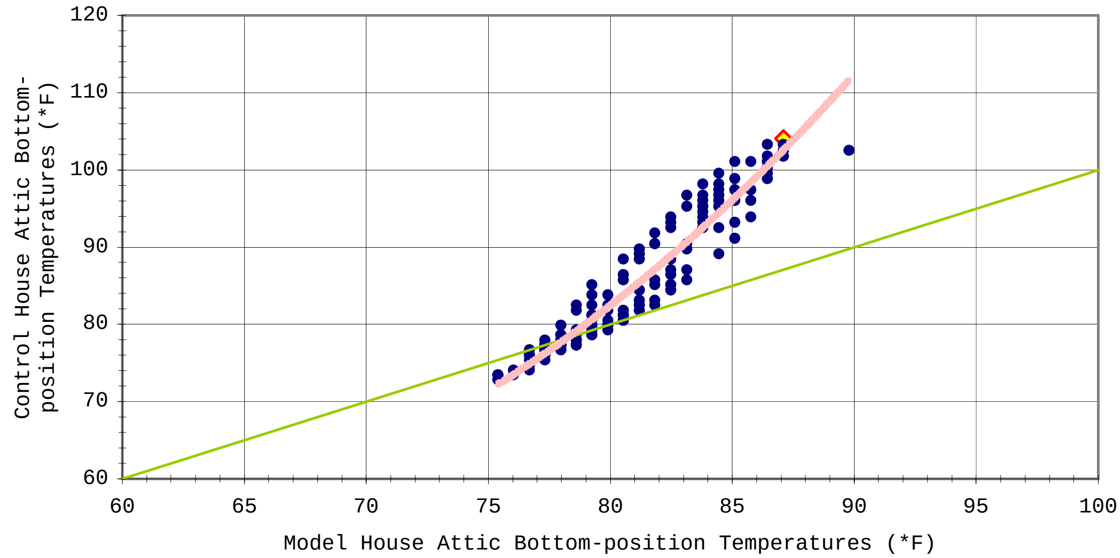


Fig. 2.15 - Control House Attic Bottom-position Temperatures versus Model House Attic Bottom-position Temperatures from 09/16/01 to 09/19/01

- Similarly to Fig. 2.09, Fig. 2.15 depicts an increase in temperature difference between the control and the model house's attic bottom-position as the attic temperature rises. The control house's attic tends to become cooler than the model house's attic when temperatures are inferior to 79°F (generally between 2200 and 0800) with a maximum temperature difference of 2.56°F. The maximum temperature recorded at the control house's attic bottom-position was 104.02°F, while its minimum recorded temperature was 72.83°F, averaging 84.82°F. The maximum temperature recorded at the model house's attic bottom-position was 89.79°F, while its minimum recorded was 75.39°F, averaging 80.73°F.

2.4. CONTROL AND MODEL HOUSES LIVING ROOM TEMPERATURE DIFFERENCES:

- Fig. 2.16 and 2.17 graph the comparison between the living room temperatures and the exterior temperatures for the control and the model house respectively.

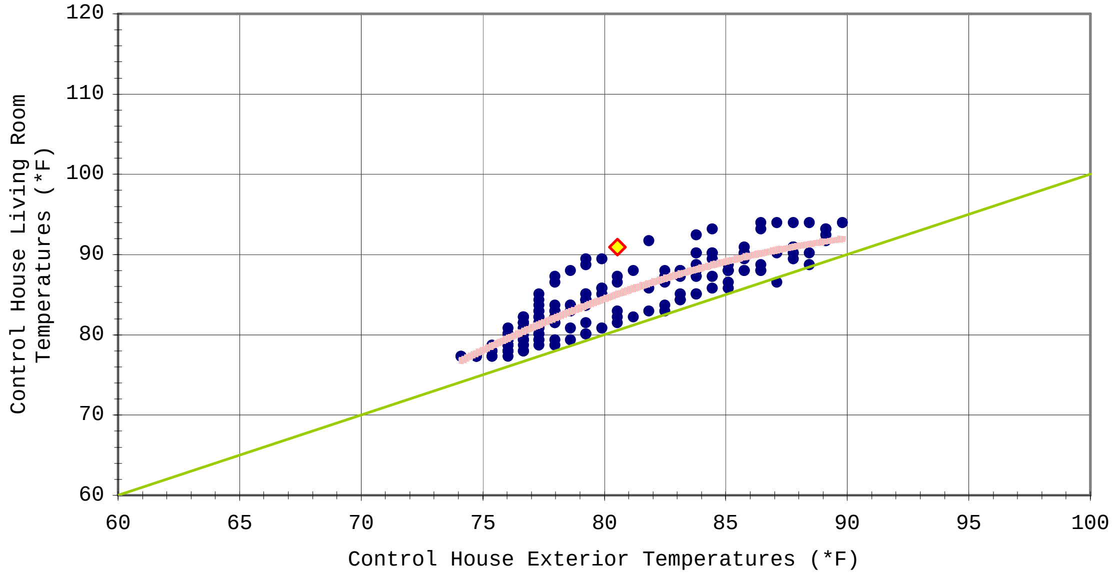


Fig. 2.16 - Control House Living Room Temperatures versus Control House Exterior Temperatures from 09/16/01 to 09/19/01

Fig. 2.16 shows that the control house's living room temperatures are consistently warmer than the exterior temperatures, with a maximum-recorded temperature difference of 10.42ºF (◇), and averaging 3.86ºF above the exterior temperatures.

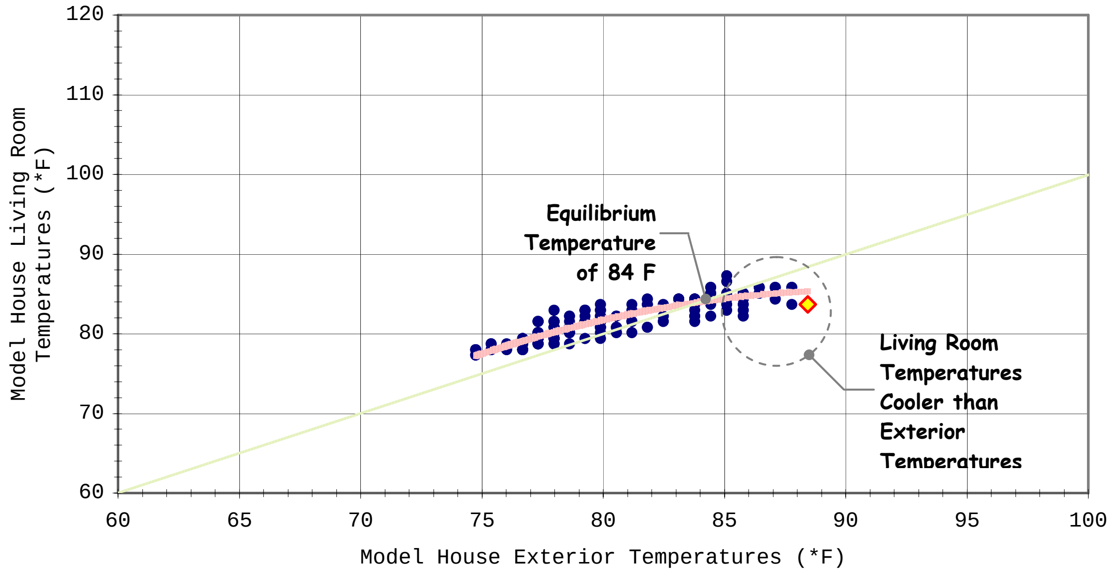


Fig. 2.17 - Model House Living Room Temperatures versus Model House Exterior Temperatures from 09/16/01 to 09/19/01

- Fig. 2.17 shows that the model house's living room temperatures remain higher than the exterior temperatures up to an equilibrium temperature[4] of about 84°F, when the living room temperatures become lower than the exterior temperatures, with a maximum difference of 4.77°F (◇) below exterior temperature. Below the equilibrium temperature, the model house's living room temperatures are higher than the exterior temperatures, with differences of up to 4.98°F. Although the model house's living room temperatures average 1.28°F above exterior temperatures, the important factor is that during the hottest period of the day (after the 84°F equilibrium temperature is reached) the model home's living room is actually cooler than the outside, making it more comfortable.

[4] The equilibrium temperature refers to that common temperature that is reached at the same time by different monitored spaces. The equilibrium temperature always occurs on the line of slope one.

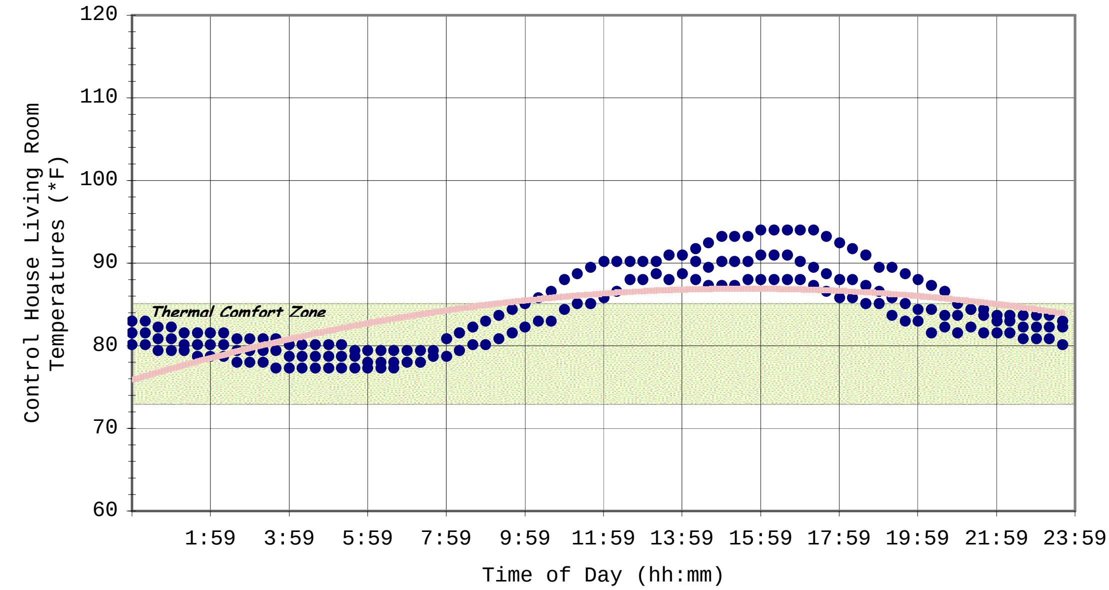


Fig. 2.18 - Control House Living Room Temperatures versusTime of Day from 09/16/01 to 09/19/01

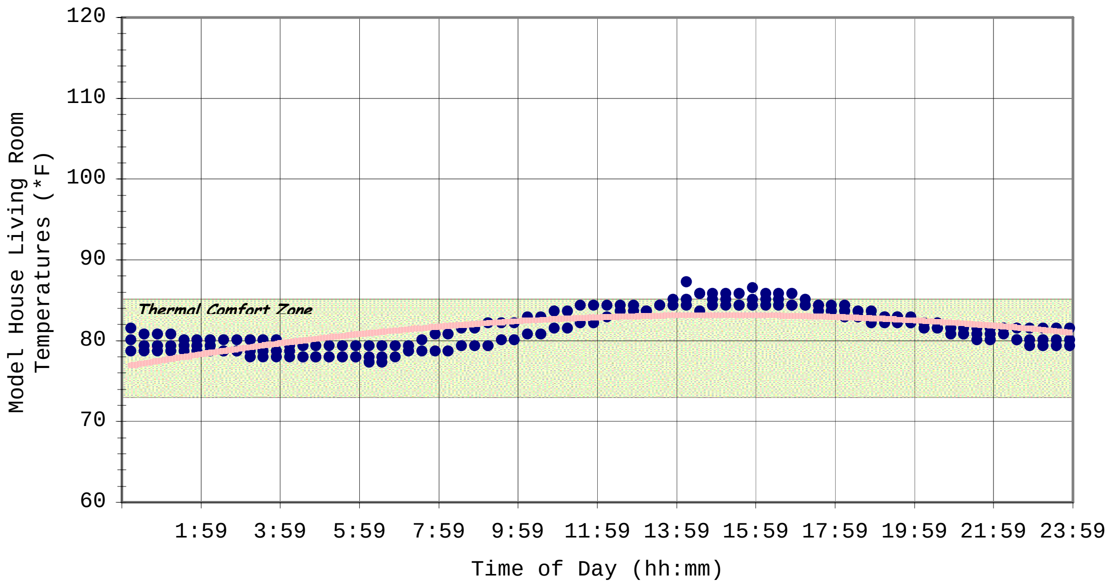


Fig. 2.19 - Model House Living Room Temperatures versusTime of Day from 09/16/01 to 09/19/01

- Fig. 2.18 and 2.19 represent the living room temperatures versus the time of the day for the control house and the model house respectively. Again, the green band across the graph represents the thermal comfort zone range, adjusted to our tropical climate. The graphs show that the warmest living room temperatures in the

- control house occur between 1600 and 1800, while in the model house, the warmest living room temperatures occur between 1400 and 1600, and remain predominantly within the thermal comfort zone. The coolest living room temperatures occur between 0400 and 0800 in the control house, while they occur between 0600 and 0800 in the model house.

- Fig. 2.20 illustrates the patterns of the living room temperatures for the control and the model house, as well as the average exterior temperature recorded from 09/16/01 to 09/19/01. The graph shows there is a noticeable difference between the control house and the model house living room temperatures. The control house's living room tends to be on average 2.45°F warmer than the model house's living room, with a maximum temperature difference reaching 8.87°F on September 17 at 17:15.

- Fig. 2.21 compares the living room temperatures of the two houses to one another. The red trend line sharply rises above the line of slope after reaching the equilibrium temperature around 78°F. Below the equilibrium temperature, the trend line shows close similarity between the two living room temperatures. The maximum temperature recorded at the control house's living room was 93.97°F, while its minimum recorded temperature was 77.31°F, averaging 83.91°F. The maximum temperature recorded at the model house's living room was 87.28°F, while its minimum recorded was 77.31°F, averaging 81.46°F.

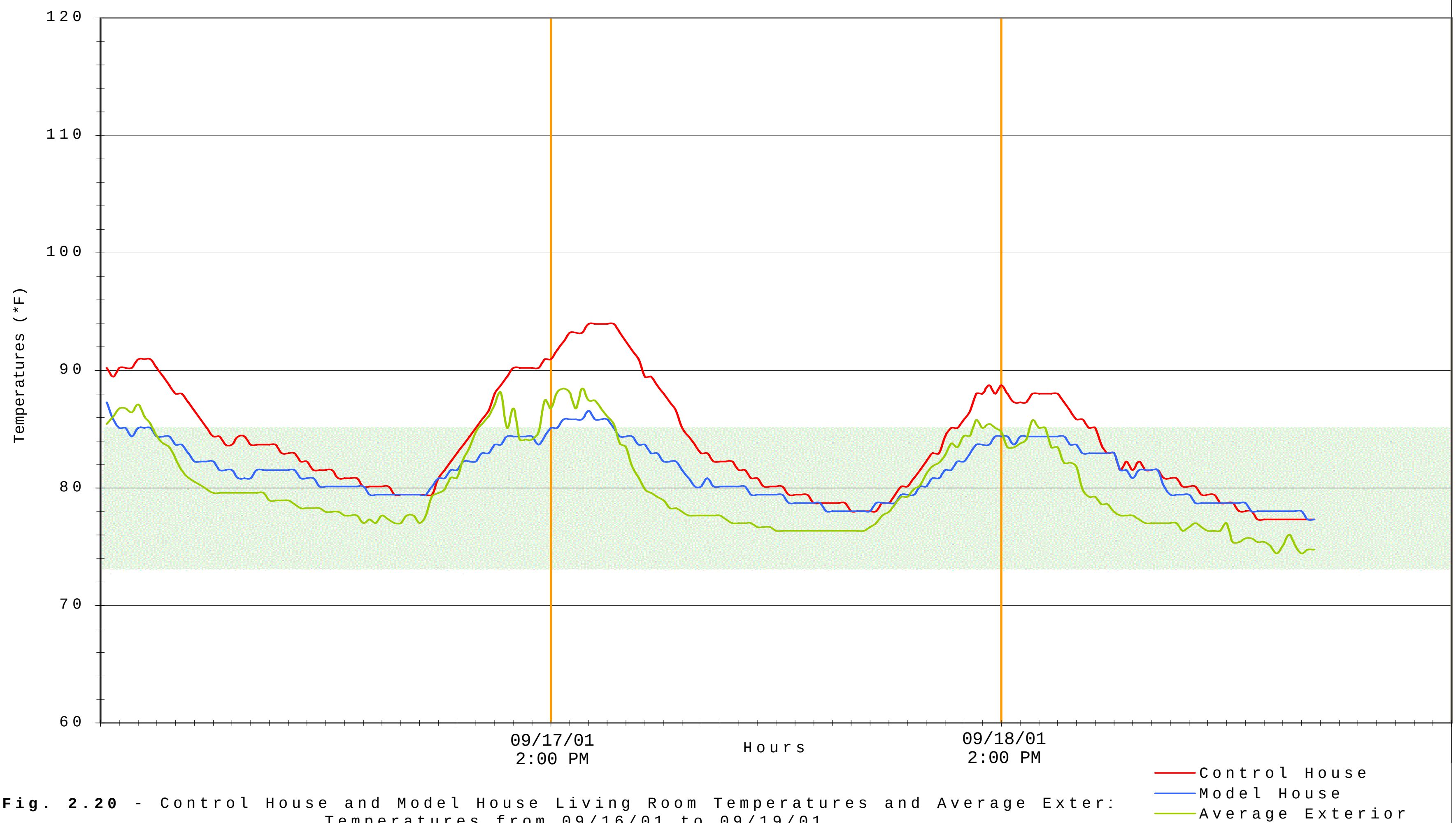


Fig. 2.20 - Control House and Model House Living Room Temperatures and Average Exter: Temperatures from 09/16/01 to 09/19/01

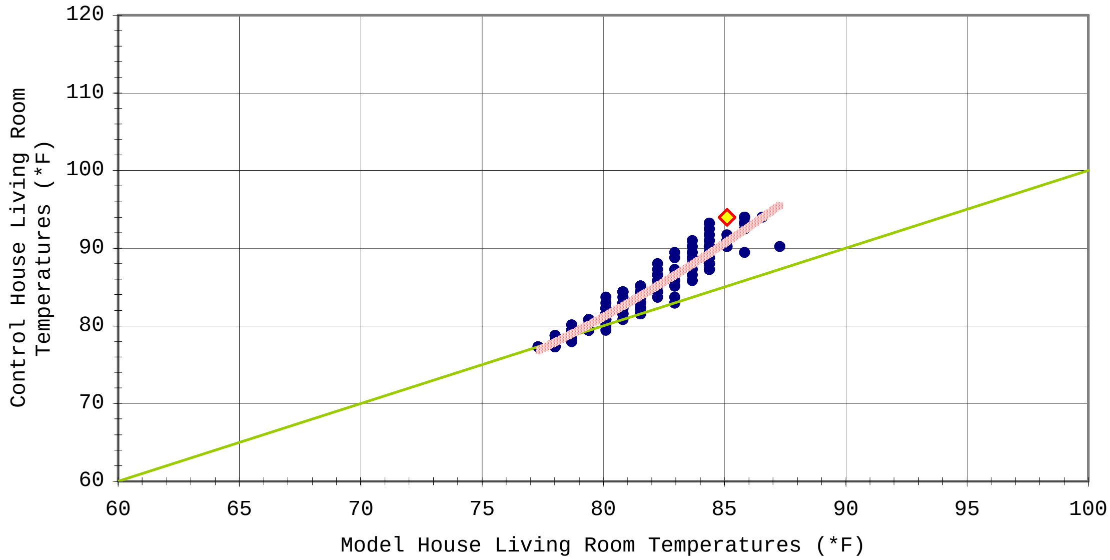


Fig. 2.21 - Control House Living Room Temperatures versus Model House Living Room Temperatures from 09/16/01 to 09/19/01

- The loggers used in recording the living room temperatures for the control house and the model house recorded relative humidity from 09/16/01 to 09/19/01. The data show that the control house's living room relative humidity averages 53%, with a maximum of 60% and a minimum of 42%. On the other hand, the model house's living room tends to be a little more humid, averaging 59% of relative humidity, with a maximum of 66% and a minimum of 44%. These data are valuable to assess thermal comfort levels in both houses [Fig. 3.01].

2.5. CONTROL AND MODEL HOUSES DINING ROOM TEMPERATURE DIFFERENCES:

- Fig. 2.22 and 2.23 show comparisons graphs between the dining room temperatures and the exterior temperatures for the control and the model house respectively recorded from 09/16/01 to 09/19/01. Fig. 2.22 graphs the control house's dining room temperatures as consistently warmer than the exterior temperatures, with a maximum temperature difference of 10.70°F(◇), and averaging 3.65°F above exterior temperatures. The model house's dining room temperatures, on the other hand, tend to become cooler than the exterior temperatures after an equilibrium temperature of about 83°F, as seen in Fig. 2.23. The maximum temperature difference between the model house's dining room and the exterior was 5.31°F below exterior temperatures. The dining room temperatures never rose more than 3.86 F above the exterior temperatures. The model house's dining room temperatures average 0.76°F above exterior temperatures.

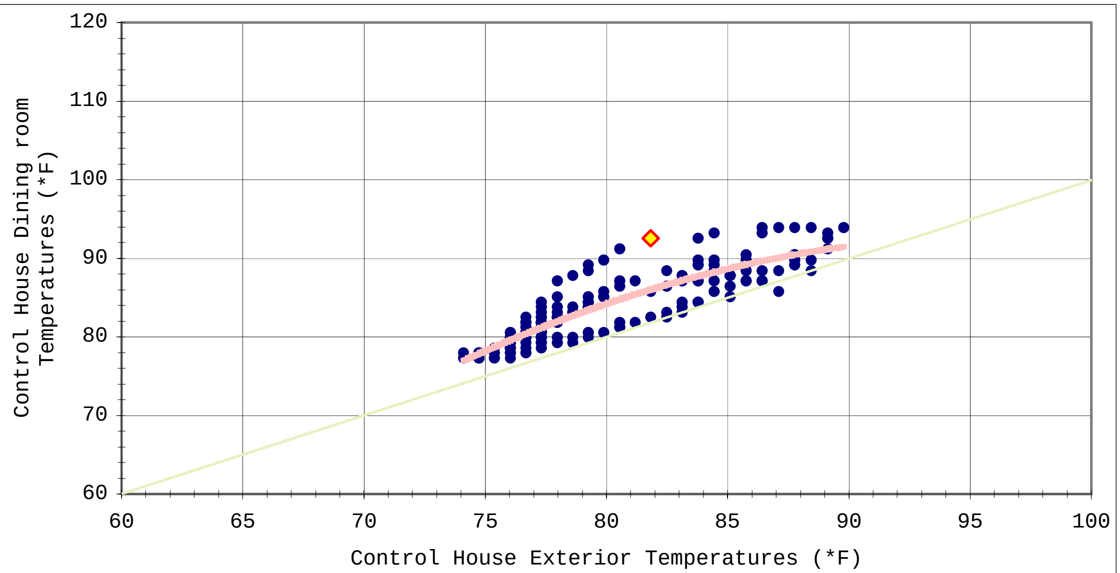


Fig. 2.22 - Control House Dining Room Temperatures versus Control House Exterior Temperatures from 09/16/01 to 09/19/01

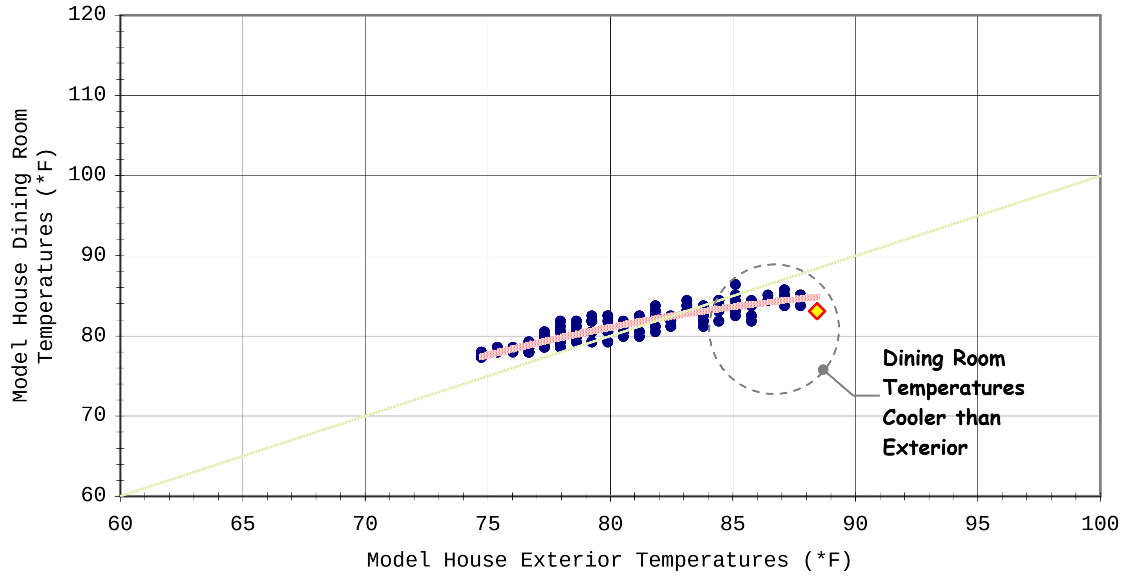


Fig. 2.23 - Model House Dining Room Temperatures versus Model House Exterior Temperatures from 09/16/01 to 09/19/01

- Fig. 2.24 and 2.25 represent the dining room temperatures versus the time of the day for the control house and the model house respectively.

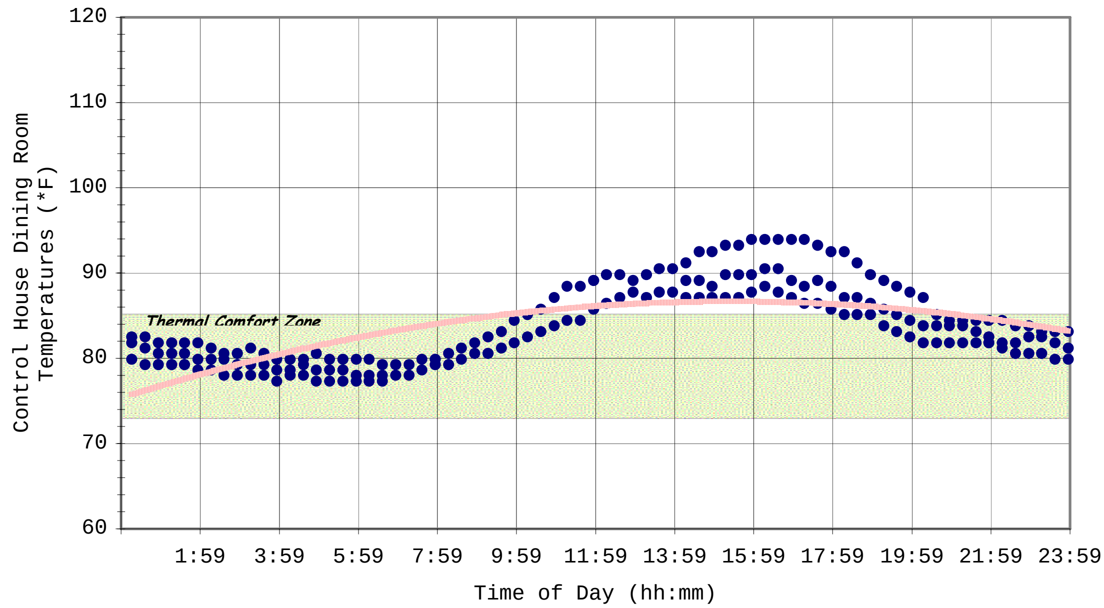


Fig. 2.24 - Control House Dining Room Temperatures versus Time of Day from 09/16/01 to 09/19/01

The graphs show that the warmest dining room temperatures in the control house occur between 1600 and 1800, while in the model house, the warmest dining room temperatures occur between 1400 and 1600 and remain predominantly within the thermal comfort zone. In both houses, the coolest dining room temperatures tend to occur around 0600.

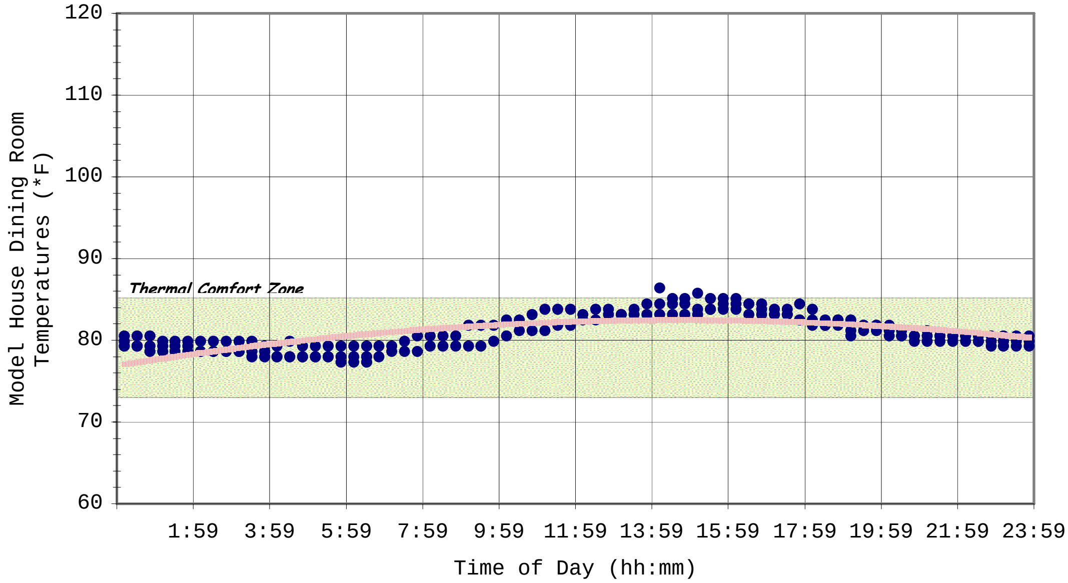


Fig. 2.25 - Model House Dining Room Temperatures versus Time of Day from 09/16/01 to 09/19/01

- Fig. 2.26 illustrates the patterns of the dining room temperatures for the control and the model house, as well as the average exterior temperature recorded from 09/16/01 to 09/19/01. The graph shows there is a noticeable difference between the control house and the model house dining room temperatures. The control house's dining room tends to be on average 2.76°F warmer than the model house's dining room, with a maximum temperature difference reaching 10.13°F. Fig. 2.27 compares the dining room temperatures of the two houses to one another. The red trend line sharply rises above the line of slope one after reaching the equilibrium temperature around 78°F. Below the equilibrium temperature, the trend line shows close similarity between the two dining room temperatures. The maximum temperature recorded at

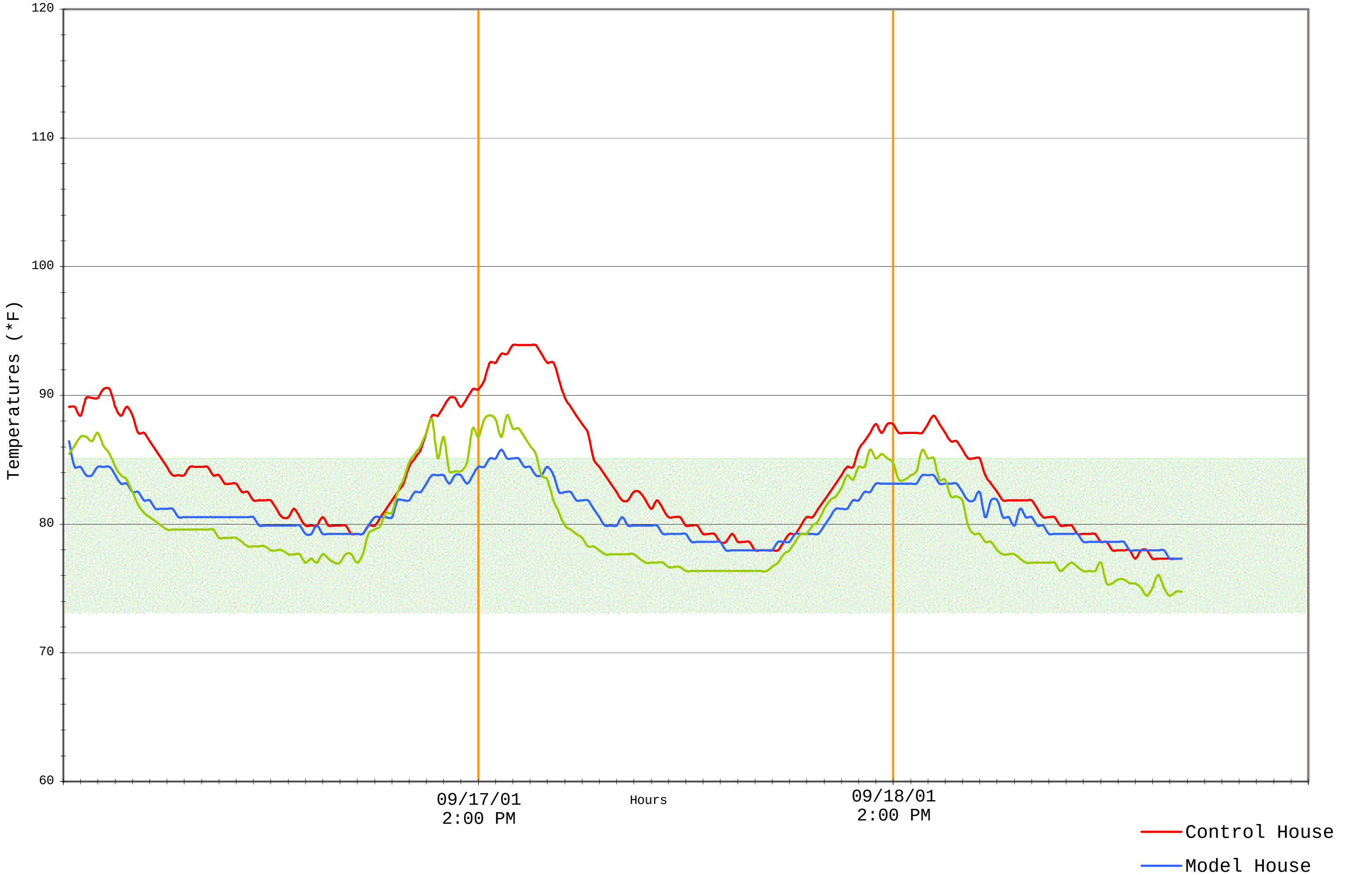


Fig. 2.26 - Control House and Model House Dining Room Temperatures and Average Exterior Temperatures from 09/16/01 to 09/19/01

- the control house's dining room was 93.92ºF, while its minimum recorded temperature was 77.32ºF, averaging 83.70ºF. The maximum temperature recorded at the model house's dining room was 86.43ºF, while its minimum recorded was 77.32ºF, averaging 80.94ºF. The thermal characteristics of the dining room look very similar to the living room's in both the control and the model house, as in both houses the dining room and the living room are opened to one another.

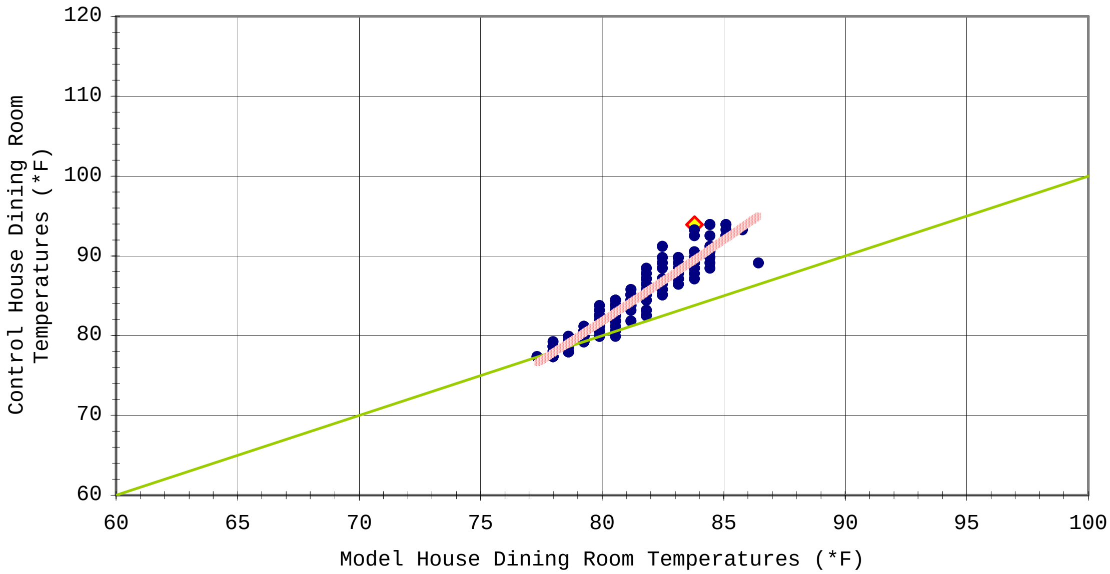


Fig. 2.27 - Control House Dining Room Temperatures versus Model House Dining Room Temperatures from 09/16/01 to 09/19/01

2.6. CONTROL AND MODEL HOUSES BEDROOM TEMPERATURE DIFFERENCES

- This bedroom is located on the western corner of each house. They are similar in area configuration location in the building.

- Fig. 2.28 and 2.29 show comparisons graphs between the bedroom temperatures and the exterior temperatures for the control and the model house respectively recorded from 09/16/01 to 09/19/01. Fig. 2.28 describes control house's bedroom temperatures consistently warmer than the exterior temperatures, with a maximum temperature difference of 17.03°F (◇), and averaging 5.11°F above exterior temperatures. The model house's bedroom temperatures, on the other hand, tend to become cooler than the exterior temperatures after an equilibrium temperature of about 82°F, as seen in Fig. 2.29. The maximum temperature difference between the model house's bedroom and the exterior was 7.25°F (◇) below exterior temperatures. The bedroom temperatures never rose more than 4.54°F above exterior temperatures. The model house's bedroom temperatures average 0.39°F above exterior temperatures.

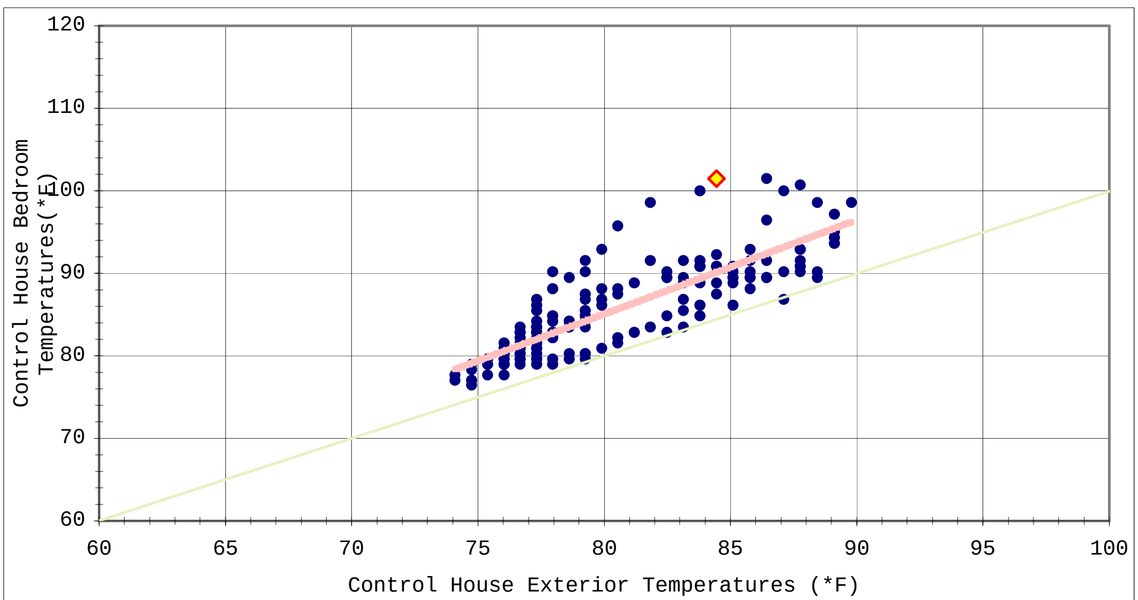


Fig. 2.28 - Control House Bedroom Temperatures versus Control House Exterior Temperatures from 09/16/01 to 09/19/01

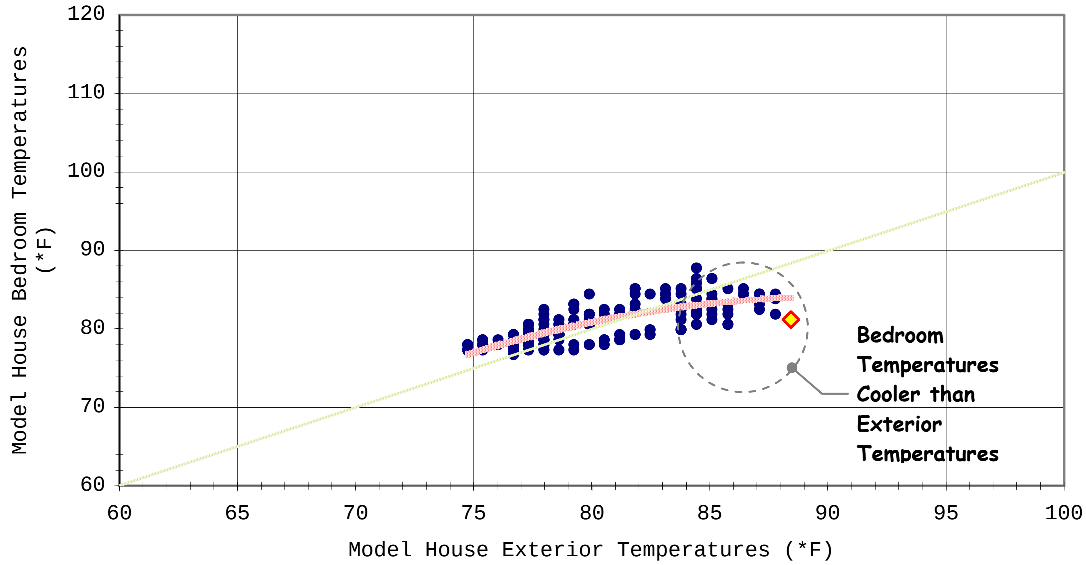


Fig. 2.29 - Model House Bedroom Temperatures versus Model House Exterior Temperatures from 09/16/01 to 09/19/01

- Fig. 2.30 and 2.31 represent the bedroom temperatures versus the time of the day for the control house and the model house respectively. The graphs show that the warmest bedroom temperatures in both houses occur between 1600 and 1800, while the coolest bedroom temperatures occur between 0600 and 0800 at both houses. These data reflect the fact that in both houses, the bedroom is located at the western corner of the house, thus receiving direct solar heat gain later in the day. Note that the model house’ bedroom temperatures remain predominantly within the thermal comfort zone.

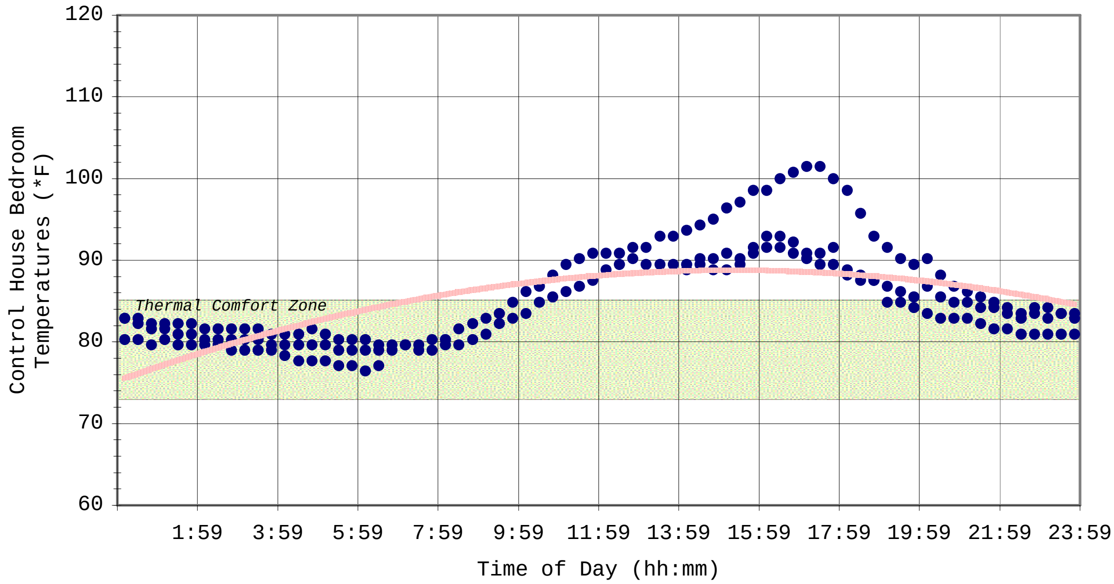


Fig. 2.30 - Control House Bedroom Temperatures versus Time of Day from 09/16/01 to 09/19/01

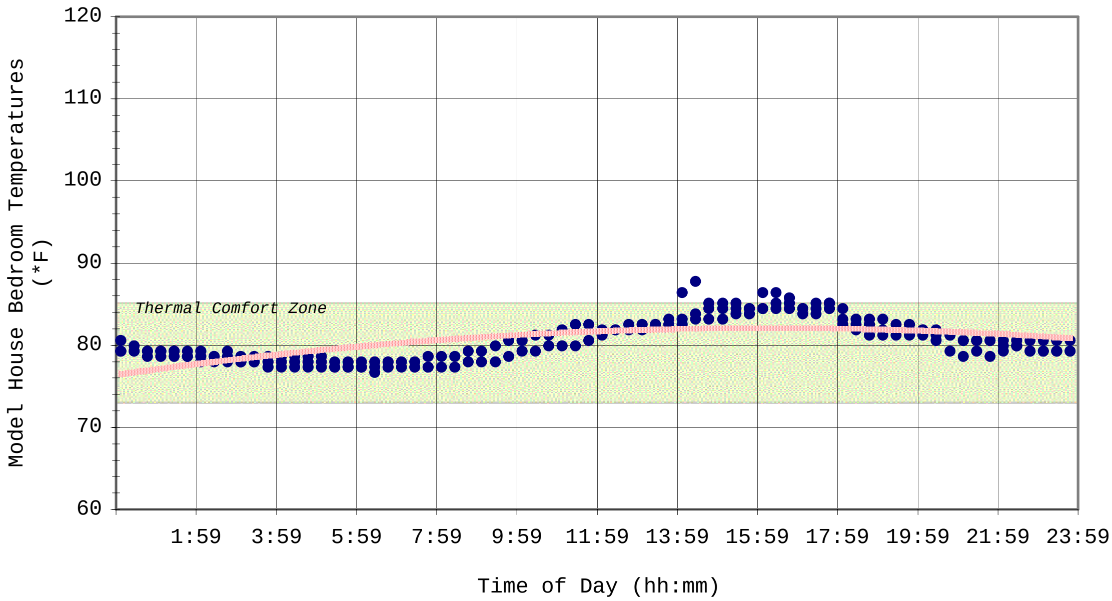


Fig. 2.31 - Model House Bedroom Temperatures versus Time of Day from 09/16/01 to 09/19/01

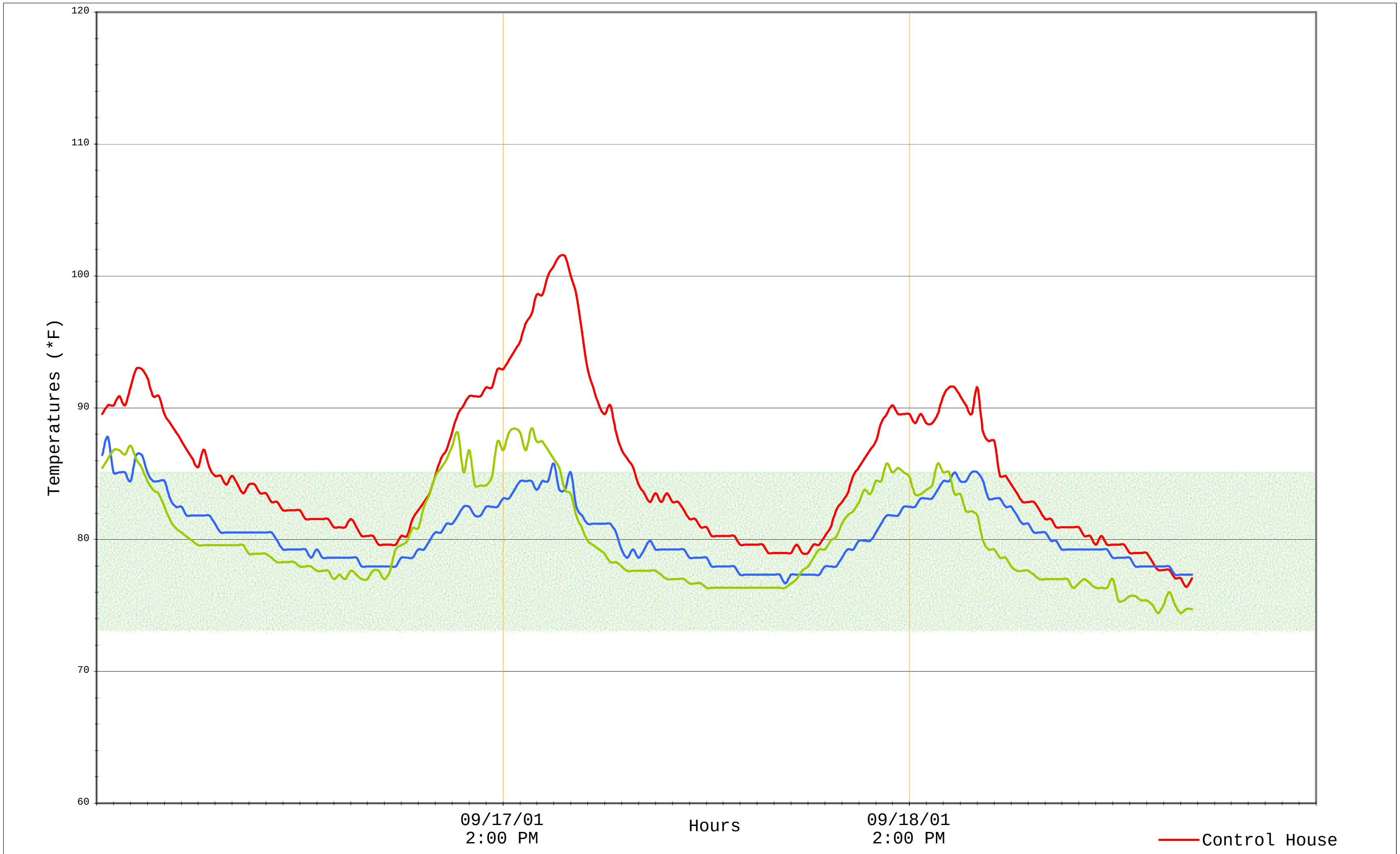


Fig. 2.32 - Control House and Model House Bedroom Temperatures and Average Exterior Temperatures from 09/16/01 to 09/19/01

Fig. 2.32 illustrates the patterns of the bedroom temperatures for the control and the model house, as well as the average exterior temperature recorded from 09/16/01 to 09/19/01. The control house's bedroom tends to be on average 4.59°F warmer than the model house's living room, with a maximum temperature difference reaching 17.68°F. Fig. 2.33 compares the bedroom temperatures of the two houses to one another. The red trend line sharply rises above the line of slope one from an equilibrium temperature of about 76°F. Below the equilibrium temperature, the trend line shows close similarity between the two bedroom temperatures. The maximum temperature recorded at the control house's bedroom was 101.47°F, while its minimum recorded temperature was 76.42°F, averaging 85.17°F. The maximum temperature recorded at the model house's bedroom was 87.77°F, while its minimum recorded was 76.68°F, averaging 80.58°F.

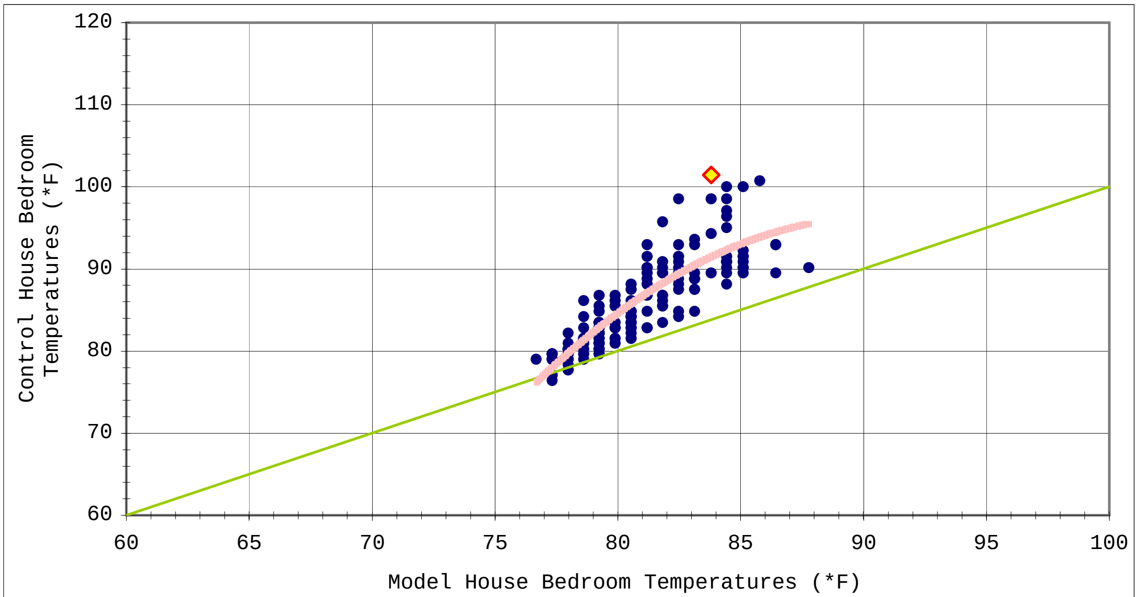


Fig. 2.33 - Control House Bedroom Temperatures versus Model House Back Room Temperatures from 09/16/01 to 09/19/01

2.7. CONTROL HOUSE ATTIC TOP-POSITION AND CONTROL HOUSE LIVING SPACES TEMPERATURE DIFFERENCES

- Fig. 2.34 compares the control house's attic top-position temperatures with the attic bottom-position temperatures. The red trend line of the graph depicts a decrease in attic bottom-position temperatures from the attic top-position temperatures after the temperatures equalized around 80°F. The temperature difference never exceeded 5.65°F (◇).

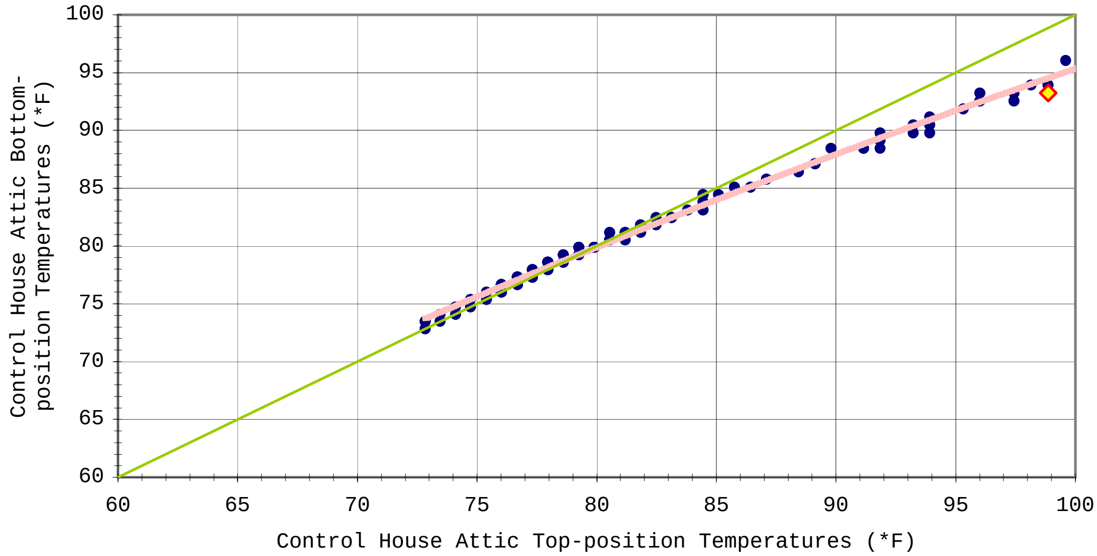


Fig. 2.34 - Control House Attic Bottom-position Temperatures versus Control House Attic Top-position Temperatures from 09/16/01 to 09/19/01

- Fig. 2.35 compares the control house's attic top-position temperatures with the living room temperatures. The red trend line of the graph depicts a noticeable decrease in living room temperatures from the attic top-position temperatures after the temperatures equalized around 83°F. The temperature difference reached 12.32°F (◇). Below the equilibrium temperature (around 83°F) however, the living room temperatures tend to be warmer than the attic top-position temperatures, with differences of up to 4.48°F.

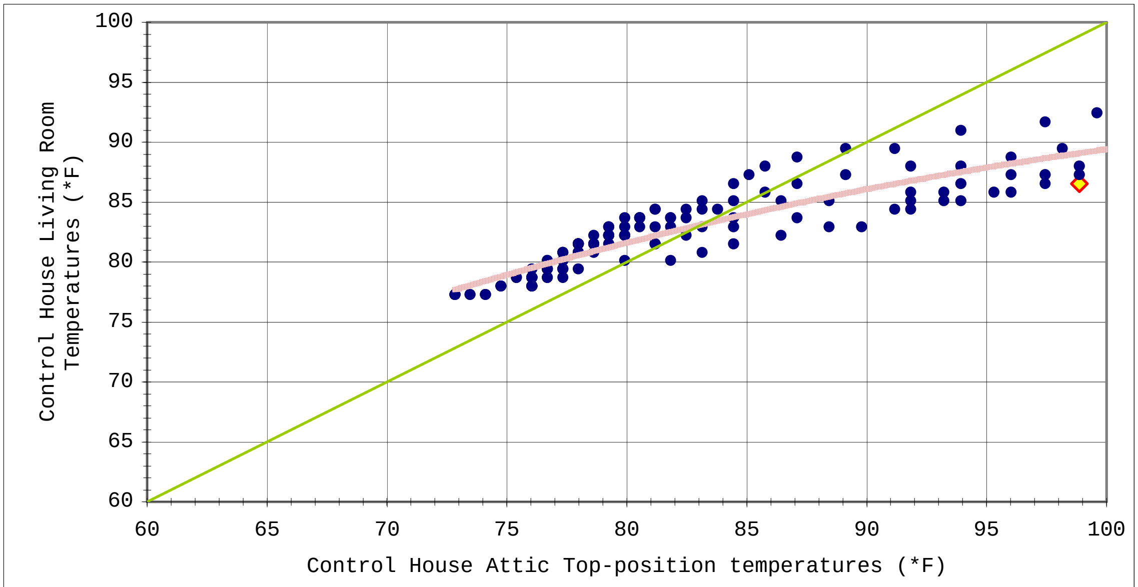


Fig. 2.35 - Control House Living Room Temperatures versus Control House Attic Top-position Temperatures from 09/16/01 to 09/19/01

- Fig. 2.36 compares the control house's attic top-position temperatures with the bedroom temperatures.

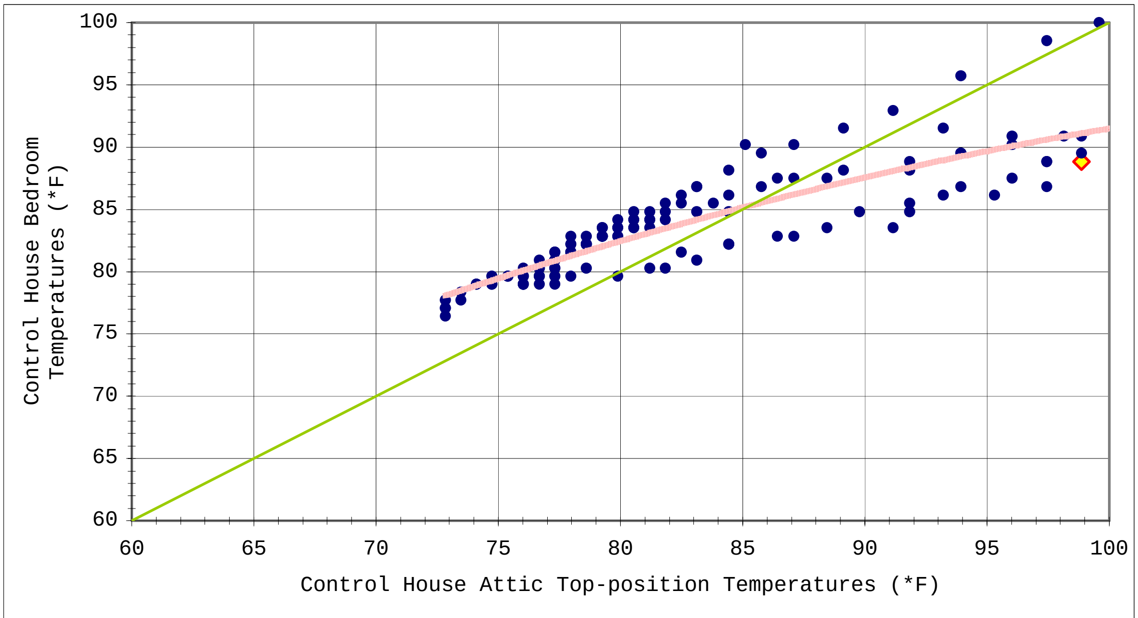


Fig. 2.36 - Control House Bedroom Temperatures versus Control House Attic Top-position Temperatures from 09/16/01 to 09/19/01

The red trend line of the graph depicts a decrease in bedroom temperatures from the attic top-position temperatures after the temperatures equalized around 85^{o}F, perhaps showing a slower heating rate than the living room. The temperature difference reached 10.62^{o}F (◇). Below the equilibrium temperature, around 85^{o}F, the bedroom temperatures tend to be warmer than the attic top-position temperatures, with differences up to 4.89^{o}F.

- Fig. 2.37 compares the control house's attic top-position temperatures with the dining room temperatures. The red trend line of the graph depicts a decrease in dining room temperatures from the attic top-position temperatures after the temperatures equalized around 83^{o}F, perhaps showing a identical heating rate than the living room, since the two rooms are spatially connected. The temperature difference reached 12.44^{o}F (◇). Below the equilibrium temperature, around 83^{o}F however, the dining room temperatures tend to be warmer than the attic top-position temperatures, with differences up to 4.49^{o}F. The thermal pattern of the dining room seems to be quite similar to the living room's when compared to the attic top-position temperatures.

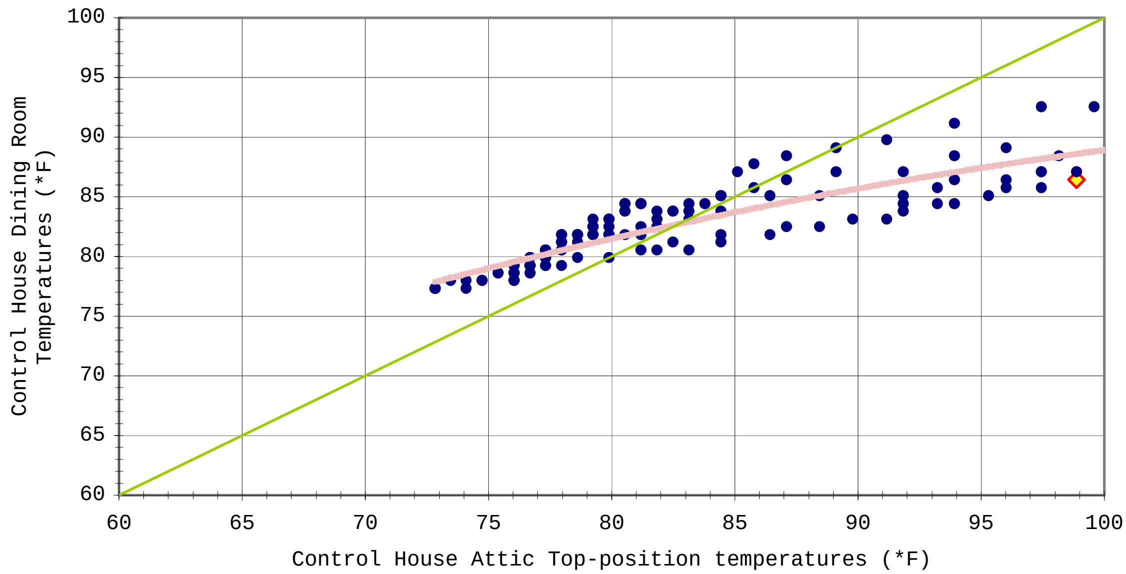


Fig. 2.37 - Control House Dining Room temperatures versus Control House Attic Top-position Temperatures from 09/16/01 to 09/19/01

2.8. MODEL HOUSE ATTIC TOP-POSITION AND MODEL HOUSE LIVING SPACES TEMPERATURE DIFFERENCES

- Fig. 2.38 compares the model house's attic top-position temperatures with the attic bottom-position temperatures. The red trend line of the graph depicts a decrease in attic bottom-position temperatures from the attic top-position temperatures after the temperatures were in equilibrium up to 80°F. The temperature difference never exceeded 4.06°F (◇).

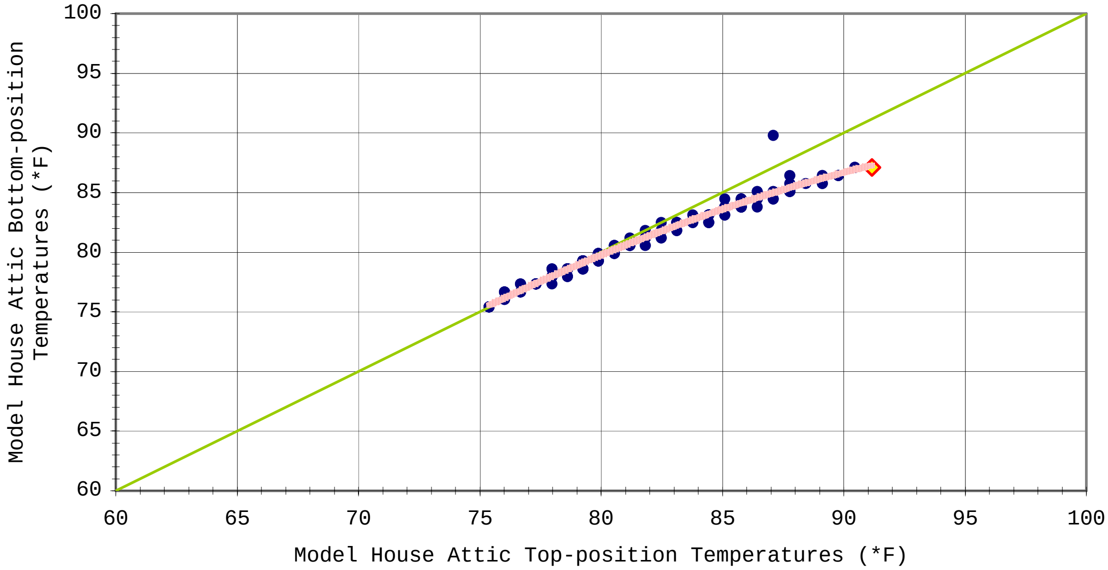


Fig. 2.38 - Model House Attic Bottom-position Temperatures versus Model House Attic Top-position Temperatures from 09/16/01 to 09/19/01

- Fig. 2.39 compares the model house's attic top-position temperatures with the living room temperatures. The red trend line of the graph depicts a decrease in living room temperatures from the attic top-position temperatures after the temperatures equalized around 82°F. The temperature difference reached 7.37°F (◇). Below the equilibrium temperature, the living room temperatures tend to be slightly warmer than the attic top-position temperatures, with differences of up to 2.58°F.

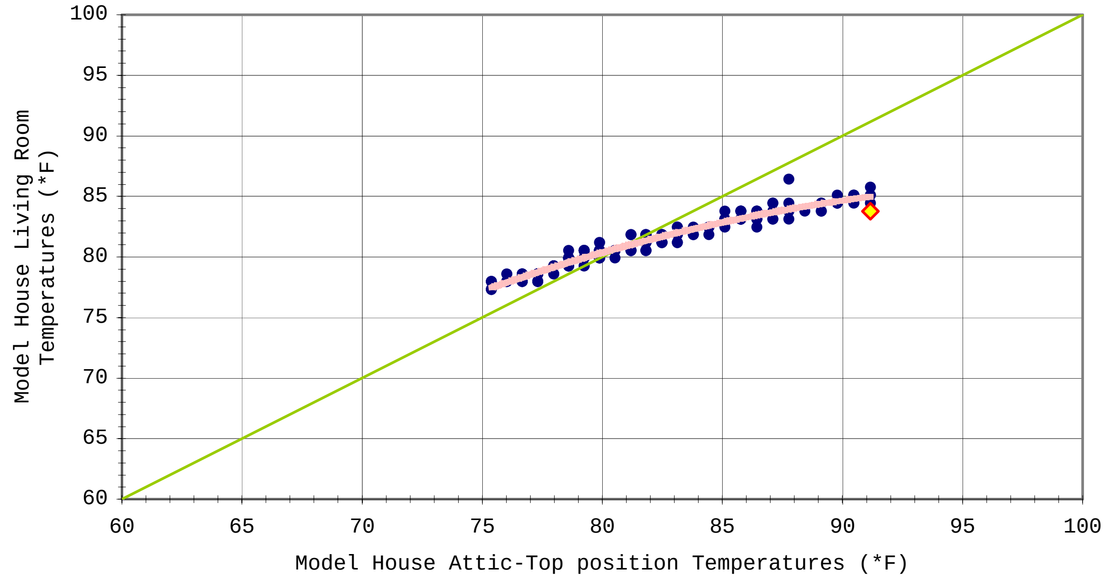


Fig. 2.39 - Model House Living Room Temperatures versus Model Attic Top-position Temperatures from 09/16/01 to 09/19/01

- Fig. 2.40 compares the model house's attic top-position temperatures with the bedroom temperatures.

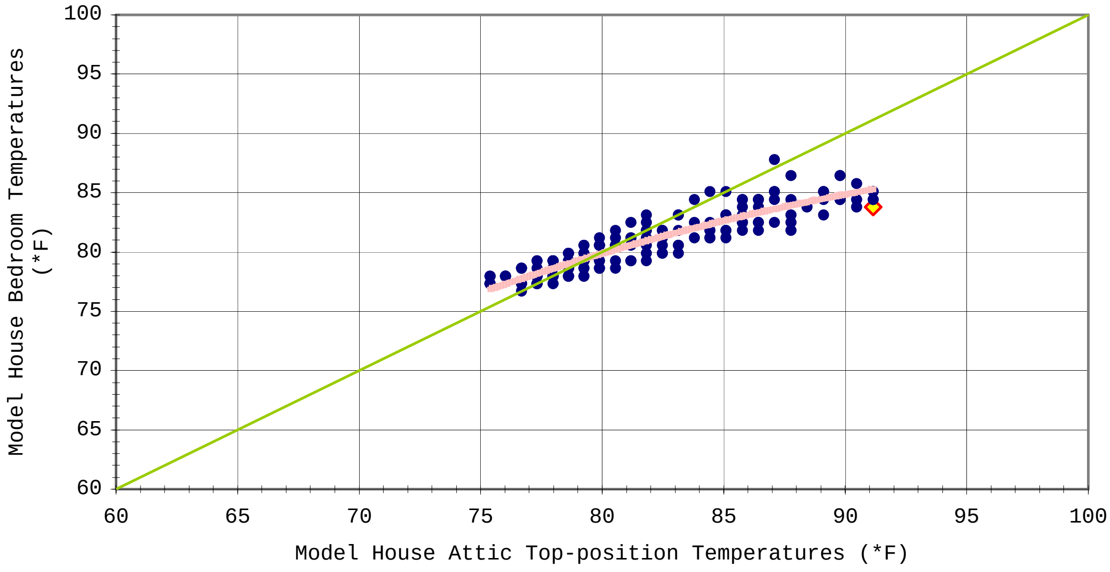


Fig. 2.40 - Model House Bedroom Temperatures versus Model House Attic Top-position Temperatures from 09/16/01 to 09/19/01

The red trend line of the graph depicts a decrease in bedroom temperatures from the attic top-position temperatures after the temperatures equalized around 80°F. The temperature difference reached 6.72°F (◇). Below the equilibrium temperature, the bedroom temperatures tend to be warmer than the attic top-position temperatures, with differences of up to 2.58°F.

- Fig. 2.41 compares the model house's attic top-position temperatures with the dining room temperatures. The red trend line of the graph depicts a decrease in dining room temperatures from the attic top-position temperatures after the temperatures equalized, again around 80°F. The temperature difference reached 7.37°F (◇). Below the equilibrium temperature, the bedroom temperatures tend to be warmer than the attic top-position temperatures, with differences of up to 2.58°F. The data and the graphs show close thermal patterns between the model house's bedroom and dining room temperatures, as compared to the attic top-position temperatures.

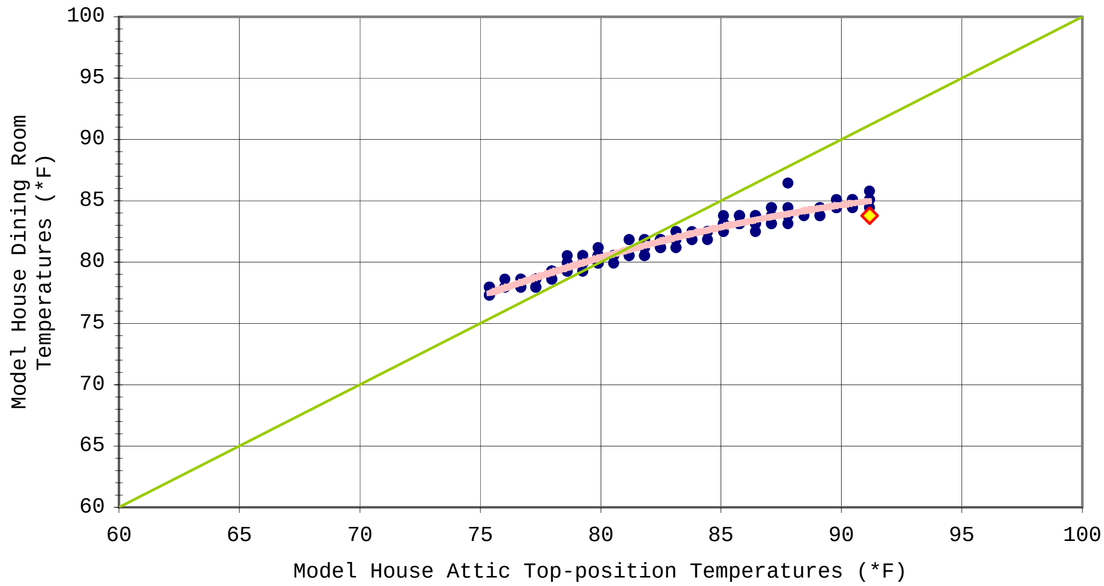


Fig. 2.41 - Model House Dining Room Temperatures versus Model House Attic Top-position Temperatures from 09/16/01 to 09/19/01

2.9. LIVING ROOM ILLUMINATION DIFFERENCES

- The loggers used in recording the living room temperatures for the control house and the model house, also recorded illuminance from 09/16/01 to 09/19/01. Fig. 2.42 and 2.43 represent the level of illumination versus the time of the day for the control house's living room and the model house's living room respectively. The illumination levels recorded in the model house's living room are much higher than at the control house's living room. On average, the model house's living room is 11.93 lm/ft^2 brighter than the control house's living room. At the model house's living room, the highest illuminance occurs around 0800 in the morning, when morning sun hits the easterly-exposed room, while at the control house, the highest levels of illuminance, however minimal, tend to occur later in the morning and early afternoon.

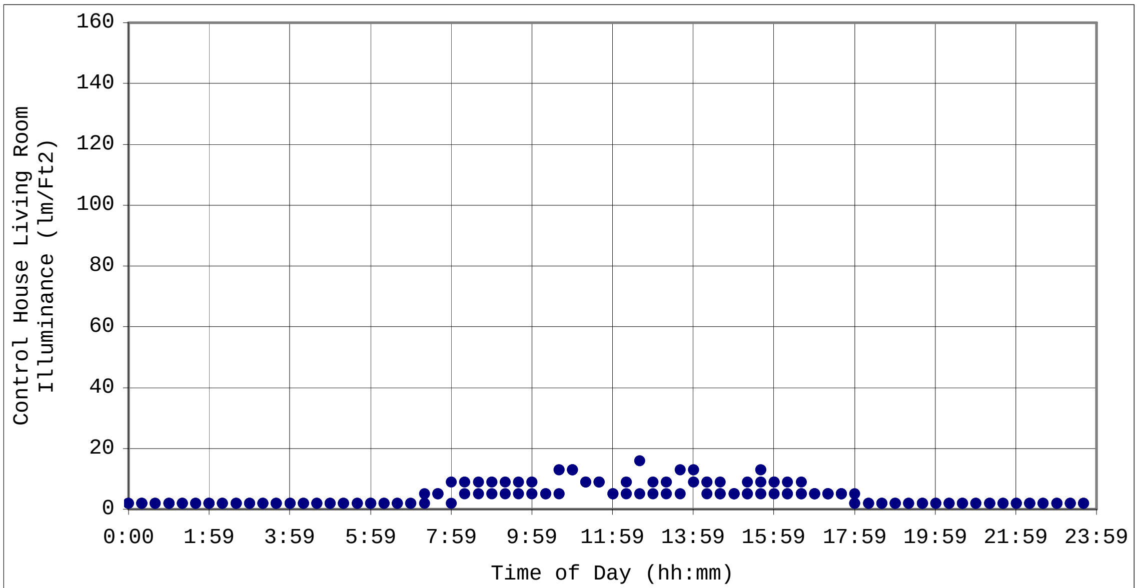


Fig. 2.42 - Control House Living Room Illuminance versus Time of the Day from 09/16/01 to 09/19/01

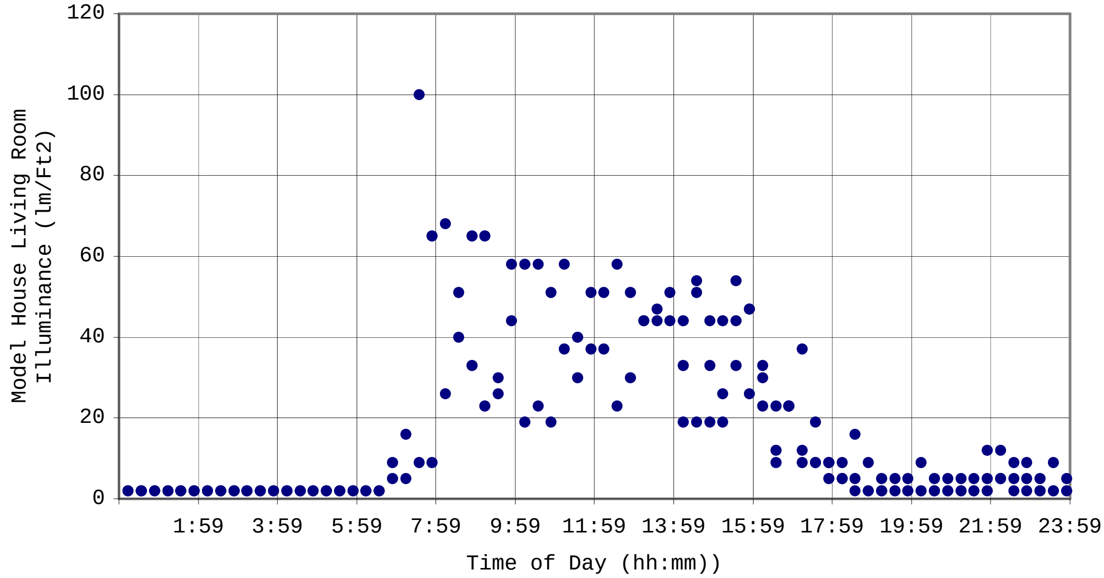


Fig. 2.43 - Model House Living Room Illuminance versus Time of the Day from 09/16/01 to 09/19/01

Both graphs show the illuminance levels dropping sharply around 1800, as the sun sets. The average illuminance recorded in the control house's living room was 3.94 lm/ft^{2,} while its maximum value reached a gloomy 16 lm/ft$^{2.}$ The average illuminance recorded in the model house's living room was 15.87 lm/ft^2, while its maximum value reached a bright 100 lm/ft^2.

3.0 CONCLUSION

Three factors affect human comfort: temperature, humidity and air movement. Higher temperatures are tolerable when air movement across the body increases or humidity levels decrease. Conversely, conditions of greater humidity are not uncomfortable when the temperature decreases and air flow increases. These are dynamic factors that must be balanced within a specific bioclimatic range for people to be comfortable. People of different climate zones acclimate to the specific conditions of their surroundings. For example, people in Hawaii are comfortable at temperature and humidity levels that people from more temperate conditions would find very uncomfortable. The bioclimatic chart in Appendix A shows the adjusted temperature comfort zone for Hawaii residents. The bioclimatic chart is used throughout this report to show the limits of the comfort range in relation to the conditions in the two houses.

Temperature was the factor of central focus for this monitoring project. Temperature readings were logged on 20-minute intervals, from 6 stations in each house, during the testing period. Humidity is a factor that is much more difficult to control through passive design strategies. The house design does not attempt to affect the relative or absolute humidity present in the building. The relative humidity readings were taken at intermittent intervals and factored in as base data. Air movement is a more variable factor. It is an important influence on the comfort of the occupants. Instantaneous airflow readings were taken with hand held anemometers during several site visits.

Passive cooling strategies usually follow the prioritized method of first mitigating heat gain through the building envelope and second, naturally ventilating out any transmitted and/ or internally gained heat. This concluding statement will take that approach. We will first examine the external heat gain through the building’s envelope and the results of efforts to mitigate that gain and secondly evaluate the comparative temperatures within the home and estimate the impacts of ventilation on those temperatures.

Through the data logging and data analysis, the research team found that the design strategies employed in the model house were largely effective at bringing the interior conditions into a comfortable range for the inhabitants. The exterior conditions for both houses are identical. Therefore the conditions that occur within the residences are a response to the architectural design.

3.1. EXTERIOR TEMPERATURES

- The differences in exterior temperatures recorded between the control house and the model house from 09/16/01 to 09/19/01 were minimal (on average 0.13ºF). It can be concluded that for analyses purposes, the control house and the model house experience the same exterior temperatures.

3.2. ATTIC TEMPERATURES

- The attic temperatures recorded from 09/16/01 to 09/19/01 at the control house and the model house differ greatly between one another. The attic temperatures of the model house are much cooler than the attic temperatures of the control house during the hottest period of the day (up to 21.44ºF of difference). The increased heat gain of the control unit’s attic eventually transmits to the rooms below, adversely affecting the comfort levels there. Mitigating the heat gain through the roof and ventilating any collected heat from the attic space helps to lower the temperatures in the model homes living spaces. The control house lacking these thermal gains and ventilating controls, experiences substantially higher temperatures in the attic space as well as temperatures that are outside the comfort range in the occupied spaces. Comparing Fig. 2.04 with Fig. 2.05 it is obvious that the temperatures inside the control house attic rose substantially above the corresponding exterior temperatures whereas the temperatures within the model house attic were only slightly higher than the exterior temperatures. At the higher temperature range the control house attic was 110-115^{0}F, more than 20 degrees hotter than the model attic.

- The radiant barrier in the roof assemble of the model house is absent in the control house. The attic ventilation in the model house is slightly greater than the attic ventilation in the control house, but the ventilation configuration in the model house’s attic substantially contributes to relieving the accumulated heat in the attic. Both houses have venting located at a low position in the attic space. They are positioned in the rafter blocking just above the walls’ top plate. The available open area of these vents is roughly equal in each house. The attic ventilation through vents in this location is pressure driven and, by themselves, do not effectively evacuate the accumulated hot air. The ridge vent that runs continuously along the model home’s roof expands the attic ventilation strategy. The ridge vent at the top of the attic space introduces a convective airflow. The ridge vent is baffled creating a negative pressure zone on both sides of the ridge and the hot air that has been stacking towards the top of the attic space can now be evacuated. The escaping air induces greater airflow through the rafter blocking vent openings and the entire attic space is more effectively ventilated. Therefore the vastly lower model home’s attic temperature, up to 21.44º F during the hottest part of the day, and its consistently lower attic temperatures, indicate the effectiveness of; The lighter colored roof shingles and the radiant barrier at reducing the radiant solar gain through the roof and the ventilation method for evacuating hot air in the attic. These combined methods therefore, reduce the temperature build-up in the attic and the eventual thermal transmittance through to the adjacent spaces via conduction and re-radiation.

- Slightly higher temperatures in the model house's attic during the coolest time of the night show that the model house's attic retains 2ºF to 3ºF of heat longer than the control house's attic. This does not have a significant bearing on the comfort of the residents. The research team suspects that this phenomenon is created because the radiant barrier in the upper zone of the model attic space is not allowing the long-wavelength re-radiated heat to escape as quickly as the control house does with no radiant barrier in the attic.

3.3. LIVING SPACE TEMPERATURES

- The model house's living spaces are cooler than the control house's living spaces. While the lowest living spaces temperatures at the model house are quite similar to the control house's, and these are a result of early morning exterior cooling temperatures, the highest indoor temperature of the control house are substantially higher than the respective temperatures in the model home. The control house highs are also higher than the corresponding exterior temperatures and are significantly higher than what is comfortable for the residents.

- The control house's bedroom is the last living space, of the two houses, to equilibrate its temperatures with attic top-position temperatures at about 85ºF (i.e. takes the longest to become cooler than the attic). The model house's bedroom, on the other hand, is the first one (with the model house's dining room) to equilibrate its temperatures with the attic top-position temperatures at about 80ºF (i.e. the first to become cooler than the attic).
- When the temperatures for each house are averaged and the relative humidity is considered, it can be said that theoretically, each house is comfortable. For example, with the current data of 53% average relative humidity and an average temperature of 83.91ºF in the control house's living room and 59% average relative humidity and an average temperature of 81.46ºF in the model house's living room, both house's living rooms fall marginally within an appropriate thermal comfort zone for the tropics. But, the approach of focusing on the averages can be misleading because it nullifies the real impacts of higher temperatures that the occupants experience during active times of the day. For example, Fig. 3.01 illustrates the real conditions in the houses in the late afternoon. We can see from this chart that the control house is well beyond the region of comfort for the residents and the model house is within the comfort zone and only slightly above it. However, with the natural venting scheme existing in the model house, the extended comfort zone provides an improved level of comfort in the model house. In this case, the model home’s comfort range would be extended to run along with the 100 ft/min. increased ventilation line, thereby encompassing the upper dot of the model into the adjusted comfort zone.
- The living and dining room of the model house remain on average 2.44ºF and 2.76ºF (respectively) cooler than at the control house with the greatest single point temperature difference running about 6ºF to 9ºF warmer in the control house. The model house's bedroom stays on average 4.59ºF cooler than the control house's bedroom with the largest differential being as much as 17ºF. Although significant, the temperature readings only tell part of the story. The graphs indicate that during the hotter times of the day the model home’s living room temperatures run from low to high eighties and the control unit’s comparable temperatures range from the low eighties to the mid

nineties. Both houses at times exceed the comfort range but much less frequently and to a much lower extent in the model. The relative humidity is about the same in each location and at times higher in the Model House. But the effect of ventilation again makes a difference here in the living space. Hand held ventilation readings in the model indicated airflow in the 100 ft./ minute range. This effectively increases the comfort zone for the residents up to an acceptable temperature of about 86ºF. This brings the few higher temperatures into a comfortable range for the residents of the model home. There is no such natural airflow in the control house and the conditions in the home remain in excess of the comfort range. An overall thermal comparison of the two houses was done and graphed for 3:15 pm and 5:15 pm on September the 17th, a particularly hot day. Both graphs [Appendix C1 and C2] explicitly reinforce the conclusion that the model house stays considerably cooler than the control house.

- These results are amplified when one considers the potential internal heat gain differences between the two homes. The model unit houses a family of seven, which includes five active children. The control house has two adults living in it. The internal gains due to more bodies, in higher levels of activity, with more cooking, dishwashing, TV time etc., puts a greater internal heat gain load on the model home.
- It can be concluded that both thermal barrier under the roof and natural ventilation throughout the living spaces provide thermal comfort in the model house. While the thermal barrier reduces the temperature dramatically during the day, in the attic and in the living spaces, natural ventilation flushes overnight heat-build-up of the living spaces in the mornings resulting in rapidly cooled spaces and adequate thermal comfort.

3.4. LIVING ROOM ILLUMINANCE

- An additional benefit beyond the fact that the model house's living room experiences cooler temperatures than the control house's living room, is that the illuminance levels are greatly superior at the model house's living room than at the control house's. Thus, the combined strategies used in the design of the model house allow for an increase in natural illuminance in the model house's living room without increasing the temperature to uncomfortable levels. Indeed, even with a considerable increase in solar illuminance, the model house remains consistently cooler than the control house by a few degrees.

3.5 FINAL COMMENTS

The model demonstration home effectively reduces electrical demand and improves the comfort level for the inhabitants. Due to the energy efficiency applications such as the solar hot water system and energy efficient lighting and appliances the home uses about 40% less energy and the family is saving over $650 a year on their electricity bills. When more homes are designed incorporating these principals, then Hawaii reduces its dependence on imported oil, reduces emissions from power plants and keeps millions of dollars in our economy.

This building is a comfortable and pleasant residence. While in the model home, one gets the impression that they have entered a comfortable, airy, well-lit space. The house exemplifies the potential that cost-effective, thorough design has on solving environmental issues and improving the quality of life for Hawaii’s residents.

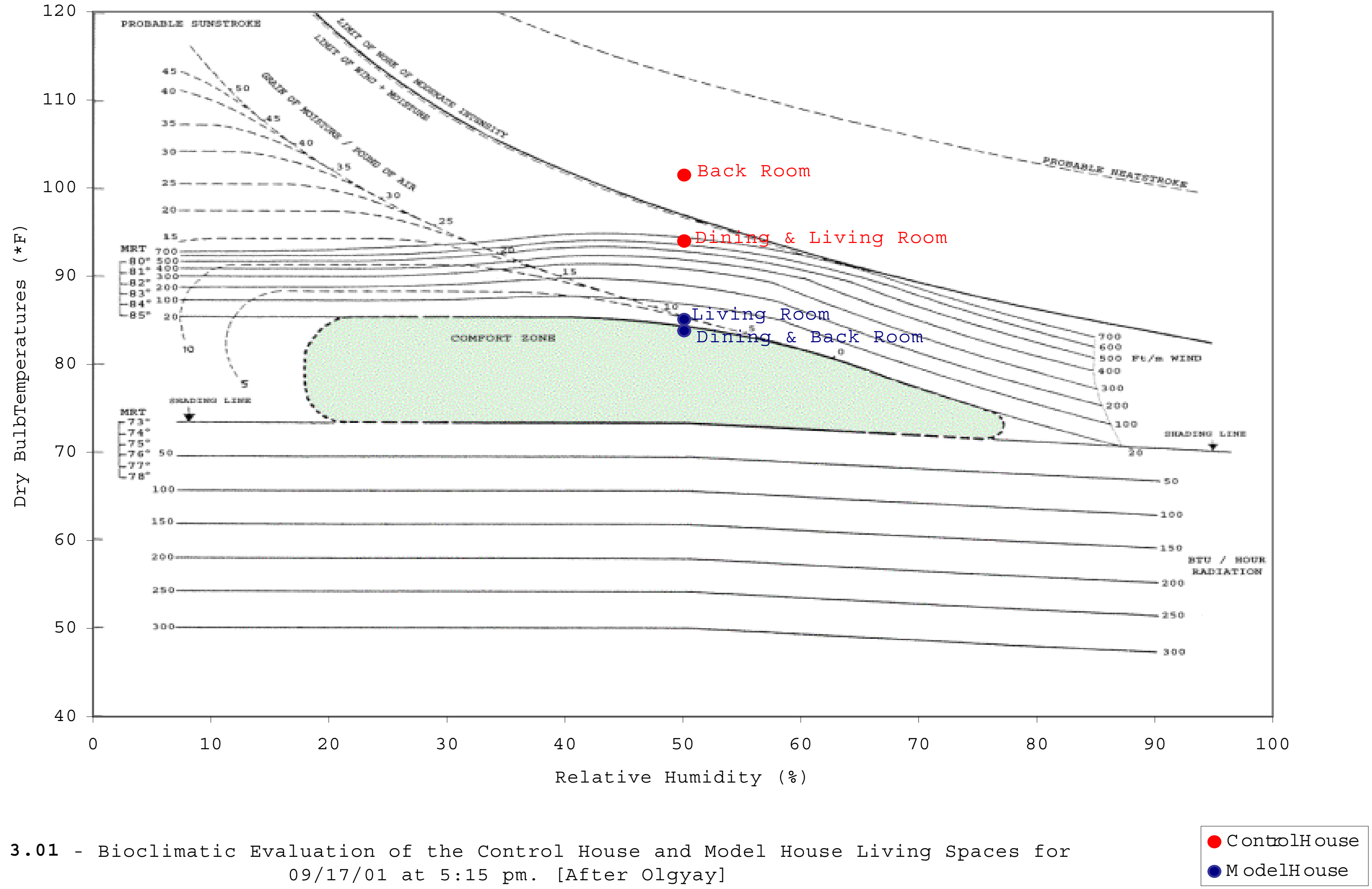
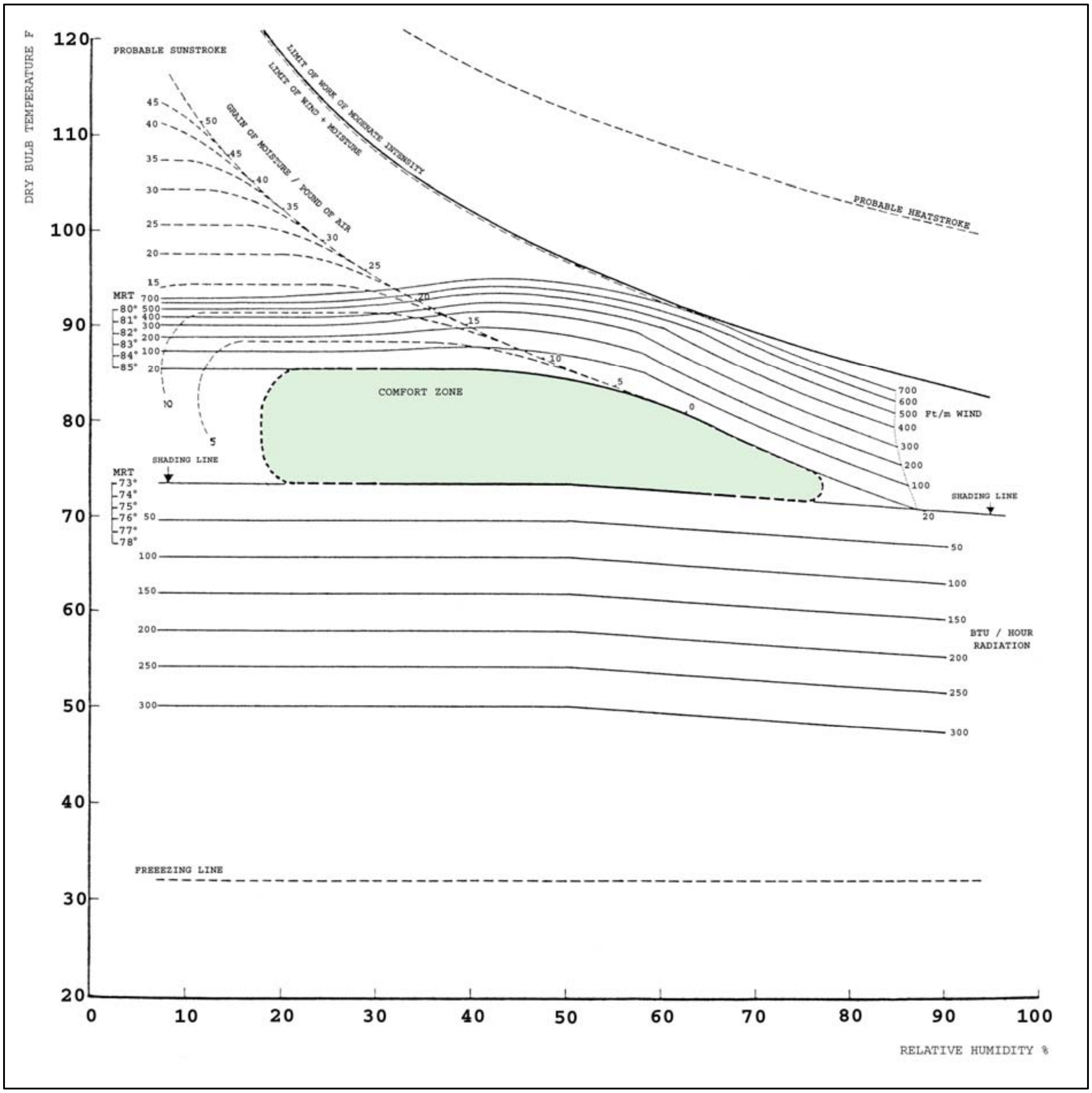


Fig. 3.01 - Bioclimatic Evaluation of the Control House and Model House Living Spaces for 09/17/01 at 5:15 pm. [After Olgyay]

APPENDIX A.
BIOCLIMATIC CHART FOR THE HONOLULU.

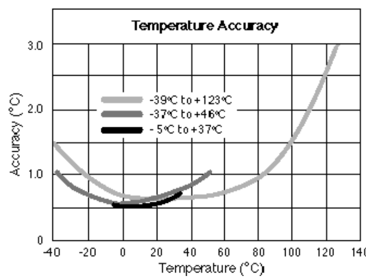


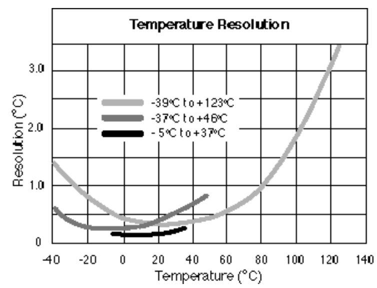
This chart was derived from V.,A. Olgyay, *Design with Climate,* and adjusted to the tropical latitude of the Hawaiian Islands.
Relative Humidity is read on the bottom axis while the temperature is read on the left axis. The airflow speed lines, drawn above the comfort zone, represent the extension of the comfort zone up to the respective airflow speed.

APPENDIX B.
INSTRUMENTS

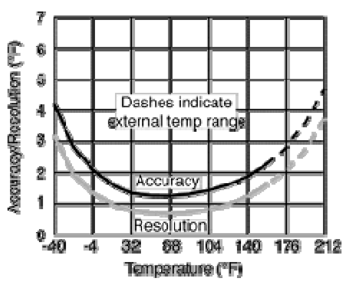
The instruments used for the monitoring of the two houses were Onset Hobo Data Loggers, as pictured bellow with their accuracy and resolution ranges. While most loggers recorded solely temperatures, the data loggers placed in the living rooms recorded temperatures, relative humidity and light intensity.

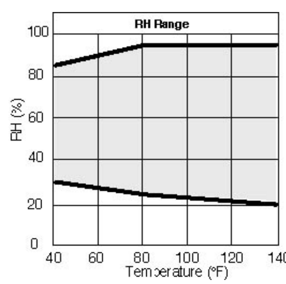
HOBO XT (Temperature):

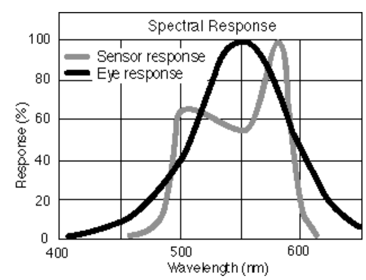




HOBO H8 (Temperature – Relative Humidity – Light Intensity):

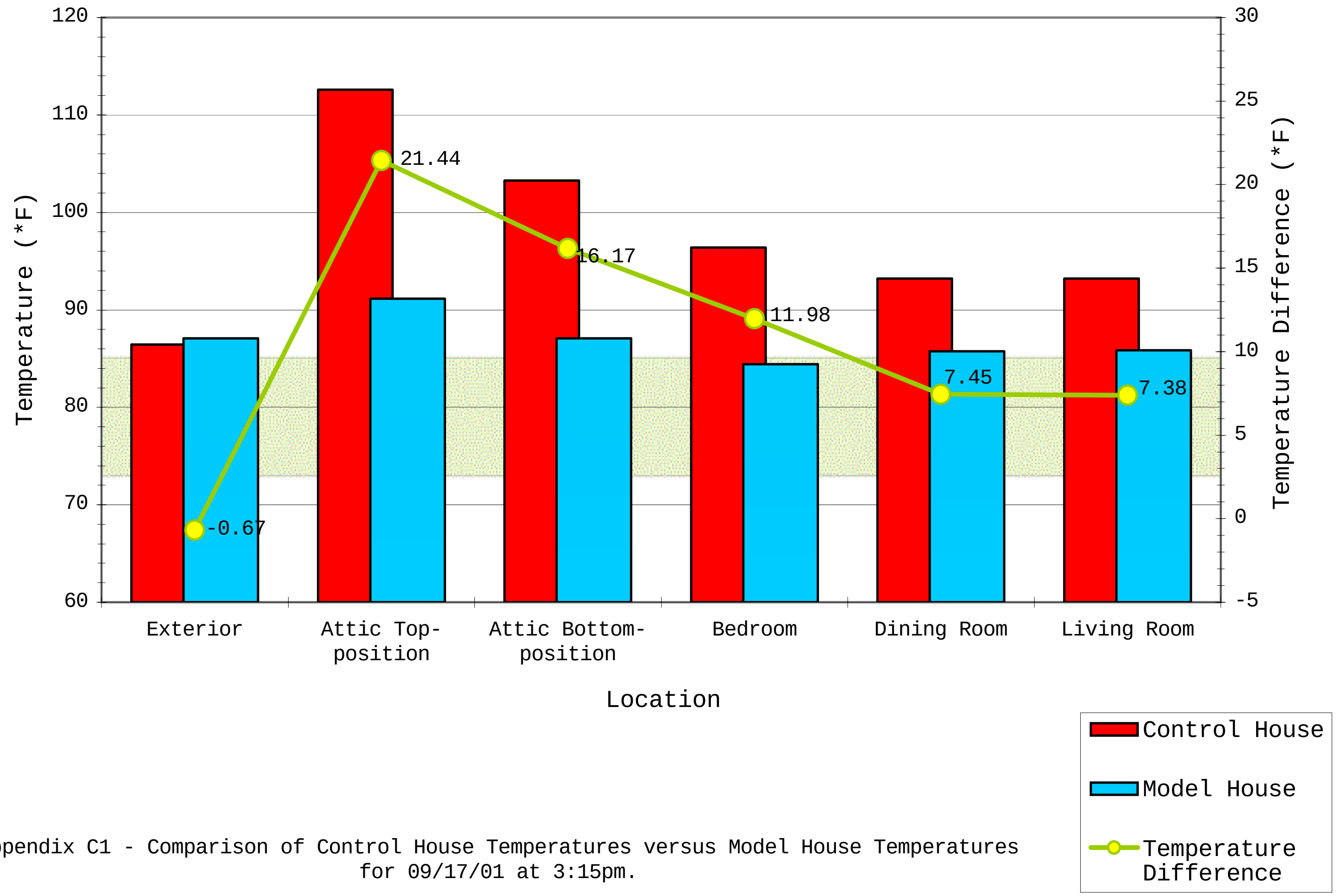




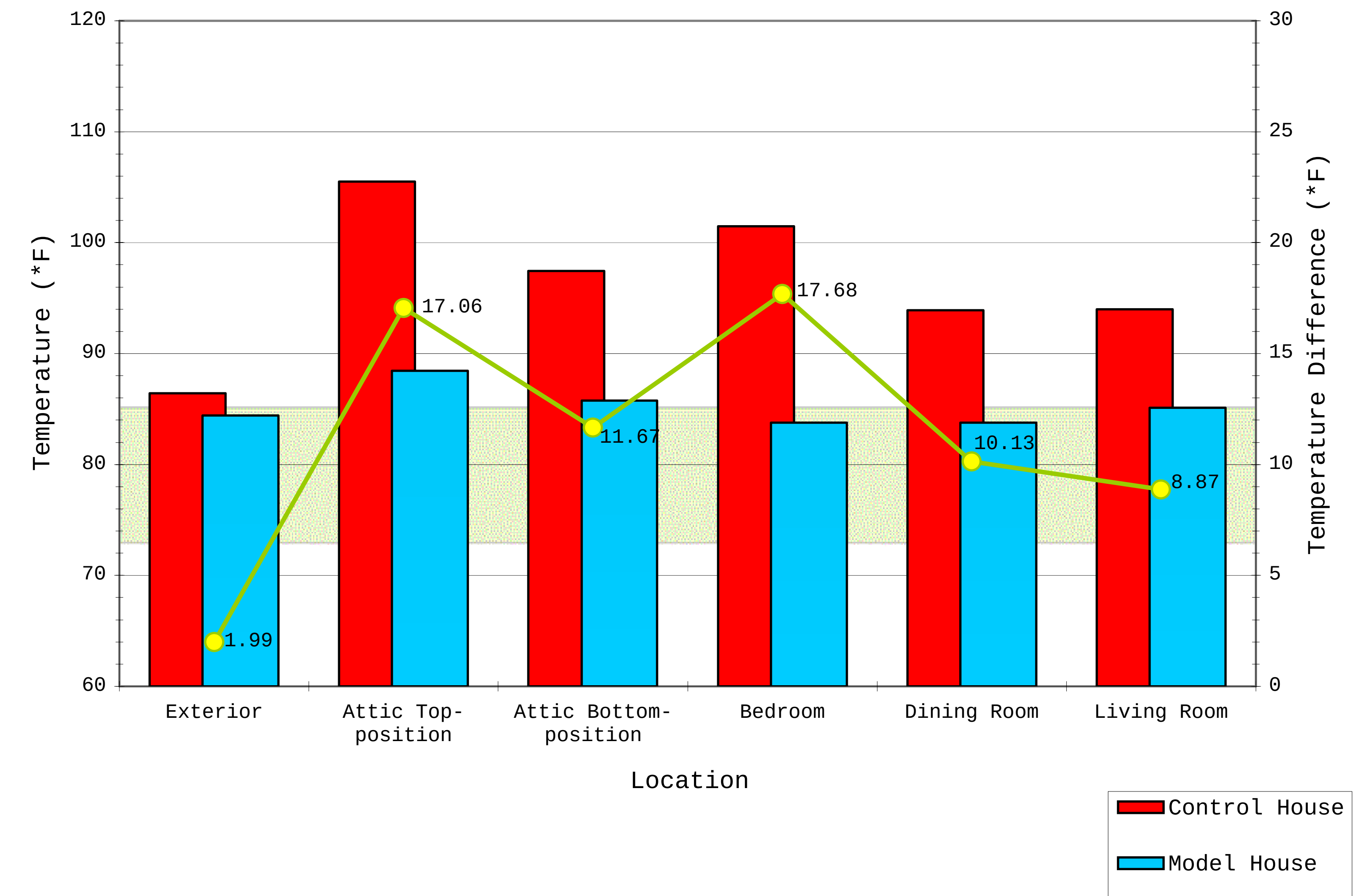


SOLOMAT ANEMOMETER

APPENDIX C - ADDITIONAL CHARTS



Appendix C1 - Comparison of Control House Temperatures versus Model House Temperatures for 09/17/01 at 3:15pm.



Appendix C2 - Comparison of Control House Temperatures versus Model House Temperatures for 09/17/01 at 5:15pm.