SYSTEMATIC TIME-BASED STUDY FOR QUANTIFYING THE

UNCERTAINTY OF UNCALIBRATED MODELS IN BUILDING ENERGY

SIMULATIONS

A Thesis

by

MUSHTAQ AHMAD

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2003

Major Subject: Mechanical Engineering

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ABSTRACT

Systematic Time–based Study for Quantifying the Uncertainty of Uncalibrated Models
in Building Energy Simulations. (August 2003)

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Co-Chairs of Advisory Committee: Dr. Charles H. Culp
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This thesis documents the usefulness and accuracy of uncalibrated simulations to determine for what end-uses these simulations should be used. The study was divided into three segments 1) comparison of the two simulation models, massless and advanced, against measured data 2) comparison of the results from two simulation models, simplistic and massless to determine the sensitivity of envelope shape and details for two weather conditions 3) identification of the parameters that have a significant impact on the simulation output.

Five buildings were selected as the test sample. Four of the buildings were multi story commercial buildings. The fifth was a single-family residential house. For the first segment of the study two simulation models were created for all the buildings; the massless model with emphasis on the envelope using massless construction and typical values for system parameters and the advanced model with the inclusion of thermal mass and extensive as-built details of the systems. For the second part of the research the simplistic model was created having a single floor one-zone with glazing and conditioned areas equivalent to the massless model. The sensitivity analysis was done using the massless model and selected variables from the loads and systems as sensitivity parameters.

By following the procedure mentioned, it was found that uncalibrated simulation models do not depict the real operating conditions of a building. For some cases the simulated values are higher than the measured data while for others they are significantly lower. The CV (RMSE) between the measured and simulated values ranges from 30 to

150%. From the comparison of the simplistic and massless model, it was concluded that the outer envelope shape and details have an impact on the heating and cooling energy use irrespective of the weather conditions. For internally load dominated buildings this impact is more on the heating loads than on the cooling loads. The conclusions from the sensitivity analysis were that outside air fraction and the total supply air have the most significant impact on the simulation output while thermal mass has a small impact.

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CHAPTER I

INTRODUCTION

The use of complex and detailed energy simulation software has increased tremendously in the past ten years as the focus is changing from energy production to energy conservation. The largest application of these software is in retrofitting i.e. the procedure of decreasing the energy use of a currently operational building by putting in high efficiency equipment, glazing or optimizing the operating conditions.

There are numerous simulation software available, some are public domain (DOE-2, BLAST) while other are proprietary software of different HVAC companies (TRACE from TRANE, HAP from CARRIER). Some software packages have a Microsoft^{TM} Windows based front end (Energy Gauge), which makes the input to the program simple as compared to programs in which complete input files are to be created with a particular syntax (DOE-2). The problem with front-end programs is that the user does not exactly know what parameters are being used and how many defaults are being incorporated into the model. This is the advantage of programs like DOE-2 in which the user has a clear understanding of what the inputs are and by intuition what the result is going to be.

The automation of manual calculation methods started in the 60's with the first one being the automatic version of the Degree Day Method. After that a long list of automated methods were created along with the formation of ASHRAE TC4.7 in 1975. Ayers and Stamper (1995) have chronologically elaborated the advances in this particular field.

The US Department of Energy (DOE), the US Post Office and the US Department of Defense were the main fund providers for the two main public domain software i.e. DOE-2 and BLAST. After the initial contribution of three or four national laboratories, the Lawrence Berkeley National Laboratory became the main contributor in the innovations and maintenance of the DOE-2 simulation program along with updating

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The format of this thesis follows that of the *ASRHAE Transactions.*

the software with new versions. The first, DOE-2.1A came out in 1980 and now the latest is DOE-2.1e (version 119), which came out in 2001. LBNL has also created auxiliary software packages, which help in the use and debugging of DOE-2. The most important software in this regard is the Draw BDL program (Joe Huang and associates 1993-94), which shows the input file as a graphical output detailing all the envelope description put in the text format.

The use of the DOE-2 and other simulation programs for predicting and verifying energy savings in different energy efficiency projects is increasing. However, the accuracy of the results obtained from these tools is questionable. HVAC BESTEST and HERS BESTEST are two of the procedures, which have been developed to test the accuracy of simulation software for particular cases. Each particular case has specific inputs related to building envelope and HVAC systems. These tests are being proposed as the standard for testing building simulation software under ASHRAE Standard 140P (Judkoff and Neymark 1999). The ASHRAE standard 140P is a guideline of how to test energy software. This guideline does not define any specific pass/fail or compliance criteria.

It is good engineering practice to use calibrated simulation models for the prediction and verification of savings (Schuldt and Romberger 1998, Haberl and Bou-Saada 1998). The extent of research in this field shows that the use of uncalibrated simulation is problematic. Simulation models are used extensively for the prediction and verification of energy savings in retrofit projects or even in new constructions. The inaccuracy of these models is common knowledge but until now no written document or literature has been published which quantifies uncalibrated simulation models.

The main scope of this research is to document the performance of five (5) uncalibrated simulation models. The DOE-2.1e Version 119 will be used as the simulation software for this research. This will be achieved by following a defined procedure of creating uncalibrated simulation models for five test buildings whose measured data is available. The simulation results will then be compared with the

measured values of whole building electric, chilled and hot water consumption. The chilled and hot water for the buildings is supplied by the central power plant

Three separate simulation models have been created for each test case. The time required to complete every single simulation model has been logged. This procedure was adopted to check the relative accuracy of simulation models compared with the level of effort (time). Of the three simulation models, one is designated as the massless model containing all the details of the envelope and the basic details of the HVAC systems, this model has massless walls i.e. in DOE-2 terms, Custom Weighting Factors are not calculated for each surface.

The second simulation model, named advanced, is more detailed then the first model. All exterior and interior surfaces are defined with correct geometries and construction. For the construction all the material layers are defined. So the envelope is not a massless U-value but the thermal storage properties of all the layers are being considered. For this custom weighting factors are calculated. In the systems portion all the different systems, which are being employed in the building for HVAC have been modeled and the zones have been divided accordingly. As for the zoning, it is the same in both models, an exterior perimeter zone and an inner zone. Increasing the number of zones in an internal load dominated building has no significant impact on the end energy usage (Hinchey 1991).

The time allotted to the base model ranges between twenty-two hours for very complex geometries to 6 hours for the residential house. This time includes procurement of drawings, walk-throughs, and the actual creation of the simulation model. After the completion of the massless model additional hours were put in to generate an advanced model. These additional hours are utilized to get more information and to enter more details about the building in the base model. The advanced model differs from the massless model in this aspect that it has all the surfaces geometrically defined and Custom weighting factors are calculated for each surface. It also has more details in the system portion of the model. Different system types, which are supplying conditioned air to different portions of the building, are defined separately. The airflow rate through

each zone is put in according to the information acquired from the engineer or the as-built drawings.

Another aspect, which is being investigated in this research, is what is the impact of envelope details on the loads portion of the input file. For this purpose the third model of each building will be analyzed, which has just one floor and equivalent area and volume of the complete building and the glazing. This model will be compared with the massless model for two different locations, one with high heating degree-days (HDD) and one with low HDDs. This comparison was performed to quantify the impact of the correct orientation, envelope details and the effect of the different envelope components on the output of the simulation model.

A sensitivity analysis was also performed. The emphasis of the sensitivity was on the system portion of the simulation model. The reason for this is that it has been shown that system parameters have a far greater impact on the overall result of the simulation model then the envelope or loads. Studies have been performed using Air Model simulation software (Wei et al. 1998) on defining guidelines about what parameters and to what degree they should be adjusted in order to calibrate a simulation model. This study has provided signatures of heating and cooling energy consumption for different design parameters. Signatures are characteristic curves depicting the variation of heating and cooling loads with the designated parameters. Some parameters from this study as well as additional parameters have been analyzed in simulations to identify which parameters have major impact on the output.

This thesis is divided in two main sections, the input file explanation and the analysis from the output of the three different simulation models.

Chapter II is the literature review encompassing calibrated simulations and sensitivity analysis, which are related with the current research. The remaining portion of the thesis is related to the explanation of the research procedure. Chapter III describes in detail the research methodology and the structure of the input file. This chapter also includes a list of parameters used for both the massless and advanced models as well as the time utilized in completing the different tasks related to the creation of the model.

Also included is the explanation of the weather data used. The third model (simple single floor), which is used to determine the effect of envelope details and the reason of using two weather files for evaluating the effect of high and low heating degree-days in relation with the envelope effects is also discussed. Chapter IV briefly describes the statistical techniques, which are used in the field of energy management along with some background on statistics.

Chapter V is based on output analysis. This describes the output variables and reports, which are used from DOE-2. The hourly reports are generated for all the simulations and the main parameters are the chill water consumption, hot water consumption and the whole building electric. In the case of John B. Connally Building the load on chiller is used since the building has its own power plant. The variables for the Habitat House are related with the furnace and the air-conditioner and the output reports are generated from the plants portion instead of the systems. The graphs used to elaborate the variations between the measured and simulated data, are scatter plots for the chilled and hot water, time series and 3D surface plots for the whole building electric. The statistical parameters explained in the earlier chapter are utilized here to elaborate the difference between the measured and the simulated values. The conclusion and recommendations make up Chapter VI while the simulation input files for the different simulation runs and the schedules used are provided in the appendices.

CHAPTER II

LITERATURE REVIEW

This chapter gives an overview of all the topics affecting the study of time-based accuracy of simulations. The in-depth review of the advent of building energy simulations have shown that most research has been done in two major areas-calibration and sensitivity analysis. Uncalibrated simulation models are widely used but have not been systematically studied.

This literature review covers the following areas:

- Background of energy simulation software
- DOE 2.1E simulation program
- Sensitivity analysis of building energy simulation models
- Graphical representation of the calibration procedure
- The use of calibrated building energy simulation models

Published literature from the above-mentioned areas, was acquired from the following conferences, journals and magazines.

- ASHRAE Transactions
- ASHRAE Journal
- Journal Solar Energy Engineering
- Proceedings of ACEEE Conferences
- Proceedings of IBPSA Conferences
- Energy and Buildings
- DOE-2 User News

In addition to these past theses and dissertations, which are related to the current research, have also been cited.

2.1 Background of Energy Simulation Software

This section reviews the background of energy simulations. The literature, which has been covered in this section include Ayres and Stamper (1995), Kusuda (1981), Kusuda (1999) Beattie and Ward (1999). The papers by Ayres and Stamper and Kusuda (1999) chronologically state the advent of building energy calculations, starting from the simple bin analysis to the modern hourly building energy simulations. Beattie and Ward discuss the advantages of the complex building simulation program available today and compare their results with the steady state methods, which were employed earlier. The other study by Kusuda (1981) compares complex simulation software with the T.C 4.7 endorsed simplified energy calculation procedure.

Serious efforts in the development of calculation procedures for energy requirements and thermal performance of buildings began in the 70s. This was instigated by the development in the computer technology and in part by the Arab oil embargo (Ayres and Stamper 1995). This study also chronologically tracks the advances in building energy calculations from the Degree Day Method to the detailed hourly simulation programs like DOE-2 and BLAST.

ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) has played a pivotal role in the advancement of energy calculations. ASHRAE Technical Committee (TC 4.7) was formed in 1975 for the purpose of enhancing research in the building simulation area. This committee also developed a simplified procedure for building energy calculation. Kusuda (1981) compared the outputs from the simplified energy calculation procedure endorsed by ASHRAE TC 4.7 to the advance simulation software available at the time. The premise of this study was that if the input details of a building are oversimplified then the results obtained from a complex model are similar to those obtained from simple energy calculation procedures. The analysts involved in this research found out the following discrepancies with the TC 4.7 simplified energy calculation procedure:

- Transient effect on controls are not included

- Morning ramp up and evening cool down cannot be simulated
- The building is to be oversimplified otherwise the computational efforts are exhaustive
- There is no incorporation of part load performance

The analysts also commented that the instructions and guidelines to use the TC 4.7 procedure were not properly laid out. Another thing was that the sample office building was made unrealistically simple and the given conditions did not depict real situation. The details of the building operations are not provided in the paper. The simulation packages used for this analysis included DOE-2.1, BLAST, ESAS, AXCESS, BLDSIM, E-CUBE and TRACE. The conclusions drawn from the study are that the T.C 4.7 simplified procedure produces similar results in comparison with detailed simulation software, if both the models are created by the same analyst and an average analyst can learn the simplified procedure in two weeks. It seems that the premise of this study is flawed because oversimplified inputs for any building will not result in accurate results so it does not matter whether a complex software is used or a any other method for energy calculations. If the T.C 4.7 simplified procedure was to be tested against complex simulation tools, the sample building should depict real situations. Another study completed by the AIA Research Corporation (1979) for four different types of building shows that the simplified procedure is 10 to 25% different from the detailed simulation packages especially for the heating loads. Conclusion from this is that the simplified procedure cannot match complex simulation software for real condition and should only be used for preliminary findings.

T. Kusuda (1999) describes in detail the changes and challenges that the field of energy simulation underwent from the early 1950's till now. This paper systematically goes through the important factors and organizations, which have been instrumental in the advancement of simulation software. This author explains how work was initiated on different fields related to energy calculations like psychrometrics, CFD evaluation of airflow and ground coupling models. The work done in these fields was then combined

to create complete simulation software which could predict the energy use of a building by employing the basic concepts of heat transfer and load analysis. However there are certain fields in which improvement can be made. These include the detailed micro scale analysis of building, thermo-physical problems and improvements in the coupling of different simulation models, which deals in the different aspects of the building operation and envelope.

In another study, K.H Beattie and I.C. Ward (1999) layout the inadequacies of using steady state calculations in place of dynamic simulation models. A case study building in Ireland was run with a steady state program based on the admittance method of the Chartered Institution of Building Service Engineers (CIBSE) which uses sinusoidal approximation for weather and thermal response factors which are based on 24-hour frequency. Then the same building was simulated with a dynamic simulation software whose details are not provided in the paper. Three zones were selected with different features to compare the loads and it was found out that the steady state model over predicts the loads anywhere from 30 to 90%, depending on the condition of the zone. The worst difference, 91% comes from the zone facing south. The conclusion is that the use of steady state methods oversize the plant considerably. The reason is that the plant is always designed for peak loads and from this study it shows the peak loads are being over predicted as much as 90%. So if a plant is designed on this basis it will always be working on part loads which compromises efficiency and performance of the equipment. The emphasis in this study is that to better design a building HVAC equipment, steady state methods should be avoided. The other thing, which is important, is that the designer should have correct information about the magnitude and occurrence of the peak heating and cooling loads and their variation over the season.

2.2 The DOE-2.1e Simulation Program

This section covers the explanation and development in the DOE-2 simulation software. This section also includes the papers by Kusuda (1999) and Ayres and Stamper (1995). This section also includes the paper by Crawley et al. (1997), which describes

the advancements in the two main public domain software, DOE-2 and BLAST. For explaining the basic structure of DOE-2, different editions DOE-2 user news and the DOE-2 reference manuals have also been cited.

The DOE-2 simulation software has its roots in a sophisticated energy calculations program developed by GARD/GATX (T. Kusuda 1999). The Lawrence Berkeley National Laboratory (LBNL) was later given the responsibility to maintain, document and develop the software. The lab has generated five versions of the DOE-2 program along with numerous revisions (LBNL 1993a, LBNL 1993b). The latest is DOE-2.1e (version 119) has the ability to simulate a thousand zones (DOE-2 User News 2001). The DOE-2 simulation software is by far the most widely used software in the industry with a number of different non-standard versions available. The latest addition to this is the web based DOE-2 simulation software called the Home Energy Saver, developed by Lawrence Berkeley National Laboratory (LBNL 1998). It can be used to determine the energy consumption of single-family residences. There are advantages to a web based simulation package. The distribution cost is minimal, no need for redistribution after an upgrade since all the changes are made on the host server. However there are certain restrictions associated with this application. First of all it can only be used for single-family residences. There are a limited selection of envelope details and glazing which can be used for simulating the residence. The accuracy of results depends on the extent of defaults used. On the same lines as the Home Energy Saver, the Energy Systems Laboratory has launched its own web based simulation program, Emissions Reduction Calculator (2002). The first version of this software is restricted to residential buildings in the Houston area. Further developments are underway to expand this program to all the counties in the state of Texas.

Since 1960 the U.S government has continuously supported two building simulation software, DOE-2 and BLAST (Crawley et al. 1997). DOE-2 originated from the GARD/GATX energy calculation procedure, which was used to create the energy program for the United States post office. BLAST, sponsored by the Department of Defense (DOD), emerged from the NBLSD (National Bureau of Standard Loads

Determination) program developed at the National Bureau of Standards (now NIST). The basic difference between these two programs is the load calculation scheme; DOE-2 uses a room weighting factor approach while BLAST uses a heat balance approach.

The DOE-2 simulation software, as mentioned in the last paragraph, works on the Weighting Factor Method (WFM) developed by ASHRAE (Mitalas and Stevenson 1967, Mitalas 1969). The WFM uses a two step routine to calculate the cooling load; first it uses the response factor method (RFM) (Mitalas 1969) to calculate the heat transfer through all the surfaces, which is the base of BLAST, then these gains are modified by weighting factors to get the cooling and heating load. Different sets of weighting factors have been generated for typical building construction through the basic laws of heat transfer. The problem is that the weighting factors being used were calculated for different generic building operations. So these factors may not match the operations of the building being simulated. This can induce some errors into the simulation model (Ayres and Stamper 1995).

The system simulations in DOE-2 simulate HVAC systems based on the heating and cooling loads, which are using the inputs in the loads portion of the simulation. The user has a choice of selecting from a variety of HVAC systems depending on which system most closely matches the actual situation. Every system has its own set of DOE-2 commands, which better simulate the model to the actual working of that particular system. The DOE-2 is a quasi-steady state model (Ayres and Stamper 1995), since the minimum time step it can simulate is one hour. It means that the system response, if it is changing within the hour, will not show up in the model, but the changes will be registered hour by hour. Also, most of the time the HVAC system is working at part load. So, for this purpose DOE-2 and almost all other sophisticated software use polynomial curves to predict the part load performance. Figure 2.1 shows the flow diagram of the DOE-2 software.

DOE-2 also has the ability to simulate a host of different plant schemes with the HVAC systems defined in the systems portion of the input file, ranging from a simple plant consisting of a hot water boiler and a chiller to highly complex combined cycle and
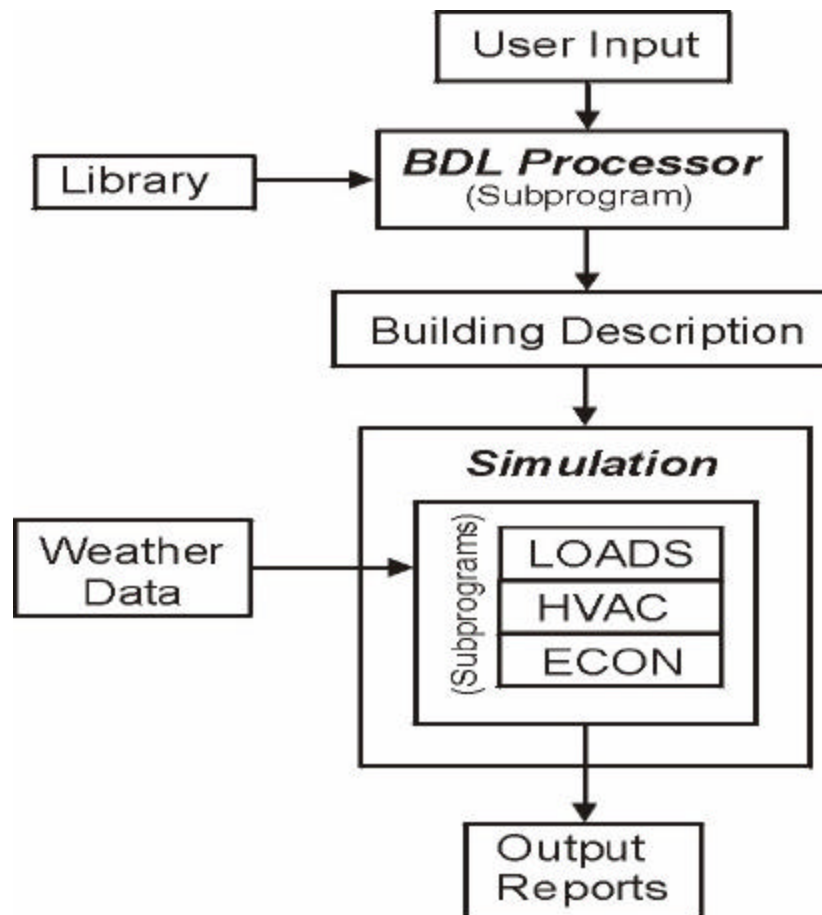
Fig 2.1 DOE-2 flow diagram (www.gundog.lb1.gov)

cogeneration plants with user defined turbines and boilers. The performance and operation of all these different equipment is governed by polynomial curves, which are available as default in the DOE-2 simulation. Provision is provided so that the simulator can enter his/her own curves for any specified equipment through the prescribed commands (DOE-2 reference manuals). The "functions" command gives great flexibility in simulating a wide variety of equipment and conditions. One such example is the simulation of a fuel cell using a function command related to a gas turbine model. This is

done by changing the coefficients of the default performance curves of the gas turbine with user defined numbers related to the fuel cell (Building Energy Simulation User News, 19(3)).

The economics portion of the DOE-2 simulation program is a very detailed and comprehensive tool for determining the economic feasibility of the designed system. It can also be used to determine the savings if the model is being used to evaluate retrofit performance.

2.3 Sensitivity Analysis of Building Energy Simulations

This section covers the research, which has been done in sensitivity analysis. The paper which have been covered in this section are Shaviv and Capeluto (1992), Jones and Hepting (2001), Corson (1992), Kaplan et al. (1992), Mahone et al. (1992), Lam and Hui (1996). The sensitivity by Shaviv and Capeluto emphasized the importance of envelopes in hot climates. Hepting and Jones studied the importance of correct orientation and layout of building being simulated in DOE-2.1e. Corson completed a sensitivity study on a bigger scale and compared 25 loads and systems parameters for two climatic conditions. Kaplan et al. have derived the guidelines for energy simulation models, including a list of system parameters, which have significant impact on the simulation. Mahone et al. completed a sensitivity analysis for five different weather conditions and studied the effect of several parameters in relation with the climate. Lam and Hui completed a sensitivity study on a commercial building in Hong Kong. 60 parameters were chosen from the different portions of the simulation software to determine what parameters have high impact on the output.

The study by Shaviv and Capeluto (1992) investigated the importance are the envelope details in creating a model of an apartment building. The simulation model used was written by the authors and is a time dependent model. The model simultaneously solves the heat transfer through all the surfaces and the time dependent equation uses this information to create an implicit finite difference set up which can be solved numerically. The variables scrutinized in this study were all related to the

building environment like the building materials, building color, area and orientation of windows and infiltration. It was concluded that the glazing has the most influence of all the parameters. The glazing can increase or decrease energy use from anywhere between 10 to 30%. As for the other parameters, the output is not really sensitive to the U-values and infiltration. However, Shaviv and Capeluto (1992) used their own code to conduct this research, so it cannot be verified.

The research by Jones and Hepting (2001) specifically addressed the importance of the orientation and definition details of the DOE-2.1e simulation software and how much it affects the complete simulation model. The results are based on the comparison of annual energy use and peak loads. This study basically compares the two methods by which the outer envelope can be defined in DOE-2.1e. One is the basic geometric approach in which all the surfaces are defined irrespective of the correct orientation. The other one is the complex XYZ approach, in which each surface and layer of the envelope is defined so that the model is exactly depicting the real building. The study was done on two buildings of different proportions, at two different locations in Canada. Six different runs were performed for each building, starting by creating a model with the complex XYZ approach and finally simplifying it to the basic geometric approach. It was found out that the total energy use does not drastically change. It was also concluded that the cooling load is influenced most by correct geometry and orientation. Since the study was performed in Canada with a very small number of cooling degree-days, it cannot be said how influential the correct orientation and complex geometry would be in a climate with high cooling degree-days.

Another sensitivity study (Corson 1992) did the same analysis on a broader scale by considering system parameters as well as parameters from the loads. Twenty-five parameters were selected from different portions of the input and the simulations were run for two different buildings. The two buildings selected were different in climatic conditions; one with 4726 65°F Heating Degree Days (HDD), while the other was in a climate with 4892 65°F HDD. Five simulation software programs were used to generate independent models of the two buildings in accordance with the details provided. The

program are: (The first four are proprietary while the fifth is a public domain simulation software program)

- ADM-2 4.1(R) (ADM Associates)
- SEA 6 (Ferreira and Kalisinski)
- TrakLoad 3.1 (Morgan Systems)
- VCACS 9.10 (Volt Energy Management)
- DOE-2.1 C/D (Lawrence Berkeley National Laboratory)

The key finding was that the overall energy use is influenced more by system parameters than by envelope design parameters. The system parameters can change the annual energy use from 10 to 80% as compared to the loads and envelope details where the maximum change is below 30%, caused by occupancy load and schedule. A better study would have been to use a single software program and simulate more than two buildings.

Kaplan et al. (1992) have published generalized guidelines to help building energy simulators in the process of creating a better simulation model. These guidelines have been created by gaining experience in the DOE-2 simulation software during the Energy Edge program. This program was funded by Bonneville Power Administration to evaluate individual energy conservation measures in 28 commercial buildings, which were constructed to demonstrate cost effective energy conservation measures with no loss in occupant amenities (Center of Building Science News # 1, 1993). These guidelines are based on a detailed study in which calibrated simulation models were created for 27 test buildings. A part of this analysis was published earlier (Kaplan et al. 1990). This paper is discussed further in the calibrated simulation model section of this chapter. In these guidelines, the author has also identified different input parameters, which according to the author, can be a major source of error if these variables are assumed or inputted incorrectly. These variables include equipment power density, schedules, window and wall U-values, shading, thermal mass and infiltration. The main

objective of these guidelines is to document that there is uncertainty about using computer simulation for savings estimate from Energy Conservation Measures. However following these guidelines and the prescribed values can lead to the creation of better simulation models.

Mahone et al. (1992) performed another sensitivity study for the California Energy Commission (CEC). Five different weather sites were chosen, ranging from moderate to extreme and the same prototype commercial building was simulated for the five weather conditions. Four groups of parameters were chosen as the sensitivity variables. It was concluded that climatic conditions are important in determining which parameters have more impact then others on the simulation output. For example, in hotter climates, the use of economizer has minimal effects as compared to moderate climates, where up to 30% of energy can be saved by its utilization.

Lam and Hui (1996) give a very detailed description of a complete sensitivity study on a commercial building in Hong Kong along with the definition of five different sensitivity coefficients, which can be used to determine the relative importance of one parameter compared to another. The parameters whose sensitivity was to be evaluated were grouped according to the divisions of a typical DOE-2 input file i.e. building loads, HVAC system and HVAC plants. 13 variables were used as sensitivity parameters for this study. From the results it showed that the most influential parameters are the chiller COP and the outside air cfm. The variation in these two parameters can result in a difference in energy consumption from anywhere between 10 to 30%. Other parameters like thermostat set points, chiller supply temperature, window to wall ratio cause changes but the impact below 10%.

2.4 Graphical Representation of the Calibration Procedure

Use of graphical techniques to analyze simulation output is an important factor in building energy simulations. This can have a major impact on the final output, especially with of DOE-2. Arranging the hourly data into a suitable format is a time consuming task. Application of visual techniques i.e. different type of graphs is the best solution for

hourly data analysis. Scatter plots, time series and 3-D plots are normally used for this purpose.

The papers discussed in this section include two papers by Haberl et al. (1992). One of the papers discusses the use of statistical software for the generation of 3-D surface plots for the whole building electric. The second paper explains the procedure of calibrating a model by comparing simulation graphics against the actual metered weather data for the site.

The early research and the 3-D plots using DOE-2.1c simulation software have been reported by Haberl et al. (1992). The statistical software SAS was used to set up an automatic routine which was able to extract the output data from the DOE-2 output and then form a matrix to create the required plot. Nowadays with the advancement of the computers as well as the availability of user-friendly and advance software all this can be done within a very small time frame. With just a few basic commands of any computer language, data can be extracted and then any graphical software can be used to generate the plots.

Another paper by Haberl et al. (1992) reported creation of a procedure for calibrating a simulation model by comparing the simulation graphics with the actual metered weather data. For this purpose a cluster of mini computers was set up. In addition to DOE-2, graphical and spreadsheet software were used to extract data and create different types of plots. The plots were then compared with the measured data to determine whether the model has been calibrated or not. Another thing in this project was that actual weather data of the site was taken. The weather processing techniques provided with the DOE-2 software were used to create a TRY (Test Reference Year) weather file with the actual site data. This step removed the variability resulting from different weather conditions. The result is that when a packed TRY weather file is used the percentage difference is 11.3 as compared to 11.6 for a TMY (Typical Meteorological Year) weather file. Major differences occur for peak heating and cooling where the difference between the two runs is from 10 to 30%.

2.5 The Use of Calibrated Simulation Model

  Extensive research has been done in the field of calibrations. Ranging from automated calibration procedures to the statistical aspects of calibration, there have been a number of studies striving to define a single standard procedure for calibrating a simulation model.

  The paper discussed in this section include Schuldt and Romberger (1998), Haberl and Bou-Saada (1998), Kreider and Haberl (1994), Soebarto (1997), Arney (1994), Yoon and Lee (1999), Kaplan et al. (1990), Katipamula and Claridge (1993), Wei et al. (1998). Schuldt and Romberger explain three methods of creating an accurate baseline and also for better calibrating the simulation model. Haberl and Bou-Saada explain in detail the statistical techniques, which are required to calibrate a model. It also gives a list of requirements and information needed to create a calibrated simulation model depicting the actual operation of the facility. The paper by Kreider and Haberl gives the details of the contest held to come up with the most accurate method for calibrating simulations. Soebarto discusses the importance and the resulting accuracy of a simulation model calibrating using short term measured data. The papers by Arney and Yoon and Lee also emphasize the importance of short-term measured data and utility bills in calibrating a simulation model. The study by Kaplan et al. is a very detailed discussion of the procedure followed and the statistics used to calibrate simulation model under the Energy Edge program. Katipamula and Claridge discuss the use of an airside simulation model to calculate the energy savings due to a VAV retrofit. Wei et al. discuss the calibration process by using system analysis tool and then generating generic results, which can be used for calibrating models.

  A study by Schuldt and Romberger (1998) put forward three methods for better calibration of hourly simulations. First the authors go through the different methods of defining a baseline. These methods are:

- Pre-period characteristics, which use the pre-retrofit operating characteristics of a building to create a baseline. This method can only be used for retrofit projects.

- Control building characteristics, which uses the pre-retrofit operating characteristics of a building, which is similar to the building understudy. The accuracy of this baseline depends on how well the control or reference building operations match with the building under study.

- In measure removal method, simulation model is created with the energy conservation removed to depict the pre-installation conditions. However the baseline created in this manner may not depict the actual pre-retrofit conditions.

- Reference characteristics means that the operations of a building are being compared to a standard reference like a building code, energy code or common practice of a particular state.

The authors also emphasize the importance of the quality of available measured data to be used for the calibration process, which can then be used to determine savings in a retrofit project. Calibration can be done by using a single annual energy consumption value, monthly average or the detailed hourly profiles of the consumption. Maximum accuracy is achieved by using the hourly profiles. The resulting calibrated model comes within 3 to 5% of the monthly end-use measured data. The three methods of calculating energy savings are:

- Test/reference method is used for new construction and uses a reference building as the pre-installation condition. For the case study, accuracy of within 4% of the measured monthly energy consumption was achieved.

- Before/after method is for retrofit projects. The test building itself acts as a reference. Two separate calibrated simulations for the pre and post

retrofit periods are created and compared. For the case study building accuracy of 15% with the measured monthly consumption was achieved.

- Measure removal method is used both for new construction and retrofitting. As already discussed, the baseline is created by removing the energy efficiency measures from a fully calibrated post-retrofit model. Then each of the retrofit is added again. The energy savings are calculated from the difference in energy consumption between the baseline and the simulation model with the retrofit. The baseline as discussed may not depict the correct operations of the building before the retrofit. The accuracy is 30% of the monthly HVAC consumption of the baseline model.

The conclusion from the study by Schuldt and Romberger (1998) is that several methods, which are available for measuring savings, have different applications. The accuracy range varies from 5% to 30% of the baseline simulation model or the measured baseline, depending upon the method used.

A paper by Haberl and Bou-Saada (1998) explains how the hourly output from a simulation program can be depicted through different graphical techniques. This study also explains which statistical parameters are important in describing a goodness of fit than just simple residual techniques used in many projects before this study. Finally it explains the different calibration steps used to fit the simulation model to the actual data. This paper states that the combined analysis of the Coefficient of Variance of the RMSE, CV (RMSE) and the Mean Bias Error, MBE, is a better judge of the goodness of fit of the model to the measured data. The fully calibrated model for this study had a CV (RMSE) of 23.1% and MBE of –0.7%. This value according to the authors is reasonable since earlier study by Kreider and Haberl using artificial neural networks (1994) came up with a CV (RMSE) within 10 to 20%. The further reduction of this value required major changes in the schedules for occupancy. This study also gives a very intensive list of procedures and information required to create an accurate model. The list includes

that as-built drawings, schedules (equipment, lighting, HVAC system), indoor temperatures for all zones, blower door test data, details of exterior shading and six to nine months of measured whole building electric, heating, cooling and equipment end use data.

A study by Soebarto (1997) illustrates a contrasting view by stating that the reasonable accuracy of simulation models can be achieved by utilizing a very short term set of measured data (two to four weeks) as compared to six to nine months for the study by Haberl and Bou-Saada (1998). This approach is feasible for small-scale, low budget retrofit projects. The study was done on two buildings situated in College Station, Texas. The main emphasis was to correctly measure all the internal loads including occupancy, lighting, receptacles and fan energy use, obtained by subtracting lighting and receptacles from the total load. The simulation software used for this research is ENERWIN, of the department of Architecture, Texas A&M University.

The results show that the whole building electric and the internal loads from the simulation model compare favorably with the short and long term measured data and the CV (RMSE) is less than 20%. However the difference in monthly chilled water when compared with the yearly measured CHW usage, ranges from 5% in summer to 45% in winter. This shows that the model calibrated using short-term measured internal loads data is not predicting the monthly chilled water usage. It can be concluded that short term measured can be used for calibrating if there are budget constraints or the project is on a small scale. But if accurate energy savings analysis is required then calibration of a simulation model should be based on long term measured data including whole building electric, heating and cooling loads as well as operating schedules of the particular site.

The study by Arney (1994) gives a general outline as to how short term measurements can used to create hourly schedules for all types of internal gains. The schedules are then used for calibrating the simulation model. This methodology is both time and cost effective, and can be readily applied in areas where the retrofit savings do not amount to a large sum. A case study from the FEMP (Federal Energy Management Program) Super ESPC (Energy Savings Performance Contracts) Program was used to

elaborate the procedure. Eleven energy conservation measures were considered for the case study by using the DOE-2 simulation software and comparing its results to the short term measured data. It was found out that just the lighting retrofit was coming out to be cost effective with a payback of 4 years. So it is feasible to use short-term data for retrofits like lighting. The conclusion from the study is that calibrated simulation models are becoming more and more popular in the field of performance contracting because of stringent time constraints and cost effectiveness.

A study by Yoon and Lee (1999) focuses on the use of monthly utility bills and utility meter reading for accurate calibrations where hourly data is not available. This method is being used to check the feasibility of different energy conservation measures on a high rise building in Korea. This study basically explains the seven steps, which are considered to be mandatory by the authors to get a better understanding of the energy use of a building and the investigation of the feasibility of the energy conservation measures proposed. The emphasis is on creating a base model, which has all the physical details of the actual building and then putting in all the internal loads based on wattmeter readings and utility bill analysis. The first calibration is done after these two steps to make sure that the model follows the heating and cooling profile by tweaking the plug loads and lighting. After this step, another site visit and interview with the personnel insures the right values for all the schedules and HVAC equipment, and then the model is calibrated according to these new values, and further different runs are added for different ECMs to check their feasibility. By following this procedure the authors were able to come with a CV (RMSE) of 3.6% for electric 22.7% for gas. The MBE was 2.3% for electric and –15.8% for gas. The values are good for electric but are on the high side for gas.

Another study by Kaplan et al. (1990) was conducted as part of the Energy Edge Program sponsored by a Bonneville Power administration. This program is undertaken to analyze the cost effectiveness of individual energy conservation measures (ECMs) for 28 buildings. These buildings were constructed in the Pacific Northwest to demonstrate cost effective energy savings with no loss in occupant amenities (Center of Building

Science News # 1, 1993). A test study on a small office building is presented in the paper. DOE-2.1c simulation software was used to create a calibrated and baseline model of the building. The different aspect in this study was that the model was tuned (calibrated) zone by zone. This is a very exhaustive procedure and the author himself acknowledges that this is only feasible for a detailed research study. The calibration process was not completed for the entire year. A peak winter month (February), a peak summer month (July) and a temperate month (October) were chosen to compare the simulation results. Nine iterations were performed by changing a number of variables in the input file like lighting and receptacle load, infiltration, infiltration method, thermostat schedule, setpoints, throttling range, fan schedule and material properties. Monitored data and as-built information was used to create an as-built model of the building with the ECMs incorporated. This model was then converted to baseline by removing the ECMs and replacing the site-specific weather w1ith standard TMY weather. This step is not clear, because the TMY tape may not depict the weather conditions of that particular site. The conclusions drawn from this study were that:

- Comparing simulation model and monitored data on an end-use hourly basis can be used to detect gross errors in modeling. Even a finely tuned does not ensure that the savings estimated from it are accurate.

- There is no concrete rule to define what tolerances (% deviation from the measured data) should be used to judge the accuracy of the model. Tolerances within 5% are achievable for loads, which can be accurately measured like lighting and equipment.

- For heating and cooling loads the tolerances are 20% for monthly averages and 30% for daily averages.

This study by Kaplan et al. indicates that even when using calibrated simulation models, there is uncertainty in calculating savings from ECMs. So it can be inferred that uncalibrated simulation models should not be used to predict energy savings or building.

Extensive research has been done on the use of simplified energy models, which can be easily calibrated as compared to intensive models like DOE-2 and BLAST. One study (Katipamula and Claridge, 1993) uses a simplified model to predict the energy savings in a building due to a VAV retrofit. The model uses the ASHRAE T.C 4.7 SEAP (air-side system) (ASHRAE Technical Committee 4.7) to perform the load and VAV system calculations. For this, no pre-retrofit data was available so two models were created. One model was created for VAV and calibrated with post-retrofit data. The second model was created for DDCV system and calibrated loads from the VAV models were used because of the absence of pre-retrofit data. The VAV model was calibrated within 7% for daily consumption and 20% for hourly consumption. The conclusion is that the ASHRAE T.C. 4.7 SEAP is a good option for creating calibrated simulation models using post retrofit data and predicting retrofit savings when pre-retrofit data is not available.

To help simplify the procedure of calibrating simulation models, especially the HVAC system simulation models, calibration signatures were produced by Wei et al. (1998) using the Air-Model software created at Texas A&M University. By calibration signatures it means that different parameters like outside air flow, supply air, hot and cold deck temperatures are changed in a controlled set up and the effect of these changes on the hot and chilled water consumption are depicted graphically. These signatures can serve as a guideline for calibrating simulation models. These also indicate the importance of different system variables. However, the research was done using Air-Model, any other simulation program may not show the same sensitivity to the variables which were studied.

2.6 Summary

This chapter provides an overview of the research fields, which have a connection to the current research. The main portions of building energy simulations discussed are the background, the DOE-2 simulation software, the numerous ways of

doing sensitivity analysis, graphical representation of the hourly output from DOE-2 and the importance and applications of calibrated simulation models.

In the past twenty years there have been major improvements in the performance and increased sophistication of simulation software. Steady state methods like Degree-Days and Bin Analysis have given way to hourly simulation model like DOE-2 and BLAST (Building Systems Laboratory, University of Illinois Urbana-Champaign) (Ayres and Stamper). The innovations are continuing in this field and more advance simulation software programs with time steps less than an hour are available (Energy Plus, Department of Energy). The use of neural networks and artificial intelligence for energy simulations is also increasing and accuracies in the range of 1% are being reported (Marshall 2002), it was actually back in 1987 that an expert system was first devised to measure the energy use through knowledge based techniques (Haberl and Claridge 1987).

Even with the advancement in this field, the DOE-2 simulation software still remains one of the most powerful and frequently used tools. Although it is now more than twenty years old, the LBNL team ensures that the software remains up to date in all aspects and updated versions are periodically released. The latest version is 119 of the DOE-2.1e and it is complete with its own set of manuals and updates. This software is public domain. The engineer creates the input file so all the inputs can be traced back to the source. In comparison, many new simulation software programs, which have a graphic user interface, ask the user for a few parameters and the user never finds out how many defaults are being used for the simulation.

The sensitivity analysis of the DOE-2 simulation software is extremely important because the complete program contains a large amount of input variables and it is not possible to specify all the variables because of time and monetary constraints. Extensive research has gone into different studies focused on different parts of DOE-2. This range from zoning (Hinchey) to geometrical interpretation (Hepting and Jones 2000) to effect of different parameters with change in weather conditions (Mahone et al. 1992). From all these studies it can be concluded that a complete sensitivity analysis is not possible

because each variable behaves in a different fashion for various conditions. Another conclusion is that system parameters have more effect on the output than the loads and envelope portion.

The use of graphical techniques with the DOE-2 simulation software is important. These techniques are used to determine the variation of the model from the actual data. To better visualize a large number of data points, it becomes necessary to use 3-D, box-whisker and other types of intensive graphical software to judge the accuracy of the model (Haberl et al., 1988).

The majority of the research in building energy simulation has been done on calibrations and the advantages of calibrated models. Most of the research has been done on calibrating a simulation model to hourly measured data in order to minimize errors (Haberl and Bou-Saada 1998, Bronson et al. 1992), but there have been studies, which advocate the use of short-term measurement or the values from monthly utility bills (Soebarto 1997, Yoon and Lee 1999). The conclusion is that if the energy savings calculations are required to have less than 15% error, then it is necessary to used simulation models calibrated to hourly measured data. Because calibration to monthly averages or utility bill analysis results in errors in the range of 20 to 30%. This alternative can be used for buildings that do not have data acquisition facilities (Yoon and Lee 1999).

There are other topics related to building energy simulations, like the validation of different simulation software, and the impact and explanation of the different weather files, which can be used with DOE-2 simulations. These topics are not discussed in this chapter in detail but will be referenced in different portions of the thesis as required.

CHAPTER III

METHODOLOGY

3.1 Building Description

The aim of this research is to document the accuracy of 5 uncalibrated simulations. For this purpose five buildings have been chosen as a test sample. Four are commercial buildings with different end-uses, ranging from offices to classrooms and laboratories. The fifth is a single-family residential house located in Bryan, Texas. All the four commercial buildings are located in College Station. Three of the buildings are on the main Texas A&M University campus. The buildings are:

- Wisenbaker Engineering Research Center (WERC)
- Harrington Tower
- Wehner Business Building
- John B. Connally Building
- Habitat House

WERC is located on the east side of the main campus of Texas A&M University. It was built in 1983. It is a 177,074 square foot building with three floors and a basement. The construction is of high mass with concrete floors and basement walls of poured concrete. The basement was converted to offices from an underground garage in the 1990's. Today the building houses offices of different research organizations. It addition to that it also has a number of different laboratories including a very large material testing lab which is a separate structure constructed of sheet metal. The heating and cooling system consists of ten air handlers, both constant volume and variable air volume. Of these two air handlers are completely fresh air handlers supplying the basement. In addition to this forty fan-coil units are also used for conditioning the basement.

Harrington Tower is an eight-story office building. It also has a basement, which is used to house the system equipment. It is also located on the main campus of Texas A&M University. This building was built in 1973. The total conditioned floor area is 130,844 square feet. It is essentially an office building housing the offices of different academic department as well as student counseling. This building has generic operations of a typical academic and office facility. The HVAC system consists of one dual duct air handler, which supplies the entire building. In addition to this three small constant volume air handlers provide the first floor with its primary heating and cooling needs. The distinguishing feature of the system layout is that a vertical chase runs through all the floors from the basement supplying conditioned air. The ductwork on each floor is branched from the central vertical duct.

The Wehner Business Building is a state of the art academic building consisting of offices, classrooms and lecture theaters. It is a four story structure plus an under floor. The under floor houses the air handlers for the lecture theaters on the periphery and the auditorium. The total conditioned area is 192,000 square feet. A new wing is under construction, which will increase the area to 248,000 square feet. This building is located on the west campus of Texas A&M University. This building houses the Lowry Mays School of Business Management. The building consists of auditoriums, lecture theaters, classrooms, audio/visual rooms and offices. The envelope layout is complex and 35% of the whole façade is glazing. The HVAC system consists of 16 variable volume air handlers supplying to the entire building. In addition to that a single duct air handler supplies conditioned air to the large auditorium north end of the building.

The John B. Connally Building (State Headquarters) houses the administration and human resource department of the entire Texas A&M University system. It is not located on the main campus, but east of it in the city of College Station. It consists of six floors and a basement. The total conditioned area is 123,961 square feet. The building consists of offices and meeting rooms. Due to its location away from the campus the building has its own chiller and boiler plant to furnish the heating and cooling needs of the building. The HVAC system consists of 21 single duct VAV air-handlers with

terminal reheat. Of these two are outside air air-handlers. The plant consists of three centrifugal chillers, two are rated at 280 tons while the third auxiliary chiller is 32 tons. For hot water there are two hot water boilers rated at 2.1 MMBtu/hr each. The boiler efficiency is 80%.

The residential house chosen for the research is a low cost construction situated in Bryan, Texas. This house is built under the Habitat for Humanity project, an international organization first established in 1976. This organization provides low cost interest free houses for low-income families. This particular house is being studied by Victor Kootin Sanwu of The Energy Systems Laboratory for his PhD research. It is a single story house with a total conditioned area of 1170 square feet. The HVAC system consists of 2.5 ton, 10.5 SEER air-conditioner and a 36000 Btu/hr, 75% AFUE gas furnace.

3.2 Design Information and Data Acquisition

The DOE-2.1e simulation software requires extensive information about the building in order to create a simulation model. For this purpose the following resources were used.

The facilities office on the Texas A&M campus is responsible for the construction records of all the building and facilities associated with the Texas A&M University system. The architectural and mechanical drawings of the buildings being simulated were obtained from this office. However in some cases the drawings are not updated. The physical changes related to both structure and systems, which have been incorporated into the buildings after the initial construction, have not been added to the drawings. So in addition to obtaining information from the drawings, detailed walk-throughs were also conducted for each building.

Walk-throughs are beneficial in acquiring detailed information about the envelope and the architectural layout of the building. In addition to this a survey of a typical room or a lecture hall can provide a good estimate about the lighting and equipment load per square foot of the building.

System information was obtained from the engineers of the Energy Systems Laboratory (ESL). All the four buildings are still in the commissioning process by ESL. The commissioning of Wisenbaker building was completed in September 2002. The major retrofits like the variable frequency drives (VFD) and conversion of constant volume air –handlers to variable volume were done earlier. The recent inspection by the ESL engineers and technicians was more focused on the small maintenance and operation problems. It was found out that there were problems in all the terminal boxes, mostly related to stuck valves and faulty pneumatic controls. System information about this building was obtained from the commissioning engineer. This information included the type and number of air-handlers, design airflow etc.

The Harrington Tower was retrofitted with a variable air volume system in 1995 and the study of the evaluation of this retrofit and other energy efficiency measures was published in 1998 (Giebler et al. 1998). Information about the system for this building was obtained from this publication and from the author.

A walk-through study was performed at Wehner Business Building. Recommendations have been put forward to the maintenance personnel about the current operational malfunctions of the building. Since the construction is relatively new, no major problems are present in the building. The key problem was with the main chilled and hot water valves. In addition this minor maintenance issues related to the thermostats and VFD controls have also been reported. The as-built system information was obtained from the commissioning engineer.

The John B. Connally Building has not been completely commissioned but its chiller operation has been studied in detail and according to ESL staff engineer, the chillers are currently working at optimal efficiency. The plant data, nameplate information about the equipment and design values for the air-handlers were obtained from private communication with the staff engineer who implemented the chiller retrofits.

The ESL also monitors houses built under the Habitat for humanity project, many students have completed their research on the different aspects of residential

energy use by studying these houses. The structural details along with the system specifications were obtained from these students.

The information obtained from the above-mentioned sources was required to create the simulation models. After creating the different models and completing the simulation sets, the next step was to check their accuracy by comparing the simulation output with measured data. First of all only those buildings were chosen whose measured data was available. The Energy Systems Laboratory maintains an extensive database of all the campus buildings as well as other buildings under ESL contract of monitoring. For all campus building, the whole building electric, the chilled and hot water consumption is monitored on an hourly basis. Some buildings which have been used for detailed energy studies have various parameters being monitored, e.g. for the Zachry Engineering Center, in addition to the chilled and hot water consumption and whole building electric, the flow rates and the electricity consumption by the auxiliary pumps and equipment is being measured. This building also has a weather station and hourly data on outside dry bulb temperature, relative humidity, wind speed and solar radiation is also available.

For the buildings being simulated, measured data for chilled water, hot water and whole building electric was extracted for several years. Effort was made to use recent data, which corresponds to the current operation of the building. A few problems were encountered while compiling the data for the different buildings. Better data was available for the Wisenbaker and Wehner Buildings. The hot water data from the Harrington Tower is off by a factor of thousand, which shows a scaling error on the logger. For the State headquarters only the chiller electric and the whole building electric is available, there is no measured data for the hot water use and the boiler operation. So for State headquarters, the simulation results will only be compared with the electricity.

For the Habitat House, hourly data (1999) for whole building electric as well as the furnace and domestic hot water heater gas usage was provided by Victor Kootin Sanwu. The gas data however is not useful since only less than 6 months of data is available.

3.3 Time Allocation

The initial emphasis of this research was on determining the relation between the time consumed in creating an uncalibrated simulation model and its accuracy when compared with measured data. For this purpose it was initially decided that twenty hours would be allocated to create the first model and another twenty hours to increase the details of the model created. However all buildings have different layouts and complexity. In addition to this the information available for different buildings is not the same. So the time allocation for the two steps was made flexible. However time was logged for every step in completing the simulation model. The time spent on the initial model ranges from 22 hours for the Wehner Building to just 7 hours for the Habitat House.

It was decided that for the initial model, emphasis would be on the envelope. The system description will be simplified, which means that a single system will be considered for the entire building. Hence 70% of the time to complete the initial model was utilized in defining loads. The time includes walk-throughs and taking tape measures at the site to determine the correct dimensions of the structure. The rest of the time for the initial model was divided in the system description, cleaning the input file etc. The initial building models are all massless i.e. the custom weighting factors were not calculated. The system information consisted of a single system type with all the zones in the building at the same conditions.

For the second simulation model, more time was invested in the loads portion of the input file to define all the construction layers as well as the all the interior walls with correct coordinates. This procedure was conducted so that the impact of thermal mass could be considered in the simulation. In the system portion, all the systems, which are being used to supply air to different zones, are defined. The airflow through different zones is also entered separately. This information was obtained from as-built drawings and from the commissioning engineer.

3.4 Description of the Simulation Model

The simulation models were divided into three main categories:

- Massless
- Advanced
- Simplified

The massless model was the first cut at the building being simulated. For this model the emphasis was on the envelope details and the correct layout of the building. The construction was considered massless. This means that all the interior and exterior walls are being considered as U-values and the effect of thermal storage is being neglected. The system description was minimal with the just one system supplying all the zones with the same amount of air per square foot.

In the advanced model, each construction was defined in layers and not as a static U-value. The transient effects of thermal mass are being considered. All the interior walls were defined with the correct coordinates. This is a requirement if the custom weighting factors are to be calculated. In the systems portion, all the different types of systems being used to supply air to the various zones in the buildings were put in. Also from the as built and design data, correct amount of airflow was designated to each zone.

The simplified model was developed to check the sensitivity of overall energy use on the envelope details with changing weather conditions. This model consists of single story rectangular shape having the equivalent conditioned floor and glazing area of the complete building. The system portion of the input file is a minimum description of the actual system being used to provide air to all the zones.

Following is detailed description of the input files for all the models of the five buildings:

- Wisenbaker Engineering Research Center
- Harrington Tower

- Wehner Business Building

- John B. Connally Building

- Habitat House

3.4.1 Wisenbaker Engineering Research Center

   Wisenbaker Engineering Research Center (WERC) is a 177,704 sq. ft. building located on the main campus of the Texas A&M University, College Station, Texas. This is a multi purpose building catering to the different requirement of the academic field. It mainly consists of offices, laboratories and conference rooms. It is three stories high facing 44° north of east. The underground parking lot was converted to a basement and now they serve as offices and laboratories for different departments.

   The sources of information for this building were the as-built drawings and the commissioning engineer. Figure 3.1 shows the Wisenbaker Engineering Research Center. Figure 3.2 depicts the building created through the DOE-2.1e simulation model. The software used for this purpose is the Draw BDL (Joe Huang and Associates 1993-94). Table 3.1 summarizes the details of the simulation models, which have been explained as follows:

3.4.1.1 Massless Input File

   The time spent for creating the massless simulation model of WERC was 18 hours. Of these 18 hours approximately 12 hours were spent in the input of all the

Fig 3.1 Wisenbaker Engineering Research Center (WERC)
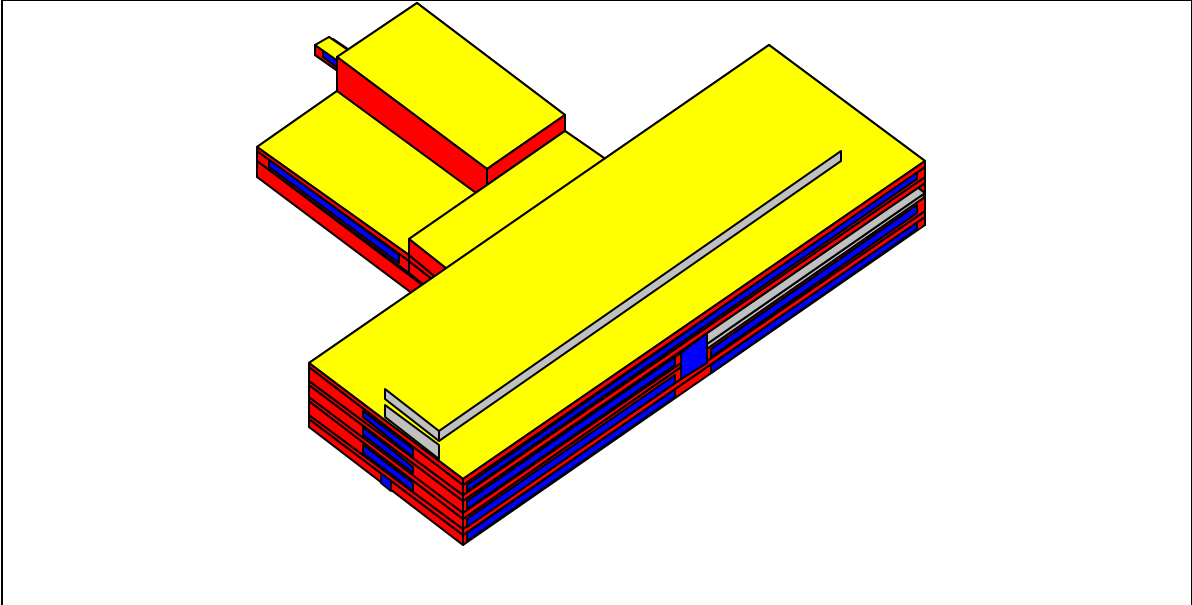
Fig 3.2 DrawBDL rendering of Wisenbaker Engineering Research Center (WERC)

TABLE 3.1
Model description for WERC

Sections of the Input file	MASSLESS	ADVANCED
Level of effort	18 hours	13 hours
Loads (source: drawings , survey)	**12 hours**	**5 hours**
Envelope		Thermal mass considered, detailed construction is defined for all the envelope elements
	Massless construction	
	All floors and exterior details defined according to as-built drawings	All floors and exterior details defined according to drawings. All the interior floors and ceilings defined with the correct coordinates
	4 floors , 8 zones	3 floors + basement, 8 zones
	Conditioned and glazed area obtained from field measurements and as-built drawings	Conditioned and glazed area obtained from field measurements and as-built drawings
Schedules	Typical schedules for an office building with 50% load on weekends to account for graduate students	Typical schedules for an office building with 50% load on weekends to account for graduate students (Sharon Hinchey's thesis on Zachry building)
Shading	No shading	Shading due to adjacent buildings is being considered
Space conditions		
General space	200 sq ft /person	150 sq ft /person (survey based)
	1.5 Wsq ft for lighting	1.5 Wsq ft for lighting
	3.0 W/sq ft for equipment	3.0 W/sq ft for equipment
	0.25 airchanges/hr	0.0 airchanges/hr (pressurized)
Laboratory		
	300 sq ft /person	300 sq ft /person
	1.5 Wsq ft for lighting	2 Wsq ft for lighting
	3.5 W/sq ft for equipment	3.5 W/sq ft for equipment
	1.25 airchanges/hr	2 airchanges/hr (loading dock open)
		People heat gain is 850 Btu/ hr for slight physical work
Basement		
	Treated as above ground	150 sq ft /person
		1.5 Wsq ft for lighting
		3 W/sq ft for equipment
		0 airchanges/hr

TABLE 3.1
(contd.)

Sections of the Input file	MASSLESS	ADVANCED
Systems (source: Chenggang Liu for the advanced model)	**6 hours**	**8 hours**
Type	Dual Duct VAV	7 Single Duct VAV w/ terminal reheat, 1 Single Zone Const. Volume, 40 Fan Coil units
Schedules		
Fans	100% during peak hours, 50% during weekends	100% during peak hours, 50% during weekends
Temperature	Winter set point is 70F w/ setback to 60F, summer set point is 76F w/ setup to 78F	No setbacks, summer set point is 78F, winter setpoint is 68F
Reset	No reset for heating and cooling	Only reset for cooling, Supply temperature is 63F if outside temperature is 65F, it is 55F if outside is at 80F
Zone Commands		
General space	1.5 cfm/sq ft	From spec sheets, different for different zones
	20cfm/per outside air	From spec sheets, different for different zones
	Inside temperature 72F for heating and 77F for cooling	Inside temperatures are the same as thermostat setpoints
Plenum	Inside temperature 70F for heating and 95F for cooling	Inside temperature 70F for heating and 95F for cooling
Lab	3.0 cfm/sq ft	2.0 cfm/sq ft
	25cfm/person outside air	2000 cfm (from design spec sheets)
	Heating design temperature 72F and cooling design temperature 77F	Heating design temperature 70F and cooling design temperature 95F
System Specification		
	Max and min supply temperatures 105Fand 55F	Max and min supply temperatures 105Fand 55F
	VAV cycling down to 50% of low loads	VAV cycling down to 50% of low loads, the temperature rise across the reheat coil is 50F, cool reset is being used with the fan coil units, the rest of the details are from the spec sheets
RESULTS:		
ANNUAL ENERGY CONSUMPTION (MMBtu)	**22806**	**12768**
ANNUAL ENERGY CONSUMPTION PER UNIT AREA (kBtu/ sq ft)	**347.6**	**194.6**
RMSE(%) (Comparison to measured data)		
CHW	37.16	50.26
HW	94.54	113.48
WBE	43.30	35.58
MBE(%)		
CHW	-25.15	-44.26
HW	-72.92	-92.68
WBE	40.76	32.69

envelope details. Walk-throughs were performed to determine the correct dimensions of the windows and walls, lighting and equipment wattages per ft^2 and occupancy. The rest of the time was utilized in defining the system and removing the bugs from the input file.

3.4.1.1.1 Loads

For the massless model it was assumed that thermal mass and storage has no effect on the building operations. In DOE-2 terms, it means that custom weighting factors were not calculated for each layer and just steady state calculations are being performed.

a) Construction Details

For the exterior, interior walls and floors typical construction is assumed. The exterior wall is made up of 4 inch common brick, ½ inch plywood, ¾ inch light weight gypsum plaster on the outside, mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a ¾ inch gypsum board was assigned with an R-value of 0.67. The drop ceilings are acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof gravel, 3/8 inch built-up roofing, polyurethane insulation and ¾ inch wood. The floor construction is considered to be 6-inch lightweight concrete. The glass for the doors and windows is single-pane tinted. The material testing laboratory at the rear of WERC is made of mild-steel sheets and the door of this laboratory is assumed to be made of hardboard, wood and plywood. The floor weight is taken as 70lbs/ft^2, for concrete construction.

b) Zoning

All the floors are divided into two zones i.e. exterior and interior zone. The interior zone is defined by stepping 20ft from the exterior wall in each direction.

c) Schedules

In the loads portion the schedules for occupancy, equipment, lighting and infiltration are considered.

- Occupancy: It is assumed that the occupancy is maximum between 8:00 am and 9:00 am in the morning and from 2:00 pm to 5:00 pm in the afternoon. Due to the presence of students in the building 24 hours it is assumed that the minimum occupancy level is 10% of the maximum value. For the weekends, the occupancy is 50% of the maximum between 10:00 am to 5:00 pm, while it is 5% from 6:00 pm to 9:00 am.
- Equipment: Equipment load varies from 70% to 100% of the watt per square foot defined in the space conditions, between 8:00 am in the morning to 9:00 pm in the night. For the rest of the time it is assumed to be at 50%, including the weekends.
- Lighting: The lighting level varies from 60% to 80% of the lighting watt per square foot defined in the space conditions, between 8:00 am to 6:00 pm and it goes back to 50% during the night hours and 40 % for the weekends.
- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command in the space-conditions. For the massless model it was assumed that the building is not pressurized. However this assumption was wrong for the main building so the infiltration was removed. The materials lab at the back of the building is not pressurized so infiltration was just defined for that portion

d) Space Conditions

For the massless model, WERC was divided into two main spaces according to the conditions. They are the OFFICE and LAB. The OFFICE conditions apply to all the interior and exterior zones of the main building. The LAB conditions are for the material testing laboratory at the rear of the WERC. For the OFFICE it was assumed that the

space available for each person is 200ft^2. The lighting is 1.5 watts/ft^2 and the lighting type is recessed fluorescent vented to return air. So the lighting load into the room was considered to be 80% while the remaining is being added to the return air. The equipment is 3watts/ft^2. The infiltration rate is taken as 0.25 ACH. This assumption was wrong and the main building was considered positively pressurized for the advanced case.

The LAB conditions differ slightly from these conditions mainly because of the structure and operations of the material testing laboratory. It is a three story high steel structure with a variety of heavy equipment. It has a walkway on the second floor, which connects WERC to the Civil Engineering/TTI Building. There is a large door at the ground floor. This door is mostly open thus allowing for a considerable of amount of infiltration and exfiltration. For this facility it is assumed that each person has 300 ft^2 of space. The lighting intensity and type is considered to be the same. The equipment watts/ft^2 is 3.5 instead of 3 for the earlier space conditions. Since the large loading dock door is open most of the time, the outside air infiltration is more and the rate is considered to be 1.25 ACH.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates.

3.4.1.1.2 Systems

For the massless model, a Variable Air Volume dual duct system (DDVAV) is assumed. This system is supplying air to the entire building with the same conditions except for the material testing laboratory.

a) Schedules

- Fan Schedule: It is assumed that during weekdays the fans are at 100% from 8:00 am in the morning to 6:00 pm in the night. During the night fans are cycled between 20 to 50%. On the weekends the fans are at 50%.

- Thermostat Schedule: Thermostat setback and setup are assumed for the massless model. The heating set point is 70°F between 8:00 am and 6:00 pm. During night it is being assumed to have a set back of 60°F while for the evenings and weekends it is 68°F. For cooling the set point is 76°F between 8:00 am and 6:00 pm. It is set up to 82°F during the night and at 80°F during the weekends.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

In the zone command the outside air is defined per person. For the space designated by OFFICE, the outside air fraction is 20 cfm/per (ASHRAE Fundamentals). While for the LAB it is 25. The fresh air for the LAB is taken as more because the nature of work and also because the loading dock is mostly open. For the spaces the airflow is defined as cfm/ft^2. It has a value of 1.5 for all the zones other then the material testing laboratory where 3 cfm/ft^2 is being supplied. The set points for heating and cooling are 78°F and 68°F respectively. Thermostat is assumed to be reverse acting. These commands are followed for all the zones in the building.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The heating and cooling controls are constant. This means that the supply air temperature do not vary with the outside air temperature. Since this is a variable volume system that FAN-CONTROL is defined as SPEED, which simulates it as a VFD. This allows the fan motor to vary its speed according to the load. The static and efficiency of the supply and return fan are assumed. MIN-CFM-RATIO is given a value of 0.5, which allows the system to modulate airflow between the maximum and minimum value set at 0.5. So the air supply to the zone will be modulated according to the different load schedules. There is no dual duct variable volume system in DOE-2 so

plaster, 12 inch hollow concrete block and polyurethane insulation. The floors above ground are vinyl tiles, gypsum plaster and 12 inch hollow concrete block. The glass for the doors and windows is single-pane tinted, the glass type is taken from the DOE-2 window library and the frame is aluminum without thermal break. The door of this laboratory is assumed to be made of hardboard, wood and plywood. Thermal mass is being considered so the floor weight is taken as 0.

b) Zoning

Zoning for the advanced case is same as the massless model. Every floor of the building is considered to be divided in two zones, exterior and interior. The interior zone is defined by stepping 20 feet from the exterior wall in each direction.

c) Schedules

In the loads portion the schedules for occupancy, equipment, lighting and infiltration are considered.

- Occupancy: The occupancy schedule for the advanced case has been taken from a thesis done by Sharon Beth Hinchey on Zachry Building (Hinchey, 1992). Since the operation of these two buildings is similar, the same values have been used. From 7:00 pm to 8:00 am, the occupancy is at 10% while it becomes maximum during the morning hours from 9:00 am to 11:00 am and then towards the afternoon from 3:00 am to 6:00 pm. For the weekends it is 5% during the nights and lies between 40 to 50% 10:00 am to 6:00 pm.

- Equipment: Equipment load varies from 70% to 90% of the maximum between 8:00 am in the morning to 9:00 pm in the night. The load is at 70% till midnight and then it is assumed to drop to 20% till 7:00 am. For the weekends it is assumed to be at 60%.

- Lighting: The lighting schedule is the same for this model as it was for the massless model.
- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions.

d) Shading

Shades have been added to WERC for this model. All these shades are from adjacent buildings i.e. they are permanent shades, so the transmissivity does not vary, it will always be zero. Hence the shade schedule, which regulates the transmissivity, is always off.

- Shading Commands: For the advanced model, shades due to the adjacent buildings and an overhang on the rear side of the building have been added to the file. BUILDING-SHADE command has been utilized in the input of these shades. The transmittance of the shades is kept at 1 but since the shading schedule is 0, this implies that the shades are opaque.

e) Space Conditions

In the advanced model, WERC is divided into three regions according to space conditions. They are the OFFICE, BASEMENT and LAB. The OFFICE conditions apply to all the interior and exterior zones of the main building other then the basement. For the OFFICE it was assumed that the space available for each person is 150ft^2. The lighting is 1.5watts/ft^2 and the lighting type is recessed fluorescent vented to return air. So the lighting load into the room was considered to be 80% while the remaining is being added to the return air. The equipment is 3watts/ft^2. The infiltration rate is taken as 0.0 ACH. This means that positive pressurization is assumed in the building. In addition to this, commands related to custom weighting factors have also been added. It is

assumed that 20% of the floor is covered with furniture which of heavy type and the weight is assumed to be 1lb/ft^2.

The basement conditions are defined separately. They are similar to the office conditions. The only difference is that instead of recessed return air vented fluorescent lights, they are of the suspended type so that the load from the lights is being added to the space. Positive pressurization is also assumed for the basement.

In the lab conditions the lighting fixtures for this case have been assumed to be without vents, so that the complete load is being added to the space as compared to the 80% for the massless model. The LAB is not positively pressurized. Air changes/hour have been increased from 1.5 to 2, because of the observation that 80% of the operating hours, the loading dock is open. The heat gain from people is increased from 450 Btu/hr for sedentary work to 850 Btu/hr for light physical work including lifting, welding etc.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates. In the massless model, the ceilings of each floor were defined with equivalent area. But in order to calculate the custom weighting factors, each and every surface in the building is to be described completely with correct coordinates.

3.4.1.2.2 Systems

For the advanced case seven single duct VAV systems with terminal reheat, one single zone constant volume system and forty fancoil units have been simulated. The fancoil units supply the entire basement. The variable volume and the constant volume system supply to the remaining three floors and the laboratory.

a) Schedules

- Fan Schedule: It is assumed that during weekdays the fans are at 100% from 8:00 am in the morning to 6:00 pm in the night. During the off-peak hours fan are cycled between 20% to 50%. During the weekends the fans are at 50%.

- Thermostat Schedule: For the advanced case, there is no thermostat setback and setup. Since WERC does not employ setback and setup. This information was obtained from the commissioning engineer. However in WERC a reset schedule is employed which varies the supply air temperature from 63°F to 55°F, for an outside air temperature range of 65°F and 80°F. In this case the supply temperature is not fixed at 55°F for all ranges of outside air temperature.
- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

The zone commands for the advanced model are quite detailed because different systems are supplying different zones at varying rates. The value of supply air (2cfm/ft^2) for the material testing laboratory is assumed. Other then this all the values for the remaining zones, including the outside air have been obtained from the specification sheets provided by the commissioning engineer. The details of the values used for the simulation can be viewed in the appendix. The heating and cooling set points are 68°F and 78°F respectively. Thermostat is assumed to be reverse acting.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The heating control is constant. The cooling control is reset, which points towards the reset schedule already explained. This is for the constant volume and variable volume systems. For the fan coil units the heating and cooling supply air temperatures are constant at 105°F and 55°F respectively. The preheat temperature for all systems is 45°F. Outside air for all systems is temperature governed and no duct loss is being considered. For the variable volume system that FAN-CONTROL is defined as SPEED. The fan control is CONSTANT-VOLUME for the other two systems. The value for the fan static for all fans has been obtained from design

data. For the reheat variable volume system the temperature rise across the reheat coil is defined as 50°F and the minimum cfm ratio is set at 0.5.

3.4.1.2.3 Plants

a) Plant Equipment

It is assumed that the two auxiliary chillers are of the hermetic centrifugal type and they are defined as one single chiller with the equivalent size of 36 tons (0.432MMBtu/hr). The chiller model from the faceplate is 30GB 040, and from the Carrier website this model is now renamed with 30GT 040. Both have the same capacity.

3.4.1.3 Simplified Input File

This input file was created to study the sensitivity of the envelope details with different weather conditions. This file is essentially the same as the massless in all the schedules and system details. The only difference is that instead of defining all the floors, this model has just one floor and two zones. The floor is equivalent to the entire conditioned area of the whole building.

3.4.2 Harrington Tower

Harrington Tower is a 130,844 sq. ft building located on the main campus of the Texas A&M University, College Station, Texas. It is eight stories high plus the basement. It mainly consists of offices and other meeting rooms. The sources of information for this building were the as-built drawings and the commissioning engineer. Figures 3.3 and 3.4 show the Harrington Tower and the simulated version of the actual building in DrawBDL (Joe Huang and Associates 1993-94). Table 3.2

Fig 3.3 Harrington Tower
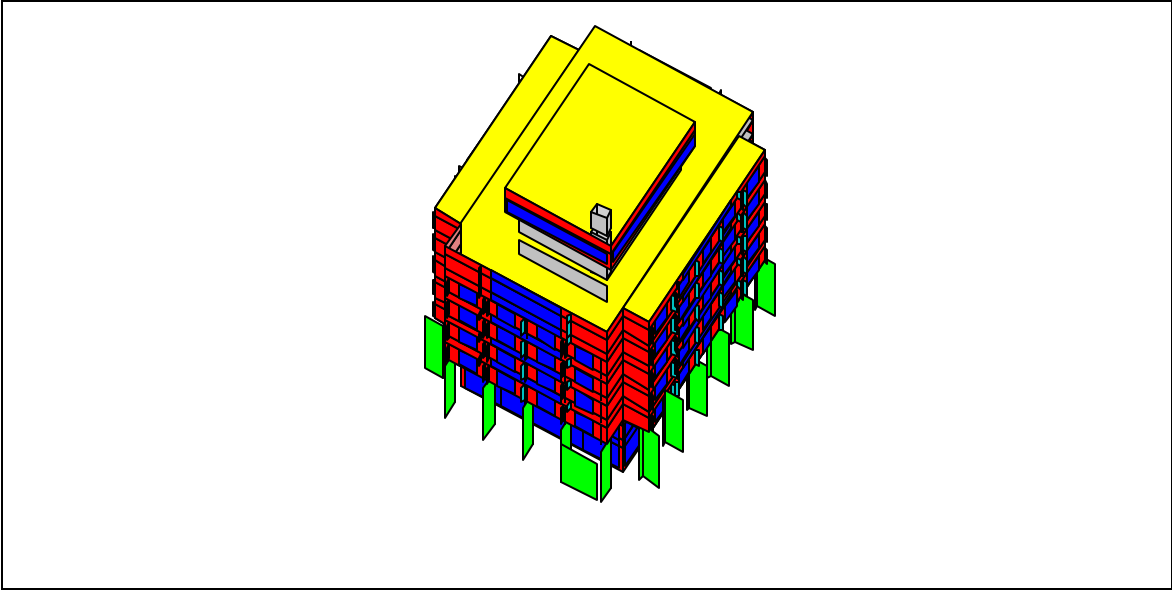
Fig 3.4 DrawBDL rendering of Harrington Tower

TABLE 3.2
Model description of Harrington Tower

Sections of the Input file	MASSLESS	ADVANCED
Level of effort	20 hours	13 hours
Loads (source: drawings, survey)	**14 hours**	**8 hours**
Envelope	Massless construction	Thermal mass considered, details construction is defined for all the envelope elements
	All floors and exterior details defined according to the asbuilt drawing	All floors and exteriordetailed defined according to the drawing. All the interior floors and ceilings defined with the correct coordinates
	7 floors + pent house, 16 zones	7 floors + pent house + basement, 17 zones
	Conditioned and glazed area obtained from field measurements and as built drawings	Conditioned and glazed area obtained from field measurements and as built drawings
Schedules	Typical schedules for an office building with 5% load on weekends	Typical schedules for an office building with 5% load on weekends
Shading	The outer pillars of the Harrington tower serve as shades as well as the Harrington center on the east side of the tower	The outer pillars of the Harrington tower serve as shades as well as the Harrington center on the east side of the tower, the tree cover on the west side has also been added
Space conditions		
General space	100 sq ft /person	100 sq ft /person
	2.5 Wsq ft for lighting	2.5 Wsq ft for lighting
	2.0 W/sq ft for equipment	2.0 W/sq ft for equipment
	0.5 airchanges/hr	0.0 airchanges/hr
Basement	no basement	unconditioned basement
Systems (source: Tim Giebler for the advanced model)	**6 hours**	**5 hours**
Type	Dual Duct VAV	Dual Duct VAV, Single Duct CV
Schedules		
Fans	100% during peak hours, 20% during weekends	100% during peak hours, 20% during weekends
Temperature	heating set point is 68F w/ setback to 60F, cooling set point is 76F w/ setup to 78F	heating set point is 68F w/ setback to 63F, cooling set point is 73F w/ setup to 75F, the cooling setpoint is obtained from the commissioning engineer
Reset	no reset for heating and cooling	reset for both heating and cooling, Supply temperature is 60F if outside temperature is 40F, it is 55F if outside is at 80F. Supply temperature is 100F if the outside temperature is 40F, it is 70F if the outside temperature is 70F

TABLE 3.2
(contd.)

Sections of the Input file	MASSLESS	ADVANCED
Zone Commands		
General space	1.5 cfm/sq ft	1.5 cfm/sq ft
	20cfm/person outside air	outside air 15% of the total supply air
	Inside temperature 72F for heating and 77F for cooling	Inside temperature 68F for heating and 78F for cooling
Plenum, duct, basement	Inside temperature 70F for heating and 95F for cooling	Inside temperature 70F for heating and 95F for cooling
System Specification		
	Max and min supply temperatures 105Fand 55F, preheat temp is 45F	Max and min supply temperatures 105Fand 55F
	VAV cycling down to 50% of low loads	VAV cycling down to 50% of low loads, the temperature rise across the reheat coil is 50F, cooling and heating reset is being used for both the systems. Economizer works between 65F and 37F
RESULTS:		
ANNUAL ENERGY CONSUMPTION (MMBtu)	**24582**	**24936**
ANNUAL ENERGY CONSUMPTION PER UNIT AREA (kBtu/ sq ft)	**238.1**	**241.5**
RMSE(%) (Comparison to measured data)		
CHW	71.48	90.69
HW	129.73	209.26
WBE	101.85	133.94
MBE(%)		
CHW	47.79	66.24
HW	-32.40	124.92
WBE	82.47	115.39

summarizes the parameters, which were used in creating the simulation model. The details of the information and the input file are as follows:

3.4.2.1 Massless Input File

The time spent for creating the massless of Harrington Tower was 20 hours. These hours include the walk-throughs, talks with the related engineer and the modeling of the building. The walk-throughs were performed to get the correct dimensions of the building, windows and to get an idea of the occupancy, lighting levels and equipment.

3.4.2.1.1 Loads

For the massless model it was assumed that thermal mass and storage has no effect on the building operations. In DOE-2 terms, it means that custom weighting factors were not calculated for each layer and predetermined factors were used for calculations by the program.

a) Construction Details

For the exterior, interior walls and floors typical construction is assumed. The exterior wall is made up of 4inch common brick, ½ inch plywood, ¾ inch light-weight gypsum plaster on the outside, mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a ¾ inch gypsum board is considered with an R-value of 0.67. The drop ceilings are acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof gravel, 3/8 inch built-up roofing, polyurethane insulation and ¾ inch wood. The floor construction is considered to be 6-inch lightweight concrete.

The glass for the doors and windows is single-pane tinted. The floor weight is taken as 70lbs/ft^2 for concrete construction.

b) Zoning

Zoning for this building and all others, which have been simulated is considered to be very simplified. All the floors are divided into two zones i.e. exterior and interior zone. The interior zone is defined by stepping 20ft from the exterior wall in each direction.

c) Schedules

In the loads portion the schedules for occupancy, equipment, lighting and infiltration are considered.

- Occupancy: Schedule for typical 8:00 am to 5:00 pm office building is assumed. It is assumed that the occupancy is maximum between 9:00 am

and 11:00 am in the morning and from 3:00 pm to 6:00 pm in the afternoon. Since this is an office building the occupancy drops down to zero during the night. For the weekends, between 10:00 am and 5:00 pm, the occupancy is 5% of the maximum, while it is 0 for the rest of the hours.

- Equipment: Equipment load is from 80% to 90% of the maximum equipment load defined, between 8:00 am in the morning to 9:00 pm in the night. For the rest of the time it is assumed to be at 10%, including the weekends.

- Lighting: The lighting level varies from 60% to 80% between 8:00 am to 6:00 pm and it goes back between 20% and 30% during the night and 20 % for the weekends.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions. For the massless model it was assumed that the building is not positively pressurized.

d) Space Conditions

For the massless Harrington is divided into two main spaces according to the conditions. They are the OFFICE and OFFICE1. The OFFICE conditions apply to all the exterior zones of the main building. The OFFICE1 conditions are for the interior zones. For the OFFICE it was assumed that the space available for each person is 100ft^2. The lighting is 2.5 watts/ft^2 and the lighting type is recessed fluorescent vented to return air. So the lighting load into the room was considered to be 80% while the remaining is being added to the return air. The equipment is 2.5watts/ ft^2. The infiltration rate is taken as 0.5 ACH. No positive pressure is considered for the massless model.

The OFFICE1 conditions only differ from the OFFICE conditions in the number of occupants since this is a very small zone. The number of occupants is 32 for the interior zone and 64 for the exterior zone.

e) Shading

The construction of the Harrington Tower is such that the floor area of the first two levels is less in area then the remaining six levels of the building and the larger floor is supported by pillars on all sides. Altogether there are 22 pillars and they have been modeled as shades since they do not contribute to anything other then blocking direct solar at different times. These shades block approximately 40% of direct sunlight to reach the first two floors.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates.

3.4.2.1.2 Systems

For the massless model a VAV dual duct system is assumed. This system is supplying air to the entire building with the same conditions.

a) Schedules:

- Fan Schedule: It is assumed that during weekdays the fans are at 100% from 8:00 am in the morning to 6:00 pm in the night. During the night fan are cycled between 20 to 30%. During the weekends the fans are at 20%.

- Thermostat Schedule: Thermostat setback and setup are assumed for the massless model. For heating temperature the set point is 68°F between 8:00 am to 6:00 pm. During nights it is being set back to 60°F while for the evenings and weekends it is 65°F. For cooling the set point is 78°F between 8:00 am and 6:00 pm. It is set up to 82°F during the night and at 80°F during the weekends.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

All the interior and exterior zones are assumed to be at the same conditions. The heating and cooling set points are 68°F and 78°F. The thermostat type is proportional and the throttling range is set at 5°F. The outside air is governed by the number of people in the zone and the value is 20 cfm/person (ASHRAE Fundamentals). The airflow for all zones is 1.5 cfm/ft^2.

c) System Commands

In the system commands, the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The preheat temperature is defined as 45°F. The hot and cold supply air temperatures are constant. Since this is a variable volume system that FAN-CONTROL is defined as SPEED, which simulates it as a VFD. This allows the fan motor to vary its speed according to the load. The static and efficiency of the supply and return fan are assumed. MIN-CFM-RATIO is given a value of 0.5, which allows the system to vary airflow between the maximum and minimum value set at 0.5. So the air supply to the zone will be modulated according to the different load schedules. The return air passage for this system is through ducts and the supply-cfm is not defined because the cfm/ft2 is already defined in the zone commands.

3.4.2.2 Advanced Input File

3.4.2.2.1 Loads

After the first 20 hours, another 13 hours were put into the massless to create an advance simulation model of the Harrington Tower. The advanced input file has all the layers defined in the form of coordinates to ensure that the custom weighting factors for all the layers and surfaces are calculated correctly.

a) Construction Details

For the exterior, interior walls and floors typical construction is assumed. For this model every layer is being separately defined. The construction is the same as it was for massless but now only the layers are spelled out. The exterior wall is made up of 4 inch common brick, ½ inch plywood, ¾ inch light weight gypsum plaster on the outside, mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a ¾ inch gypsum board on both sides and an air-gap in between. The drop ceilings are acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof gravel, 12 inch hollow concrete block and perforated roof insulation. The underground floor and wall construction is considered to be gypsum plaster and 12inch hollow concrete block. The floors above ground are vinyl tiles, gypsum plaster and 12inch hollow concrete block. The glass for the doors and windows is single-pane tinted, the glass type is taken from the DOE-2 window library and the frame is aluminum without thermal break. Thermal mass is being considered so the floor weight is taken as 0.

b) Zoning

Zoning for the advanced case is same as the massless model. Every floor of the building is considered to be divided in two zones, exterior and interior. The interior zone is defined by stepping in 20 feet from the exterior wall in all directions. In Harrington Tower a central chase runs vertically upwards carrying the hot and cold supply ducts to each floor and the terminal boxes. This vertical chase has been simulated as a closed unconditioned space for each floor. So now the every floor has three zones, exterior, interior and duct.

c) Schedules

In addition to occupancy, equipment, lighting and infiltration, shading schedule has also been added to this model. This is used because of the shades on Harrington Tower due to adjacent trees.

- Occupancy: The occupancy schedule for the advanced model is the same as for the massless model.

- Equipment: The Equipment schedule is also the same as the massless model.

- Lighting: The lighting varies from 80% to 60% between 8:00 am to 6:00 pm while it is 30% during the night. For the weekends it is 20% of the maximum value.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions. How the value of air changes/hour has been set at 0 to simulate a positively pressurized building.

d) Shading

For Harrington Tower the shading schedule is added due to trees on the west side of the building. it is assumed that the trees shed leaves during the autumn and winter so the transmissivity is high while it is low for spring and summer.

- Shading Commands: The shades for Harrington Tower are mainly used for defining the pillars around the building. In addition to this the shade due to the Harrington center on the east and tress on the west are also added.

e) Space Conditions

The space conditions for both OFFICE and OFFICE1 are essentially the same as they were in the massless model.

The massless model was created without a basement, since in the preliminary walk-through; no entrance or approach to the basement was detected. After talking with the commissioning engineer, it was found out that the basement in the tower is used just

for housing the air-handling unit. So the basement has been modeled as an unconditioned space with underground walls.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates. In the massless the ceilings of each floor were defined with equivalent area. But in order to calculate the custom weighting factors, each and every surface in the building is to be designed completely. In addition to this the unconditioned duct space for each floor has also been added to simulate the vertical chase carrying the supply and return ducts from the AHU in the basement.

3.4.2.2.2 Systems

For the advanced case one dual duct VAV systems and three single duct constant volume systems are defined. The three small single duct systems provide the first floor with the primary heating and cooling requirements. The VAV air handler is housed in the basement and supplies 138,000 cfm through a 200 hp motor to all the floors. In addition to this the first floor is also supplied by a constant volume system.

a) Schedules

- Fan Schedule: The fan schedule is same for the advanced model as it was for the massless model.

- Thermostat Schedule: For the advanced case, a setup of 2°F has been assumed on the suggestion of the commissioning engineer. During the weekends it is assumed that the temperature is 80°F. For heating a 5°F setback is assumed between 7:00 pm and 7:00 am. And for the weekends it is being assumed that the temperature is being maintained at 65°F. Reset schedule for both heating and cooling is being employed. For cooling the supply air temperature varies between 55°F and 60°F as the outside temperature varies from 80°F to 40°F. For heating the supply air temperature variation is from 100°F to 70°F as the outside temperature varies from 40°F to 70°F.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

The zone commands are slightly different from the massless model. The outside air is not being defined per person. It is being assumed that the outside air is 15% of the total amount of air being supplied and then it being divided for the different zones according to the floor area. This 15% outside air comes out to be approximately the same as 20cfm/person defined in the massless model. However since the outside air is not being modulated according the occupancy schedule in this building, so a better depiction of the correct situation is a fixed amount of outside air. The design heating and cooling temperatures are 68°F and 78°F respectively. The value for the cfm/ft^2 is 1.5. For the unconditioned spaces i.e. the ducts, basement and the plenums, the cooling and heating temperature set point is taken as 70°F and 95°F respectively. These temperatures are basically used to calculate the design airflow in the zone. Now for unconditioned zones there is no calculation of airflow rate so it is a recommended practice that design temperatures for unconditioned spaces should be a fair assumption of the temperature, which is attained in such a space if the space is adjacent to a conditioned space.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. Both the heating and cooling controls are reset, which points towards the reset schedule already explained. The preheat temperature is 45°F. The outside air is being control by temperature and the minimum value is set at 30% of the maximum. For the VAV system the fan control is SPEED while it is constant for the CV system. For the VAV system the minimum air is kept at 50% of the total while the reheat temperature rise for the CV system is 50°F. It is common practice to take the reheat coil temperature rise as the difference between the maximum supply temperature and the minimum supply temperature, which in this case are 105°F and 55°F

respectively. Harrington Tower also employs an economizer cycle. For the model it is assumed that the economizer works between 65°F and 37°F.

3.4.2.3 Simplified Input File

The simplified input file for Harrington Tower is created in the same manner as it was for WERC. The space conditions and the overall area and volume are the same as the massless but instead of defining the eight floors, everything is being incorporated in a single floor.

3.4.3 Wehner Business Administration Building

The E. L. Wehner Building at Texas A&M University houses the Lowry Mays College & Graduate School of Business. It is located on the west campus of Texas A&M University, College Station.

This is a 4-story 192,000-ft^2 academic building catering to the different needs of students, faculty and staff. This facility became functional in spring, 1995. In addition to classrooms, the building houses all staff, faculty, and administrative offices for the Mays College. Computer network accessibility from every office and classroom interconnects students, faculty, and administrative offices and provides access to Texas A&M mainframe computing facilities and the Internet. Figures 3.5 and 3.6 show the Wehner Building and the building as created by the simulation model using DrawBDL (Joe Huang and Associates 1993-94). Table 3.3 summarizes the parameter, which have been used to create the two simulation models.

3.4.3.1 Massless Input File

Because of the complex façade of the building, 18 hours were required just to create the outer envelope of the building. These hours included the walk-throughs and studying the layouts acquired from the facilities office on the campus. Another 4 hours were then utilized to put in the basic system details. For the massless model, the system

details contained many assumptions and default values. Overall 22 hours were spent in creating the model, performing walk-throughs and removing bugs from the input file.

3.4.3.1.1 Loads

As was done in the other buildings, in the massless model the effects for thermal mass and storage were neglected. Custom weighting factors for all the surfaces were not calculated and pre determined factors were used.

a) Construction Details

For the exterior, interior walls and floors typical construction is assumed. The exterior wall is made up of 4 inch common brick, ½ inch plywood, ¾ inch light weight gypsum plaster on the outside, mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a ¾ inch gypsum board is considered with an R-value of 0.67. The drop ceilings are acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof gravel, 3/8 inch built-up roofing, polyurethane insulation and ¾ inch wood. The floor construction is considered to be 6-inch lightweight concrete. The glass for the doors and windows is single-pane tinted. The floor weight is taken as 70 lbs/ft^2 for concrete construction.

b) Zoning

Zoning for this building and all others, which have been simulated is considered to be very simplified. All the floors are divided into two zones i.e. exterior and interior
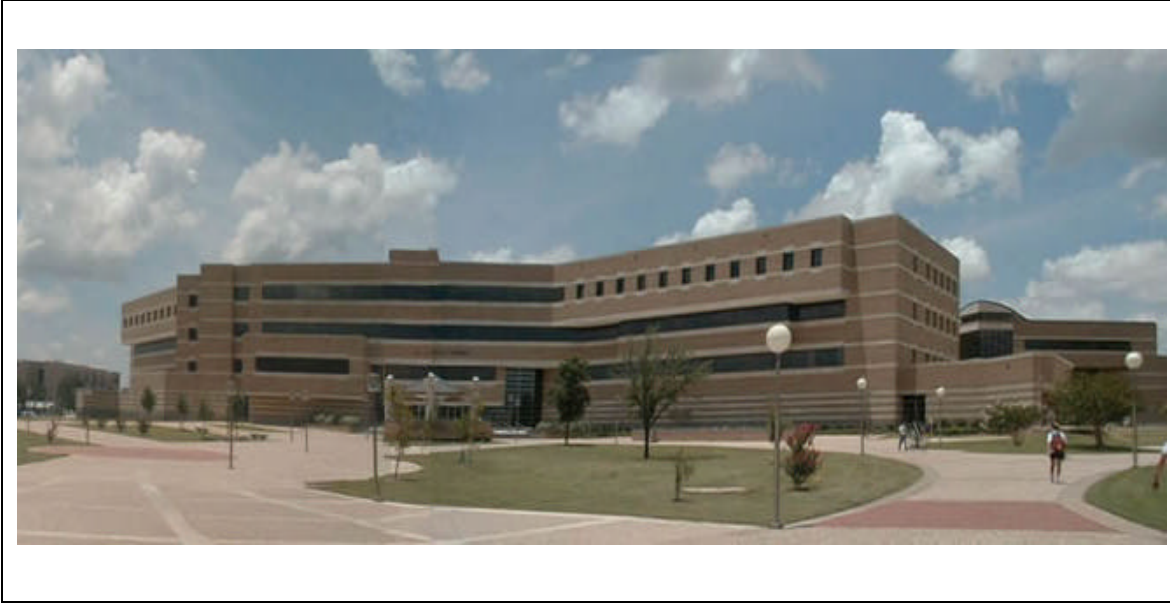
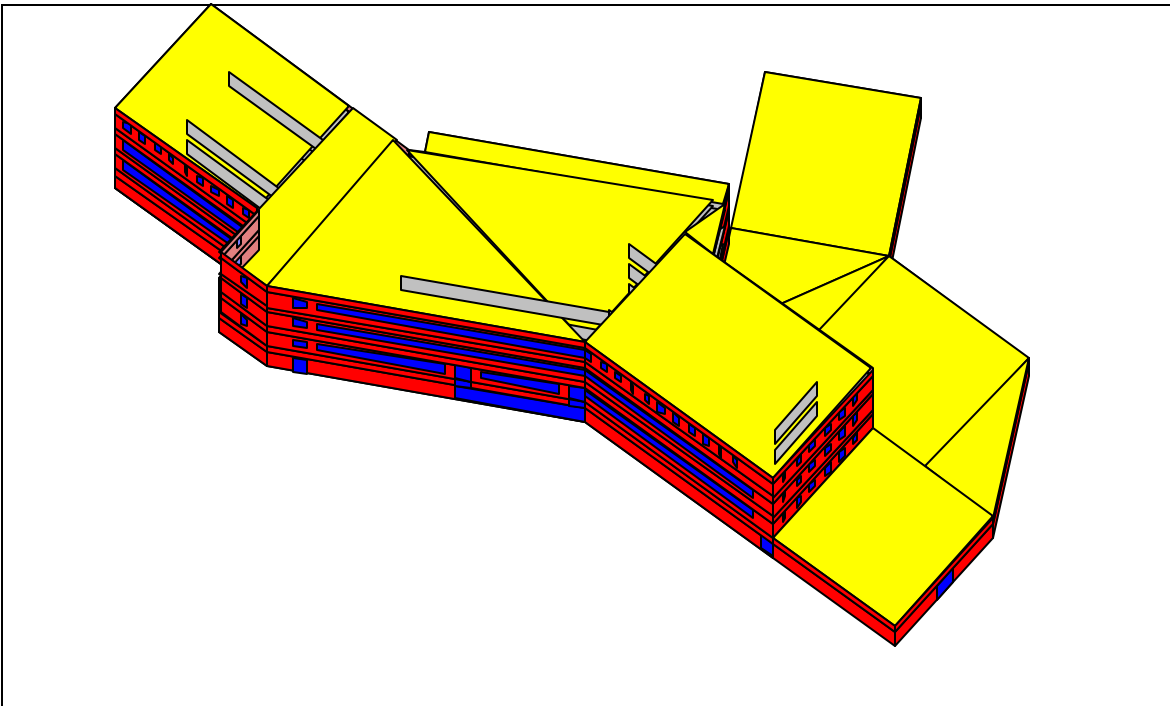**Fig: 3.5 Wehner Business Administration Building**

Fig: 3.6 DrawBDL rendering of Wehner Business Administration Building

TABLE 3.3
Model description of Wehner Business Building

Sections of the Input file	MASSLESS	ADVANCED
Level of effort	22 hours	11 hours
Loads (source: drawings,survey)	**17 hours**	**6 hours**
Envelope	Massless construction	Thermal mass considered, details construction is defined for all the envelope elements
	All floors and exterior details defined according to the asbuilt drawing	All floors and exteriordetailed defined according to the drawing. All the interior floors and ceilings defined with the correct coordinates
	4 floors, 8 zones	4 floors + 1 underfloor, 8 zones
	Conditioned and glazed area obtained from field measurements and as built drawings	Conditioned and glazed area obtained from field measurements and as built drawings
Schedules	Typical schedules for an office building with 50% load on weekends	Typical schedules for an office building with 50% load on weekends
Shading	no shading	no shading
Space conditions		
Office	100 people	100 people
	1.3 Wsq ft for lighting	1.3 Wsq ft for lighting
	3.0 W/sq ft for equipment	3.0 W/sq ft for equipment
	0.25 airchanges/hr	0.0 airchanges/hr
Class	100 people	100 people
	1.4 W/sq ft for lighting	1.4 W/sq ft for lighting
	1.0 W/sq ft for equipment	1.0 W/sq ft for equipment
	1.0 airchanges/hr	0.0 airchanges/hr
Lecture hall	100 people	100 people
	2.2 W/sq ft for lighting	2.2 W/sq ft for lighting
	1.0 W/sq ft for equipment	1.0 W/sq ft for equipment
	1.0 airchanges/hr	0.0 airchanges/hr
Basement	no basement	no occupancy
		1.0 W/sq ft for lighting
		0.5 W/sq ft for equipment
		1.0 airchanges/hr
Systems (source : Hui Chen for the advanced model)	**5 hours**	**4 hours**
Type	Dual Duct VAV	Dual Duct VAV, Single Duct CV
Schedules		
Fans	100% during peak hours, 30% during weekends	100% during peak hours, 20% during weekends
Temperature	heating set point is 68F w/ setback to 60F, cooling set point is 76F w/ setup to 78F	heating set point is 68F w/ setback to 60F, cooling set point is 78F w/ setup to 82F
Reset	no reset for heating and cooling	no reset for heating and cooling

TABLE 3.3
(contd.)

Sections of the Input file	MASSLESS	ADVANCED
Zone Commands		
General space	1.5 cfm/sq ft	supply air from spec sheets
	20cfm/person outside air	outside air from spec sheets
	Inside temperature 72F for heating and 77F for cooling	Inside temperature 68F for heating and 78F for cooling
Plenum, duct, basement	Inside temperature 70F for heating and 95F for cooling	Inside temperature 70F for heating and 95F for cooling
System Specification	Max and min supply temperatures 105Fand 55F, preheat temp is 45F	Max and min supply temperatures 105Fand 55F
	VAV cycling down to 50% of low loads	VAV cycling down to 50% of low loads.
RESULTS:		
ANNUAL ENERGY CONSUMPTION (MMBtu)	**48557**	**36025**
ANNUAL ENERGY CONSUMPTION PER UNIT AREA (kBtu/ sq ft)	**279**	**172**
RMSE(%) (Comparison to measured data)		
CHW	152.39	128.03
HW	76.98	90.38
WBE	137.35	36.37
MBE(%)		
CHW	123.81	87.97
HW	-56.87	-73.44
WBE	136.37	34.89

zone. The interior zone is defined by stepping in 20 feet from the exterior wall in all directions.

c) Schedules

In the loads portion the schedules for occupancy, equipment, lighting and infiltration are considered.

- Occupancy: Although Wehner is an academic building, the entrance and exit is controlled. Only those people who are registered with the school or the staff can go inside the building after 5:00 pm. So the occupancy schedule is more of an office building then an academic building. It is

assumed that the occupancy is maximum between 9:00 am and 11:00 am in the morning and from 3:00 pm to 5:00 pm in the afternoon. For the massless model, it is assumed that the occupancy goes down to zero during evenings and nights. For the weekends between 10:00 am and 5:00 pm the occupancy ranges from 40% to 50% of the maximum, while it is 0 during the evenings and nights.

- Equipment: The Equipment load varies from 80% to 90% of the maximum watt/ft^2, between 8:00 am in the morning to 9:00 pm in the night. For the rest of the time it is assumed to be at 10%, including the weekends.

- Lighting: This building contains motion sensors, so the lighting levels have been assumed to follow the occupancy levels but instead of being reduced to zero during unoccupied hours the minimum lighting level is kept at 10% of the maximum. For the weekends it is the same with the minimum going down to 10%.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command in the space-conditions. For the massless model it is assumed that the building is not positively pressurized.

d) Space Conditions

For the massless Wehner Building is divided into three spaces according to the conditions. They are the OFFICE, CLASS and LECTUREHALL. The OFFICE conditions apply to all the interior zones of the main building. The CLASS conditions are for the exterior zones. For the OFFICE it was assumed that the space available for each person is 145ft^2. The lighting is 1.5 watts/ft^2 and the lighting type is recessed fluorescent vented to return air. So the lighting load into the room was considered to be 80% while the remaining is being added to the return air. The equipment is 3watts/ft^2. The infiltration rate is taken as 0.25 ACH.

The CLASS condition assumes that every person has 200ft^2 approximately. The lighting is 1.4 watts/ft^2; the lighting type is the same. Equipment is 1 watt/ft^2. For the massless model the air changes per hour for the exterior zone are considered to be 1.

The LECTUREHALL is the space condition for the auditorium built on the periphery of the building. For this space each person has approximately 300 ft^2. The lighting is 2.2 watts/ft^2 and the equipment is again 1 watt/ft^2. The infiltration is 1 ACH.

e) Shading

The Wehner Building is situated in a relatively open space. The only shading it gets is from the West Campus Library or from its own facades.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates. Since the model is massless the interior ceilings and floors are defined with equivalent areas. Also since the structure is complex with numerous facades, the POLYGON command is used extensively to define the roofs.

3.4.3.1.2 Systems

For the massless model, a VAV dual duct system is assumed. This system is supplying air to the entire building with the same conditions.

a)   Schedules

- Fan Schedule: It is assumed that during weekdays the fans are at 100% from 8:00 am in the morning to 6:00 pm in the night. From 7:00 pm to 7:00 am fans are cycled down to 20%. During the weekends the fans are at 30%.

- Thermostat Schedule: Thermostat setback and setup are assumed for the massless model. The heating set point is 68°F between 8:00 am and 6:00 pm. During nights it is being set back to 60°F while for the evenings and weekends it is 65°F. For cooling the set point is 78°F between 8:00 am

and 6:00 pm and then it is set up to 82°F during the night and at 80°F during the weekends.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

All the interior and exterior zones are assumed to be at the same conditions. The heating and cooling set points are 68°F and 78°F. The thermostat type is reverse action and the throttling range is defaulting to 5°F. The outside air is governed by the number of people in the zone and the value is 20 cfm/person (ASHRAE Fundamentals). The airflow for all zones is 1.5 cfm/ft^2.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The heating and cooling controls are constant. Since this is a variable volume system that FAN-CONTROL is defined as SPEED, which simulates it as a VFD. This allows the fan motor to vary its speed according to the load. The static and efficiency of the supply and return fan are assumed. MIN-CFM-RATIO is given a value of 0.5, which allows the system to vary airflow between the maximum and minimum value set at 0.5. So the air supply to the zone will be modulated according to the different load schedules. There is no dual duct variable volume system in DOE-2 so to simulate one a DDS system is defined and then it is converted to a variable volume system by using the MIN-CFM-RATIO and FAN-CONTROL commands. The return air passage for this system is through ducts and the supply-cfm is not defined because the cfm/ft^2 is already defined in the zone commands.

3.4.3.2 Advanced Input File

3.4.3.2.1 Loads
        After the first 22 hours, another 11 hours were put into the massless model to
create an advance simulation model of the Wehner Building. The advanced input file has
all the layers defined in the form of coordinates to ensure that the custom weighting
factors for all the layers and surfaces are calculated correctly. Due to the complexity of
the layout, again the bulk of the time was consumed in defining interior floors and
ceilings with the POLYGON commands.

a) Construction Details

        For the exterior, interior walls and floors typical construction is assumed. For this
model every layer is being separately defined. The construction is the same as it was for
massless model but now the layers are spelled out. The exterior wall is made up of 4inch
common brick, ½ inch plywood, ¾ inch light weight gypsum plaster on the outside,
mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a
¾ inch gypsum board on both sides and an air-gap in between. The drop ceilings are
acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof
gravel, 12inch hollow concrete block and perforated roof insulation. The underground
floor and wall construction is considered to be gypsum plaster and 12inch hollow
concrete block. The floors above ground are vinyl tiles, gypsum plaster and 12inch
hollow concrete block. The glass for the doors and windows is single-pane tinted, the
glass type is taken from the DOE-2 window library and the frame is aluminum without
thermal break. Thermal mass is being considered so the floor weight is taken as 0.

b) Zoning

        Zoning for the advanced case is same as the massless model. Every floor of the
building is considered to be divided in two zones, exterior and interior. The interior zone
is assumed to consist of all the area, which is 20 feet from the exterior wall.

c) Schedules

For the loads portion, schedules for occupancy, lighting, equipment and infiltration have been defined.

- Occupancy: The occupancy schedule for the advanced model is the same as for the massless model.

- Equipment: Between 8:00 am and 6:00 pm the equipment load varies from 70% to 90% of the maximum. It drops down to 20% in the night. As for the weekends it is being kept constant at 50%.

- Lighting: Again the lighting is assumed to follow the occupancy schedule because of the presence of motion sensors. The minimum level of lighting is set at 30% during the evenings and nights. For the weekends it is kept at 40%.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions. The value of infiltration is 0 as the building is being considered as positively pressurized.

d) Space Conditions

In addition to the three conditions defined in the massless model, another space condition has been added to define the SUBLEVEL which houses the mechanical rooms and hallways to and from the lecture halls.

The space condition for the OFFICE and CLASS are the same for advanced case, only the infiltration in the advanced case is reduced to 0ACH.

The SUBLEVEL is an underground space with zero occupancy. The lighting and equipment watt/ft^2 are 1 and 0.5 respectively. The lighting type is the same rest of spaces. The infiltration is taken as 1ACH because the doors at the loading docks are left open for extended periods and this portion is not conditioned.

The portion in the LOADS section is used to describe the actual layout of the building with the right coordinates. In the massless the ceilings of each floor were defined with equivalent area. But in order to calculate the custom weighting factors, each and every surface in the building is to be designed completely. In the case of Wehner considerable time was required to add the right coordinates for all the interior floors and ceilings. Excessive use of the polygon commands was made. During the creation of this model, a new version of the DrawBDL program was acquired which has the ability to show triangular cross-sections. This help considerably in defining the roofs and ceiling correctly.

3.4.3.2.2 Systems

For the advanced case the same dual duct VAV system is used. The airflow through each zone has been gathered from the design specs along the exact outside air being supplied to all the zones.

a) Schedules

- Fan Schedule: The fan schedule is same for the advanced model as it was for the massless model.

- Thermostat Schedule: The thermostat schedule is also kept the same as the massless model.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

The zone commands are slightly different from the massless model. The outside air is not being defined per person. The amount of outside air through is zone is determined by the AHUs, which are supplying the different zones. And the cfm/ft^2 has also been reduced from 1.5 to 1.1; this value is extracted from the design values. The design heating and cooling set points are 68°F and 78°F respectively. For the unconditioned spaces i.e. the ducts, basement and the plenums, the design cooling and

heating set points is taken as 70°F and 95°F respectively. These temperatures are basically used to calculate the design airflow in the zone. Now for unconditioned zones there is no calculation of air flow rate so it is a recommended practice that design temperatures for unconditioned spaces should be a fair assumption of the temperature which is attained in such a space if the space is adjacent to a conditioned space.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. Both the heating and cooling controls are constant. This means that the hot and cold supply air temperatures do not modulate with the outsides air temperature. The supply static is taken as 2.7 inches of water, this is an average over all the air handlers supplying the building. For the VAV system the fan control is SPEED. For the VAV system the minimum air is kept at 50% of the total.

3.4.3.3 Simplified Input File

The simplified input file for Wehner Building is created in the same manner as it was for the other two buildings. The space conditions and the overall area and volume along with the glazing are the same as the massless model but instead of defining the four floors; everything is incorporated in a single floor.

3.4.4 John B. Connally Building

John B. Connally Building houses the administrative offices of the whole Texas A&M system. Since this building is not located on the main campus, it is not supplied by the central plant. The heating and cooling requirements for this building are provided by an onsite chiller and boiler plant. The gross area is approximately 124,000 square feet. This is a typical office building housing only offices and conference rooms. Figures 3.7 and 3.8 show the John B. Connally Building and the DrawBDL rendering of the simulation model of the building (Joe Huang and Associates 1993-94). Table 3.4 summarizes the parameters used to generate the simulation models.

3.4.4.1 Massless Input File

        Creation of the massless simulation model for this building required approximately 16 hours. This included 2 walk-throughs, actual measurement of the windows and exterior walls, survey of different floors to determine lighting and occupancy distribution and acquisition of information on the plant and HVAC system from the commissioning engineer.

3.4.4.1.2 Loads

        As with the other buildings, for the massless model, the thermal mass and storage effects were neglected i.e. custom weighting factors for all the surfaces were not calculated and pre determined factors were used.

a) Construction Details

        For the exterior, interior walls and floors typical construction is assumed. The exterior wall is made up of 4inch common brick, ½ inch plywood, ¾ inch lightweight

        Gypsum plaster on the outside, mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a ¾ inch gypsum board is considered with an R-value of 0.67. The drop ceilings are acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof gravel, 3/8 inch built-up roofing,

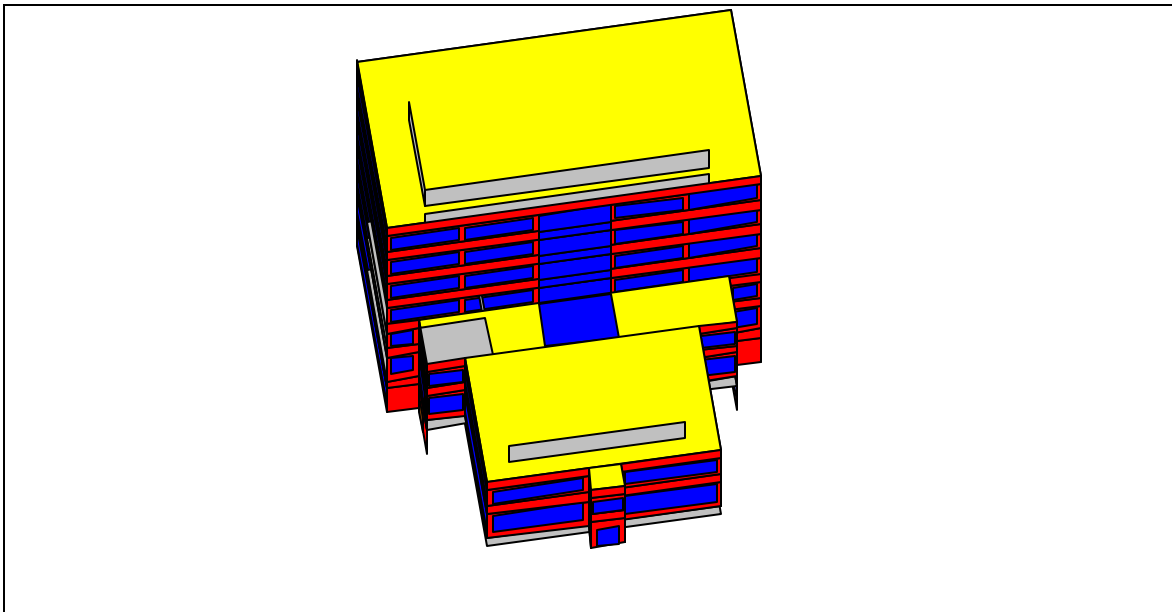**Fig: 3.7 John B. Connally Building (State Headquarters)**

Fig: 3.8 DrawBDL rendering of State Headquarters

TABLE 3.4
Model description of the John B. Connally Building

Sections of the Input file	MASSLESS	ADVANCED
Level of effort	16 hours	10 hours
Loads (source: drawings,survey)	**10 hours**	**8 hours**
Envelope	Massless construction	Thermal mass considered, details construction is defined for all the envelope elements
	All floors and exterior details defined according to the asbuilt drawing	All floors and exteriordetailed defined according to the drawing. All the interior floors and ceilings defined with the correct coordinates
	7 floors + basement, 16 zones	7 floors + basement, 16 zones
	Conditioned and glazed area obtained from field measurements and as built drawings	Conditioned and glazed area obtained from field measurements and as built drawings
Schedules	Typical schedules for an office building with 5% load on weekends	Typical schedules for an office building with 5% load on weekends
Shading	no shading	no shading
Space conditions		
General Space	150 sqft/ person	150 sqft/ person
	2.5 W/sq ft for lighting	2.5 W/sq ft for lighting
	1.5 W/sq ft for equipment	1.5 W/sq ft for equipment
	0.25 airchanges/hr	0.0 airchanges/hr
Systems (source: Tehesia Powell)	**6 hours**	**2 hours (for gathering information)**
Type	Single Duct VAV w/ reheat	Single Duct VAV w/ reheat
Schedules		
Fans	100% during peak hours, 20% during weekends	100% during peak hours, 20% during weekends
Temperature	heating set point is 68F w/ setback to 63F, cooling set point is 78F w/ setup to 83F	heating set point is 68F w/ setback to 60F, cooling set point is 78F w/ setup to 82F
Reset	no reset for heating and cooling	no reset for heating and cooling
Zone Commands		
General space	1.24 cfm/sq ft	1.24 cfm/sq ft
	Outside air defined for each zone separately	Outside air defined for each zone separately
	Inside temperature 68F for heating and 78F for cooling	Inside temperature 68F for heating and 78F for cooling
Plenum, duct, basement	Inside temperature 70F for heating and 95F for cooling	Inside temperature 70F for heating and 95F for cooling
System Specification		
	Max and min supply temperatures 105Fand 55F, preheat temp is 45F	Max and min supply temperatures 105Fand 55F
	VAV cycling down to 50% of low loads, temperature rise across the reheat coil is 50F	VAV cycling down to 50% of low loads, temperature rise across the reheat coil is 50F

TABLE 3.4
(contd.)

Sections of the Input file	MASSLESS	ADVANCED
Plants (source: Tehesia Powell)		
Plant specification		
Chiller size	3.744 MMBtu/hr (312 tons)	3.744 MMBtu/hr (312 tons)
Boiler size	2.1 MMBtu/hr	2.1 MMBtu/hr
Cooling Tower	Autosized according to the chiller	Autosized according to the chiller
Boiler efficiency	76%	76%
RESULTS:		
ANNUAL ENERGY CONSUMPTION (MMBtu)	35400	37850
ANNUAL ENERGY CONSUMPTION PER UNIT AREA (kBtu/ sq ft)	290.1	310.1
RMSE(%) (Comparison to measured data)		
Chiller electric	41.82	44.22
WBE	74.02	76.72
MBE(%)		
Chiller electric	10.46	16.11
WBE	48.22	52.30

polyurethane insulation and ¾ inch wood. The interior floor construction is assumed to have an R-value of 26. The underground floor construction is considered to uninsulated with an R-value of 2. The loading dock door is assumed to be made of hardboard, plywood and wood. The glass for the doors and windows is single-pane tinted. The floor weight is taken as 70lbs/ft^2 for concrete construction.

b) Zoning

Zoning is simplified. All the floors are divided into two zones i.e. exterior and interior zone. The interior zone is defined by stepping in 20 feet from the exterior walls in all direction.

c) Schedules

In the loads portion the schedules for occupancy, equipment, lighting and infiltration are considered.

- Occupancy: John B. Connally Building is an office building. So the working hours are from 8:00 am to 5:00 pm. It is assumed that the occupancy is maximum between 9:00 am and 11:00 pm in the morning and from 3:00 pm to 6:00 pm in the afternoon. For the massless model it is assumed that the occupancy goes down to zero during evenings and nights. For the weekends between 10:00 am to 5:00 pm the day hours the occupancy is 5% of the maximum, while it is 0 during evenings and nights.

- Equipment: The Equipment load is from 70% to 90% of the maximum watts/ft^2 defined, between 8:00 am to 9:00 pm. For the rest of the time it is assumed to be at 10%, including the weekends.

- Lighting: The lighting ranges from 50% to 80% between 8:00 am to 6:00 pm and between 30 and 40% for evenings and nights. For the weekends the level is maintained at 30%.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions. For the massless model the building is not assumed to be positively pressurized so the effect of infiltration is considered.

d) Space Conditions

For the massless John B. Connally Building is divided into two spaces. Space conditions OFFICE cover all the exterior zones while OFFICE1 is for all interior zones. For the OFFICE it was assumed the lighting is 2.5 watts/ft^2 and the lighting type is recessed fluorescent vented to return air. So the lighting load into the room was

considered to be 80% while the remaining is being added to the return air. This assumption is made since a portion of the lighting load is added to the return air passing through these vents. This load will increase the return air temperature and it is will show up in increased chilled water consumption. Adding of 20% of the lighting load is only used when return air path in the system portion is defined as a duct. The equipment intensity is 1.5watts/ft^2. The people are defined separately for each zone. The infiltration rate is taken as 0.25 ACH. The OFFICE1 conditions are same to the OFFICE conditions except for the number of people but since the occupancy is defined for each zone separately, the conditions are the same.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates. Since the model is massless, the interior ceilings and floors are defined with equivalent areas.

3.4.4.1.2 Systems

For the massless a single duct VAV system with terminal reheat is assumed. This system is supplying air to the entire building with the same conditions.

a) Schedules

- Fan Schedule: It is assumed that during weekdays the fans are at 100% from 8:00 am to 6:00 pm. During the evenings and nights, fans are operating between 20% and 30%. During the weekends the fans are at 20%.

- Thermostat Schedule: Thermostat setback and setup are assumed for the massless model. The heating set point is 68°F between 8:00 am and 6:00 pm. During nights it is being set back to 63°F while for the evenings and weekends it is 65°F. For cooling the set point is 78°F for the peak hours and then it is set up to 83°F during the night and at 80°F during the weekends.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

All the interior and exterior zones are assumed to be at the same conditions. The heating and cooling design set points are 68°F and 78°F. The thermostat type is reverse acting and the throttling range is defaulting to 5°F. The outside air and the supply air are defined separately for each zone. The values were obtained from the design data.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The heating and cooling controls are constant. This means that the hot and cold air supply temperatures do not modulate according to the outside air temperature. The preheat temperature is at 45°F. The outside air is temperature controlled. The minimum outside fraction is kept at 0.3. Since this is a variable volume system that FAN-CONTROL is defined as SPEED, which simulates it as a VFD. This allows the fan motor to vary its speed according to the load. The static and efficiency of the supply and return fan are assumed. MIN-CFM-RATIO is given a value of 0.5, which allows the system to vary airflow between the maximum and minimum value set at 0.5. So the air supply to the zone will be modulated according to the different load schedules. The return air passage for this system is through ducts and the supply-cfm is not defined because the cfm/ft^2 is already defined in the zone commands. The reheat temperature rise is 50°F. An economizer has also been added to the system, which operates when the outside temperature is below 65°F. There is no humidity control on the economizer.

3.4.4.1.3 Plants

a) Plant Equipment Commands

The cooling and heating requirements of the John B. Connally Building are provided by a captive plant comprising of three chillers and two boilers. Usually the requirements are satisfied by two chillers and a boiler, the rest of the equipment is on standby. The chillers are assumed to be open centrifugal type with a cooling tower. The two main chillers are not defined separately. The combined size of the three is 312 tons. This value is obtained from the design data. The size of the hot water boiler is taken as 2.1MMBtu/hr. This value is also from design data. The cooling tower is being auto sized according to the chillers. The chiller control is taken as standby; this means that DOE-2 will simulate the chiller operation according to the loads in the building. The boiler efficiency is taken as 76%, which is on the low side. Defaults are used for the rest of the plant parameter commands.

3.4.4.2 Advanced Input File

3.4.4.2.1 Loads

Another 15 hours were put in to create the advanced model for the John B. Connally Building. The only major change from the massless model was the all the interior layers and floors were defined with the correct coordinates and the construction was defined in the layer format.

a) Construction Details

For the exterior, interior walls and floors typical construction is assumed. For this model every layer is being separately defined. The exterior wall is made up of 4inch common brick, ½ inch plywood, ¾ inch light weight gypsum plaster on the outside, mineral wool insulation and ½ inch gypsum board on the inside. For the interior walls a ¾ inch gypsum board on both sides and an air-gap in between. The drop ceilings are acoustic tiles with an R-value of 3.7. The roof construction is assumed to be ½ inch roof gravel, 12inch hollow concrete block and perforated roof insulation. The floors, both

interior and underground are vinyl tiles, gypsum plaster and 12inch hollow concrete block. The glass for the doors and windows is single-pane tinted, the glass type is taken from the DOE-2 window library and the frame is aluminum without thermal break. Thermal mass is being considered so the floor weight is taken as 0. The construction for the loading dock door is considered to be the same as the massless model.

b) Zoning

Zoning for the advanced case is same as the massless model. Every floor of the building is divided in two zones, exterior and interior. The interior zone is defined by stepping in 20 feet from the exterior walls in all directions.

c) Schedules

For the loads portion, schedules for occupancy, lighting, equipment and infiltration have been defined.

- Occupancy: The occupancy schedule for the advanced model is the same as for the massless model.
- Equipment: Between 8:00 am and 6:00 pm, the equipment load varies from 70% to 90% of the maximum. It drops down to 20% in the night. As for the weekends the equipment load is constant at 10%.
- Lighting: The lighting ranges from 50% to 80% during the daytime and between 30% and 40% for evenings and nights. For the weekends the level is at 30%.
- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions. However since the building is positively pressurized the infiltration rate is 0 ACH.

d) Space Conditions

The space conditions are exactly the same as for the massless model.

The rest of the portion in LOADS section is used to describe the actual layout of the building with the right coordinates. In the massless the ceilings of each floor were defined with equivalent area. But in order to calculate the custom weighting factors, each and every surface in the building is to be designed completely. Due to the presence of the atrium the second floor was divided into three portions and every portion is defined separately.

3.4.4.2.2 Systems

For the advanced case the same single duct VAV system with terminal reheat is used. The airflow through each zone has been gathered from the design specs along the exact outside air being supplied to all the zones.

a) Schedules

- Fan Schedule: The fan schedule is same for the advanced model as it was for the massless model.

- Thermostat Schedule: The thermostat schedule is also kept the same as the massless model.

- Cooling and heating availability schedule: Cooling and heating for this simulation is available throughout the year.

b) Zone Commands

The zone commands are the same as the massless model. The outside air and the supply air are being defined for each zone separately. The values were obtained from the design specifications provided by the commissioning engineer. The values for the thermostatic set point, setup and setback are all the same as the massless model.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. Both the heating and cooling controls are constant. The supply static is taken as 1.25 inches of water; this value was obtained from the design data. For the VAV system the fan control is SPEED. For the VAV system the minimum air is kept at 50% of the total. The temperature rise across the reheat coil is 50°F. This value is the difference between the minimum and maximum supply air temperature, which are 55°F and 105°F respectively.

3.4.4.2.3 Plants

a) Plant Equipment Commands

The commands for the chillers and boilers for the building are the same as the massless model.

3.4.4.3 Simplistic Input File

The simplified input file for John B. Connally Building is created in the same manner as it was for the other two buildings. The space conditions and the overall area and volume along with the glazing are the same as the massless but instead of defining the four floors; everything is being incorporated in a single floor.

3.4.5 Habitat House

The Habitat House is a low budget single-family house being built under the Habitat for Humanity project. The gross square footage is 1170 and it is located in the city of Bryan. It is assumed that this particular house is occupied by three people. Figures 3.9 and 3.10 show the habitat house and the DrawBDL rendering of the simulation model created (Joe Huang and Associates 1993-94). Table 3.5 summarizes the parameters used to generate the simulation models.

3.4.5.1 Massless Input File

The completion of the simulation input of the massless model required approximately 7 hours. This included the data gathering. This house is being used as a model for research by Victor Kootin Sanwu. So the details of the house, the layout, equipment, HVAC system and other details were acquired from him. No walk-throughs were conducted for this simulation model.

3.4.5.1.1 Loads

For the massless model, the effects due to thermal storage were neglected i.e. custom weighting factors for all the surfaces were not calculated and pre determined factors were used.

a) Construction Details

IECC 2000 recommended values for climate zone 4 have been used for the envelope construction. The exterior walls have an R-value of 13, the interior partitions are considered to be made of plywood, the floor is 4" heavy concrete slab without insulation, the ceiling is R-30 while the roof is assumed to be made of asbestos shingles. The windows are double pane clear glass from the DOE-2 window library and the front door is made of steel frame and insulated (Victor Kootin Sanwu).

Fig: 3.9 The Habitat House
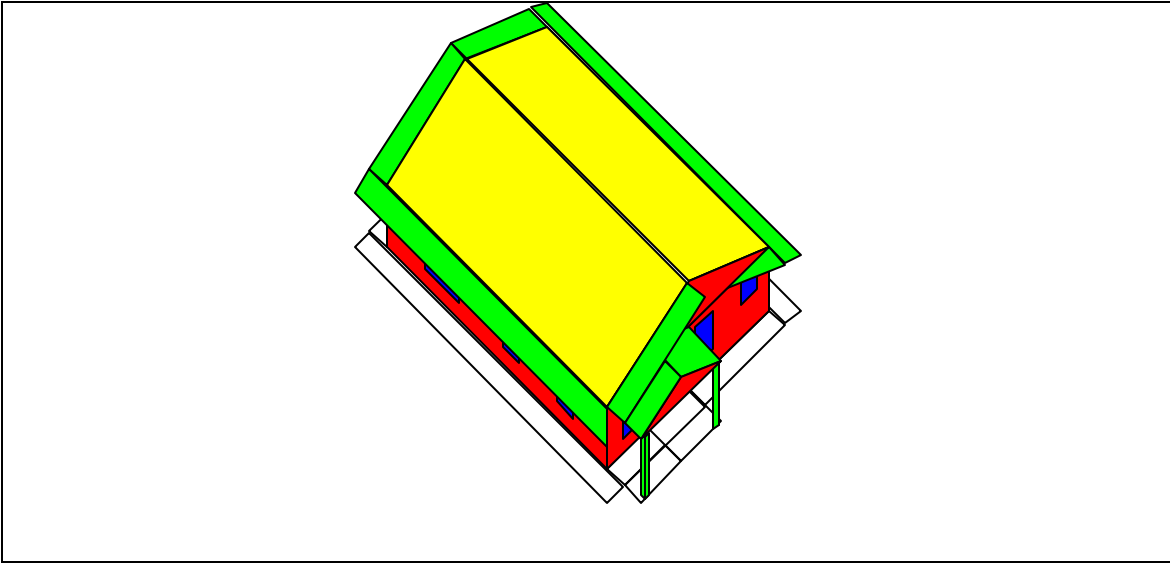
Fig: 3.10 DrawBDL rendering of the Habitat House

TABLE 3.5
Model description of the Habitat House

Sections of the Input file	MASSLESS	ADVANCED
Level of effort	7 hours	3 hours
Loads (source: Victor Kootin Sanwu)	**5 hours**	**2 hours**
Envelope	Massless construction	Thermal mass considered, detailes construction is defined for all the envelope elements
	All floors and exterior details defined according to the details provided by Victor Kootin Sanwu	All floors and exteriordetailed defined according to the details. All the interior floors and ceilings defined with the correct coordinates
	1 floor + attic, 2 zones	1 floor + attic, 2 zones
	Conditioned and glazed area obtained from th plan of the house being studied by Victor Kootin Sanwu	Conditioned and glazed area obtained from th plan of the house being studied by Victor Kootin Sanwu
Schedules	Typical schedules for a house with high load in mornings, evenings and on weekends	All schedules have measured values provided by Victor Kootin Sanwu
Shading	shading due to overhangs	shading due to overhangs
Space conditions		
General Space	3 people	3 people
	0.6 W/sq ft for lighting	0.6 W/sq ft for lighting
	1.0 W/sq ft for equipment	1.0 W/sq ft for equipment
	0.57 airchanges/hr (ASHRAE 136p)	0.57 airchanges/hr (ASHRAE 136p)
Attic	No people	No people
	0.1 W/sq ft for lighting	0.1 W/sq ft for lighting
	0 W/sq ft for equipment	0 W/sq ft for equipment
	1.0 airchanges/hr	1.0 airchanges/hr
Systems(source: Victor Kootin Sanwu)	**1 hour**	**1/2 hour**
Type	Residential system w/ gas furnace and Airconditioner	Residential system w/ gas furnace and Airconditioner
Schedules		
Fans	100%	100%
Temperature	heating set point is 72F w/ setback to 68F, cooling set point is 78F w/ setup to 80F	heating set point is 71F, cooling set point is 73 (no setbacks)
Zone Commands		
General space	1.0 cfm/sq ft	1.0 cfm/sq ft
	20 cfm/person outside air	20 cfm/person outside air
	inside temperature 68F for heating and 78F for cooling	inside temperature 68F for heating and 78F for cooling
Attic	inside temperature 70F for heating and 95F for cooling	inside temperature 70F for heating and 95F for cooling

TABLE 3.5
(contd.)

Sections of the Input file	MASSLESS	ADVANCED
System Specification		
	Max and min supply temperatures 105Fand 55F	Max and min supply temperatures 105Fand 55F
Plants (source: Victor Kootin Sanwu)	**1 hour**	**1/2 hour**
Plant specification		
Furnace size	Autosized	36000 Btu/hr
A/C size	Autosized	2.5 tons
Furnace efficiency	75%	75%
A/C efficiency	10.5 SEER	10.5 SEER
DHW size	0.028 gal/min	0.042 gal/min
DHW efficiciency	76%	76%
RESULTS:		
ANNUAL ENERGY CONSUMPTION (MMBtu)	**165.6**	**225.1**
ANNUAL ENERGY CONSUMPTION PER UNIT AREA (kBtu/ sq ft)	**70.8**	**96.2**
RMSE(%) (Comparison to measured data)		
Total electric	57.40	48.40
MBE(%)		
Total electric	-19.33	-0.81

b) Zoning

   The main house is one zone and the attic is the other zone. Both of them have different space conditions.

c) Schedules

   In the loads portion the schedules for occupancy, equipment, lighting and infiltration are considered.

- Occupancy: Typical values for a residence have been assumed. So during the night from 10:00 pm to 8:00 am the occupancy is maximum. Occupancy reduces to 20% during the daytime. Between 7:00 pm and 9:00 pm it is 80%. For weekends occupancy is maximum during the

nights from 9:00 pm to 10:00 am and ranges from 40% to 50% during the day.

- Equipment: The Equipment load is 70% between 7:00 am to 8:00 am and from 10:00 pm to 12 midnight. 80% of the total equipment wattage is being utilized between 6:00 pm and 9:00 pm. The rest of the time the equipment load is 5% of the maximum. For weekends it is set at 60%.

- Lighting: The lighting load is 10% during nights. It ranges from 50% to 75% during the rest of the occupied hours and it is 5% during the unoccupied time i.e. during the day. For weekends the load is fixed at 50%.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions. (The value is in space condition)

d) Shading

The overhangs of the roof and the front of the house are modeled as shades. The shading schedule, which varies the transmittance of the shades is fixed at zero, so that no sunlight is passing through the shades at any time during the year.

e) Space Conditions

For the massless the Habitat House is divided into two spaces. Space conditions LIVING AREA cover all the rooms and conditioned space while ATTIC defines the attic or the unconditioned space. For the ATTIC it was assumed the lighting is 0.1 watts/ft^2 and the lighting type is incandescent. So the entire lighting load is being added to the room. There is no equipment in the attic. The occupancy is also zero. The infiltration rate is taken as 1ACH. For the LIVING AREA conditions, the occupancy is 3 inhabitants, the lighting level is 0.6watts/ft^2 and the equipment load is 1watt/ft^2. The value for the air changes has been taken from ASHRAE standard 136P, which says that

ACH = 0.57 x weather factor. The weather factor depends on the city. So for this case it was assumed to be Houston. For Houston the weather factor is 0.81.

The rest of the portion in the LOADS section is used to describe the actual layout of the building with the right coordinates. Since the model is massless, the interior ceiling and floor is defined with equivalent areas. The POLYGON command is used to define the walls of the attic.

3.4.5.1.2 Systems

For the house the residential system of DOE-2 is used to model the heating and cooling of the Habitat House.

a) Schedules

- Fan Schedule: It is assumed that the system varies from 75% to 100% during the day and for the rest of the time including the weekends it is at the maximum. The fan operation is regulated with the occupancy level in the house.

- Thermostat Schedule: Thermostat setback and setup are assumed. For heating temperature is 72°F for the occupied hours. It is set back to 68°F for the rest of the time. For cooling the set point is 78°F for the occupied hours and then it is set up to 80°F during the unoccupied time.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

- Domestic hot water schedule: This schedule is kept at maximum throughout the year.

b) Zone Commands

There are two zones, ATTIC, the unconditioned zone and LIVING AREA, the conditioned zone. For the conditioned zone heating and cooling design set points are 68°F and 78°F. The thermostat type is proportional and the throttling range is defaulting

to 5°F. The outside air is 20 cfm/person and the supply air is 1cfm/ft^2. For the unconditioned zone heating and cooling design set points are 70°F and 95°F. These temperatures are basically used to calculate the design airflow in the zone. Now for unconditioned zones there is no calculation of airflow rate so it is a recommended practice that design temperatures for unconditioned spaces should be a fair assumption of the temperature, which is attained in such a space if the space is adjacent to a conditioned space.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The heating and cooling controls are constant. FAN-CONTROL is defined as CYCLING to model a residence in which the heating and cooling is governed by the thermostat setting. The static and efficiency of the supply and return fan are assumed. The COOLING-EIR is 0.325, which corresponds to an Airconditioner of 10.5 SEER. The heating system is a gas furnace with an AFUE of 76% (FURNACE-HIR = 1.33); it is assumed that this furnace has a pilot light, which is consuming 800 Btu/hr. The domestic water heater is also gas, it has a flow rate of 0.0278 gal/min. This value is calculated from IECC 2000 by the following formula:

Daily hot water consumption = (30 x a) + (10 x b)

Where,

a = no. of livings units

b = no. of bedrooms in each living unit

For the Habitat House, the living unit is one and three bedrooms are considered.

The supply temperature of water is taken as 140°F and the efficiency of the water heater is taken as 76%.

3.4.5.2 Advanced Input File

3.4.5.2.1 Loads

Another 3 hours were put in to create the advanced model for the Habitat House. The only major change from the massless model was that measured values for different schedules and correct capacities of the heating and cooling systems were used as inputs along with the calculation of custom weighting factors.

a) Construction Details

In order to calculate the custom weighting factors detailed constructions for the different envelope elements was used. From the information acquired from Victor Kootin Sanwu, the exterior walls consist of oriented strand board (OSB), cellulose fill for insulation and Wood studs. The DOE-2 material library does not have these materials, so assumptions were made in the selection of materials. OSB was approximated to hard wood; wood studs were approximated to soft wood. The insulation was available from the material library. For the interior walls a ¾ inch gypsum board on both sides and an air-gap in between. The roof construction is asbestos shingles and hard wood (approximation of OSB). The floor is 4" heavy concrete without insulation with gypsum plaster. The glass for windows is double-pane clear, the glass type is taken from the DOE-2 window library and the frame is aluminum without thermal break. Thermal mass is being considered so the floor weight is taken as 0.

b) Zoning

Zoning for the advanced case is same as the massless model.

c) Schedules

For the loads portion, schedules for occupancy, lighting, equipment and infiltration have been defined. For the advanced case all the values for the schedules have acquired from the researcher.

- Occupancy: The values are slightly changed from the massless model. Between 6:00 pm and 6:00 am, the occupancy is maximum. From 7:00 am to 5:00 pm it reduces down to zero. For the weekends occupancy is maximum 24 hours. The scheduled is simplified since no exact figures were available for the house.

- Lighting and Equipment: The lighting and plug loads have been measured by the researcher for each for the entire week, as well as holidays.

- Infiltration: The infiltration schedule is kept at a 100% throughout the year and the amount of infiltration is being governed by the Air changes/hour command down in the space-conditions.

d) Space Conditions

The space conditions are exactly the same as for the massless model.

The rest of the portion in LOADS section is used to describe the actual layout of the building with the right coordinates and the shades. For the Habitat House every detail of the envelope was already defined in the massless model. So for the advanced model only floor-weight was changed to zero and layer type construction was used to calculate the custom weighting factors.

3.4.5.2.2 Systems

For the advanced case the same system type is used.

a) Schedules

- Fan Schedule: The fan schedule is same for the advanced model as it was for the massless model.

- Thermostat Schedule: There are no setbacks and setups for the thermostat schedule. The heating set point is 71°F while the cooling set point is 73°F. These set points were obtained from Victor Kootin Sanwu.

- Cooling and heating availability schedule: The cooling and heating for this simulation is available throughout the year.

b) Zone Commands

There are two zones, ATTIC, the unconditioned zone and LIVING AREA, the conditioned zone. For the conditioned zone heating and cooling design set points are 68°F and 78°F. The thermostat type is proportional and the throttling range is defaulting to 5°F. The outside air is 20 cfm/person and the supply air is 1cfm/ft^2. For the unconditioned zone heating and cooling design set points are 70°F and 95°F.

c) System Commands

In the system commands the maximum and the minimum temperatures are set at 105°F and 55°F respectively. The heating and cooling controls are constant. FAN-CONTROL is defined as CYCLING to model a residence in which the heating and cooling is governed by the thermostat setting. The static and efficiency of the supply and return fan are assumed. The COOLING-EIR is 0.325, which corresponds to an air-conditioner of 10.5 SEER. The heating system is a gas furnace with an AFUE of 76% (FURNACE-HIR = 1.33); it is assumed that this furnace has a pilot light, which is consuming 800 Btu/hr. The domestic water heater is also gas, it has a flow rate of 0.042 gal/min. This value is calculated from the formula as described in the Massless model.

The supply temperature of water is taken as 140°F and the efficiency of the water heater is taken as 76%. The cooling system capacity is 30,000 Btu/hr while the heating system is 36,000 Btu/hr.

3.4.5.2.3 Plants

a) Plant Commands

In the plant commands the furnace and the domestic water heater have been defined again. The furnace size is defined as 0.036 MMBtu/hr while the DHW size is defined as 0.0015 MMBtu/hr. The rest of the values are taken as DOE-2 defaults.

CHAPTER IV

STATISTICAL TECHNIQUES

Measuring the variability of a given data set can be accomplished in a number of ways. The easiest is the range, which is the difference between the maximum and minimum value. The more complex parameters are the coefficient of variance (CV) and mean bias error (MBE).

Researchers have used many statistical parameters to judge the accuracy of the simulated data against the measured. In an early research project, Torres-Nunci (1989) declared the simulation model he created, calibrated just by visually analyzing the differences between the measured and simulated energy consumption through scatter plots. Hinchey (1992) in her research created several simulation models ranging from one zone to eighteen zones and found that for an internally load dominated building the effect of zoning is negligible. Annual energy consumption results show a difference of 3.5% between a one zone and an eighteen-zone model. This result was obtained by calculating residuals of the measured and simulated data. In this research, the author used averaged hourly consumption values and simple percentage difference.

Bronson (1992) used monthly percentage differences to calibrate the simulation model to non-weather dependent loads. The final calibrated model was within 1.04% of the measured data for the six months comparison period. However for weather dependent loads, the percentage differences were greater. Chilled water was still very good at –1.57% while for hot water he got –9.62%. Several other researchers have used this method and have come up with claimed accuracies within 1% depending on the type of averages used i.e. monthly, weekly or daily.

Bou-Saada (1994) used Coefficient of Variance of the Root Mean Square Error (CV (RMSE)) and the Mean Bias Error (MBE) to define the accuracy of the calibrate model. The above-mentioned variables were first used by Kreider and Haberl (1994) for the energy predictor shootout series. Over 150 contestants were provided with data sets of energy consumption of two buildings in Texas and they had to come up with the most accurate fit with the measured data by different calibration techniques for hourly energy

consumption. For this purpose the CV (RMSE) and MBE were used as the criteria of accuracy. The winner of the contest had a CV (RMSE) of 10.4% for both the datasets. Bou-Saada in his research has stated that these indices are more accurate in determining the level of calibration than the simple percentage difference or the residual analysis. Using daily or monthly percentage differences tend to average out the variations, which are present in hourly data. So for calibration purposes it is best to calculate the CV (RMSE) and MBE hourly.

Since the current research does not include the calibration of the simulation models, the use of daily CV (RMSE) and MBE to compare massless and advanced models is sufficient. In addition to this, for the sensitivity analysis the daily percentage difference has been used to quantify the importance of different parameters. For the sensitivity analysis, the massless model is considered the massless model for all sensitivity runs. The percentage difference is taken between the massless model and the sensitivity run. For example the massless model was run as is and then thermal mass was added to it without making any other changes. The values are for WERC. The percentage difference between the two for chilled water consumption was –11.65% while for hot water was 28%. The values of hot water consumption are 10 times less than that of chilled water. So the 28% change in hot water consumption does not have the same impact as that of the decrease in chilled water consumption. This example elaborates that just looking at statistical parameters do not always convey the correct result. It is necessary to have the complete information in order to do a correct analysis.

Following is a brief description of the different indices used in the research.

4.1 Percentage Difference

The average daily percentage difference is a simple calculation. This parameter was used to compare the sensitivity of different parameters by comparing each run against the basecase, which in this case is the massless model. It is given by

$$\text{percentage difference} = \left(\frac{\overline{y_s} - \overline{y_{bc}}}{\overline{y_{bc}}} \right) \qquad (4.1)$$

where,

$\overline{y_s}$ = mean of the daily energy use for the sensitivity runs

$\overline{y_{bc}}$ = mean of the daily energy use for the massless model

4.2 Mean Bias Error

The mean bias error (MBE) is measure of the sum of errors in a non-dimensional format. The total difference between the two sets of data for each hour or day, is then divided by the total number of data points minus the number of regression variables. This will give the mean bias or the mean of the residuals. This value divided by the mean of the massless model will give the MBE in percentage form. Mathematically it is given by:

$$MBE = \left(\frac{\frac{\sum_{i=1}^{n}(y_{p,i} - y_{m,i})}{n - p}}{\overline{y_{m,i}}} \right) \text{x } 100 \qquad (4.2)$$

where,

$y_{p,i}$ = predicted values

$y_{m,i}$ = measured values

$\overline{y_{m,i}}$ = mean of the measured values

n = number of data points

p = number of regression variables

4.3 Root Mean Square Error

Another index, which measures the variability of the data, is the root mean square error. For each data point the residuals are calculated and squared. These are then added and divided by the total number of data points to give the mean square error. A square root of this will provide the root mean square error (RMSE). It is given :

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_{p,i} - y_{m,i})^2}{n - p}} \qquad (4.3)$$

4.4 Coefficient of Variance of RMSE

The coefficient of variation of the root mean square error (CV (RMSE)) is essentially the non-dimensional form of the RMSE. It is obtained by dividing the RMSE by the mean of the data set, which is being used as the benchmark. It is given by

$$CV(RMSE) = \left(\frac{\sqrt{\dfrac{\sum_{i=1}^{n} (y_{p,i} - y_{m,i})^2}{n - p}}}{\overline{y_{m,i}}} \right) \times 100 \qquad (4.4)$$

This value depicts how well the simulation model fits the measured data. The main aim of calibrating a simulation model is to lower this value.

The CV (RMSE) and MBE have been used extensively in the calibration process of building energy simulation models. Soebarto (1997), Yoon and Lee (1999), Bou-Saada and Haberl (1998) have all used these parameters to show the goodness of fit of the simulation model with the measured data.

Kaplan et al. (1990) used an extensive routine for determining the accuracy of the simulation model with the measured data. It consisted of five steps ranging from simple percentage differences to normalized RMSE, which is the same as the CV (RMSE). One interesting parameter used by the author was to determine whether the simulated data was in phase with the measured data. For this purpose the RMSE of the data as is and the simulated data shifted one hour on either side was compared. If the RMSE of the shifted data was less than the RMSE of the as is data, this means that the data is out of phase. According to the author out of phase profiles indicate inaccurate schedules or deficiencies in the modeling of building thermal time constants.

For the purpose of better calibrating simulation model to the measured data, the use of hourly CV (RMSE) and MBE is justified. The reason being is that in using daily or monthly percentage differences, the dissimilarities between the model and the actual conditions are overlooked, because over longer period these changes tend to balance out. So it cannot be said with certainty that the resulting model is a true depiction of the building operations. Based on hourly calculation, a well calibrated model will have a CV(RMSE) of within 20% and a MBE of less than 1%. To achieve these kinds of accuracies the calibration can take a considerable amount of time. But to set a standard limit on tolerances is not an easy task. Other than research, in which time constraint is not a major issue, all other projects are very stringent on time and expenditure. So the limits on these indices should be according to the situation. If the savings due to retrofits amount to a large number, then the calibrated model should provide accurate information about the building operation. Otherwise methods like the percentage differences can be used for minor projects or sensitivity analyses.

CHAPTER V

OUTPUT ANALYSIS

The DOE-2.1e simulation program gives detailed outputs about the building being simulated. The outputs, which are to be generated, are defined in the input file. All the four portions of the program i.e. the loads, systems, plants and economics have separate reports. They are further subdivided into the verification and summary reports. The verification reports give all the information about the building specified in the input file. The summary reports provide the actual results from the simulation. In order to compare the simulation results with the measured data it is more feasible to use the hourly report format. This format allows the user to see the hourly change in variables of interest along with the daily and monthly averages and summations.

The output from DOE-2 is not in a user-friendly format. The data obtained in an output file must be processed before it can be analyzed. For detailed analysis of building operations, the hourly reports are used. These reports are generated for any time-period, assigned in the input file. If the report is generated for a complete year, it will contain 8760 data points for one variable. This is a significant amount of data and it is tedious to extract this data from the output file. There are different programs available solely for data extraction purposes. AWK is a programming language specifically created for data manipulation purposes. But to use this as a data extractor, the user should have the basic ability to write routines in the C-programming language. The other method commonly used is to write data extraction macros in Microsoft Excel. This requires the user to have knowledge of Visual Basic.

To facilitate data extraction for this research, a general macro was written in Visual Basic, which can be customized according to the output required. This means that by switching the different code lines, either hourly or daily data can be extracted from the output file.

For commercial buildings, the variables of interest are chilled water (CHW) and hot water (HW) usage and the whole building electricity (WBE). For a building, which is being supplied chilled water and hot water the three variables defined are enough.

However for a case where boilers and chillers are a part of a single building, more variables related to this equipment may be required e.g. boiler and chiller loads. This depends however on the measured data available. If the CHW, HW and WBE are still being measured then only these variables are sufficient for the analysis.

The DOE-2.1e simulation software provides the user with a large variety of variables ranging from outside dry bulb temperature to the capacity of domestic hot water heater. The complete list of the variables which can be selected as output in the hourly reports are defined in the DOE-2.1e supplement, Appendix A. This list is constantly updated by the Lawrence Berkeley National Laboratory for every new version. In the input, variables are defined by type and number. "Type" defines the part of the input file from which the variable is being extracted, e.g. global variable type means that the variables in this section relate to the weather file inputs like the dry bulb temperature, humidity ratio, ground temperature etc. For each variable type, different variables are assigned different numbers. So in loads, for variable-type global the outside dry bulb temperature has a number 4, while the same variable in the systems portion has a number 8. However the output of these two variables will be identical.

For this research the hourly reports were extracted from the systems portion of the input file. As stated earlier the variables chiefly used for this research along with their type and list number are:

- Outside dry bulb Temperature
  Variable-type = global
  Variable-list = 8

- Chilled water usage
  Variable name = Total cooling load
  Variable-type = user name of Plant-assignment
  Variable-list = 1

- Hot water usage

    Variable name = Total heating load

    Variable-type = user name of Plant-assignment

    Variable-list = 2

- Whole Building Electric

    Variable name = Total electric load

    Variable-type = user name of Plant-assignment

    Variable-list = 3

To better understand the significance of the hourly and daily data, various graphical techniques are employed. As already discussed in the literature review, the correct representation of the output is very important. This has a major impact on the final outcome of the simulation. Hourly data is usually depicted in the form of graphs. For this research x-y scatter plots, times series plots and 3-D surface plots were utilized to compare the measured data with the simulated.

Generating a 3-D plot requires the use of specialized tools, which recreate columnar data into matrix form. This matrix then can be used to generate 3-D plots using different graphical software. For this study the program Colrow3D (Energy Systems Laboratory 1991) and Microsoft Excel were used to create surface plots.

5.1 Analysis Approach

In this research three separate models were created for each building, the massless model, the advanced model and the simplified model. In addition to this, sensitivity on selected parameters from loads and systems was also conducted in order to find which variable impacts the output most. The primary objective is to determine the accuracy of uncalibrated simulation. Another aspect is to check whether as-built and design operating data has any effect on the simulation model or not. As stated earlier,

three simulation models were created for each test case. Measured data was compared against both the massless model and the advanced model. This analysis was performed to check whether putting in as-built and design operating values for the building will reduce the error in the simulation model when compared with the measured data.

The third model created is referred to as the simplified model of the building. This model is a single floor, two-zone depiction of the entire building with same orientation, square footage and glazing area. Time spend on this model was minimal, on the average 4 hours for any building. This model was compared with the massless model. This comparison was accomplished by using two weather tapes. One for a hot and humid climate, Houston and the other, a cold climate, in this case Chicago.

This comparison was done to investigate the importance of defining the envelope accurately, like all the floors, zones, exterior and interior details.

5.2 Wisenbaker Engineering Research Center (WERC)

Wisenbaker Engineering Research Center is a 177,071sq.ft building located on the main campus of Texas A&M University. This is a multipurpose building. It is mainly divided between laboratories and offices. A large material-testing lab is also a part of this building.

The main difference between the massless model and the advanced model is thermal mass and system description. In order to consider thermal mass in DOE-2, the materials being used in the construction have to be defined layer wise. In addition to this all the partitions, interior walls and ceiling have to be defined with the correct coordinates.

For the massless input file in the systems' section, only a single system is supplying the complete building. While in the advanced input file, different system types, which are functional in the building are used, for example fan coil units for the basement, single zone constant volume reheat for the materials lab and variable volume systems for the rest of the building. In addition to this the airflow rate through the different air handlers was obtained from the design data as compared to assumed values

in the massless version. The advanced model was considered positively pressurized and leakage through the materials lab was increased due the observation that the loading door is open for the majority of time. Detailed walk-throughs conducted for the advanced model reduced the equipment intensity and increased lighting watts. The reason for increasing the lighting was that in addition to the standard lighting, offices and labs employ additional lights. This kind of light can have a different schedule then the standard lighting, so it was defined with the task lighting command.

The measured data obtained from the LoanStar database includes chilled and hot water consumption and whole building electricity.

5.2.1 Chilled Water Usage

Figures 5.1 to 5.6 show the comparison between simulated and measured chilled water usage for the massless and the advanced model respectively. The measured data is for the year 2000. For the simulated result, the consumption of the massless model is higher then the advanced model. The following conclusions can be drawn from the scatter plot:

- For higher temperatures, the massless simulation shows similar chilled water consumption. However the simulated values are at least 35% less than the measured for lower temperatures. The high consumption of measured chilled water at lower temperatures may indicate a stuck valve. It can also be suggested that since the building is internally load dominated, it is consuming approximately 50 MMBtu/day of chilled water for the winter months as well.

- The chilled water consumption for the advanced case is lower than measured values for all temperatures. 10% to 15% for higher temperatures and 30% to 50% for the lower temperature range. It can be

suggested that this decrease in chilled water use for the advanced case is mainly due to the use of design values for defining the system parameters.

- During a discussion with the commissioning engineer, it was found out that there were many maintenance problems associated with the operation of the air handlers. Most of the problems are related to the controls and the valves. These operational errors have been completely removed by October 2002. Measured data for the chilled water consumption is available for the post-commissioning period. This was compared with the two simulation models, which shows that chilled water consumption has been reduced considerably. It was reduced from an average daily consumption of 66 MMBtu to 48 MMBtu. This is a 28% reduction in the average daily use.

Another thing, which may be inferred from this analysis, is that an uncalibrated simulation model created with as-built information is a good approximation of the optimal operation of the building and this statement is true only if the initial design was optimal.

The time series plots for both the massless and the advanced model show the same profiles as the measured data. How during the month of October the measured data is showing an increase in the chilled water consumption. This may be due to the changes in weather conditions. This profile is not depicted by the simulated data sets.

As for the comparison with the measured data, the massless model has a better fit then the advanced case. The RMSE and the MBE for the massless case is 37.2% and –25.14%. For the advanced model they are 50.33% and –44.25%. This does not provide any conclusions, since current building operations may not be close to the optimum settings initially defined.
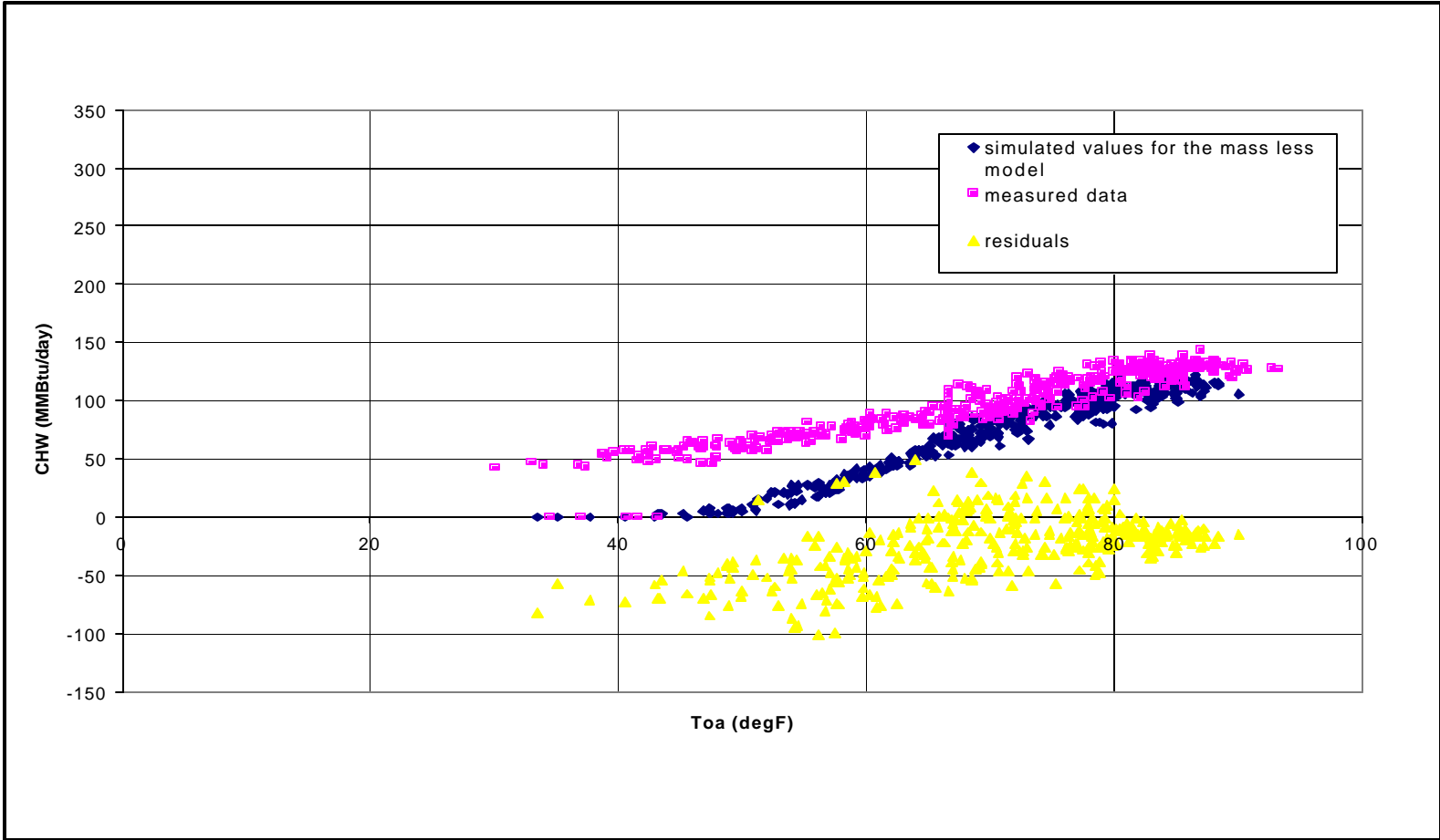
Fig 5.1 Comparison of chilled water consumption between simulated (massless model) and measured values for (MMBtu/day) (WERC)
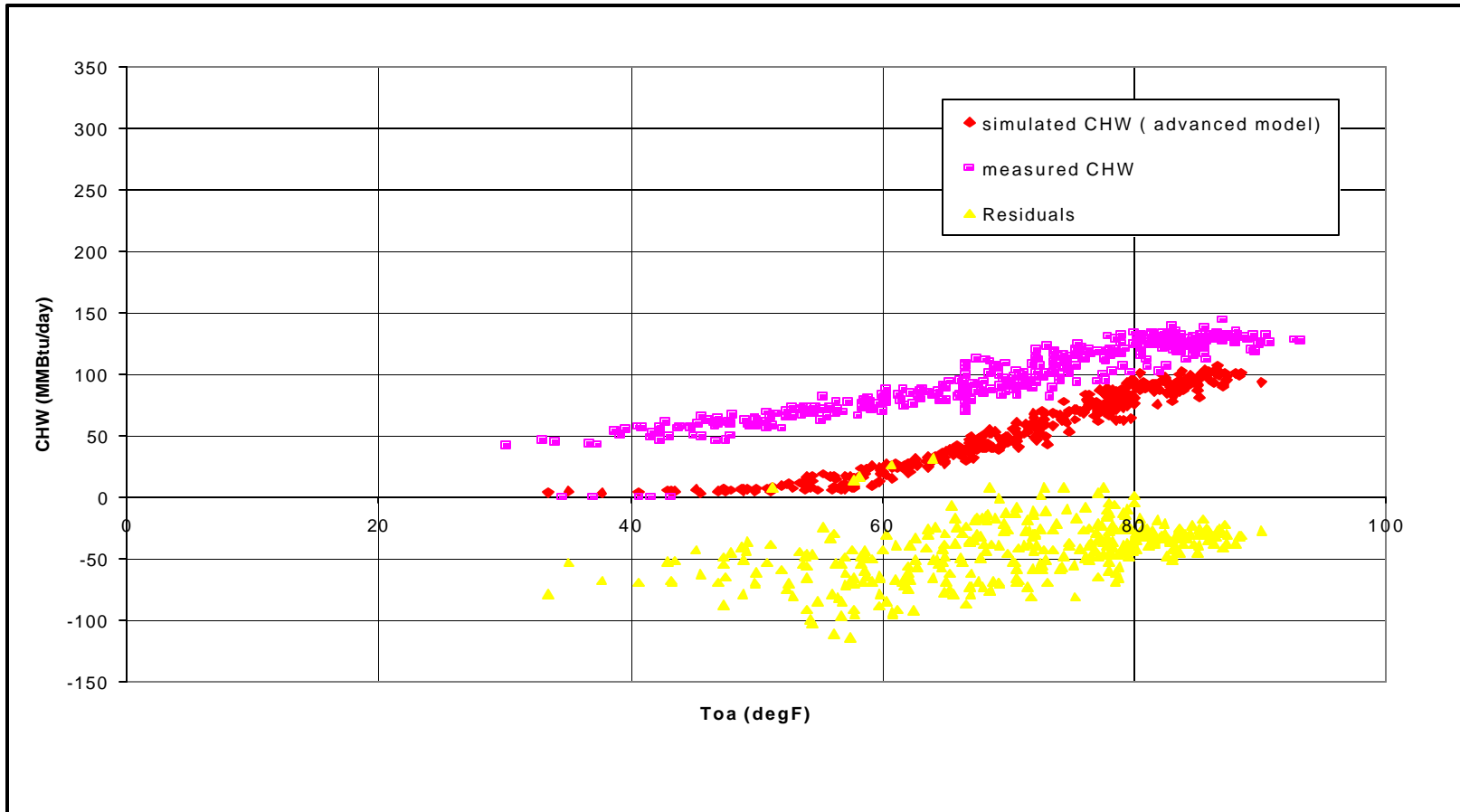
Fig. 5.2 Comparison of chilled water consumption between simulated (advanced model) and measured values for (MMBtu/day) (WERC)
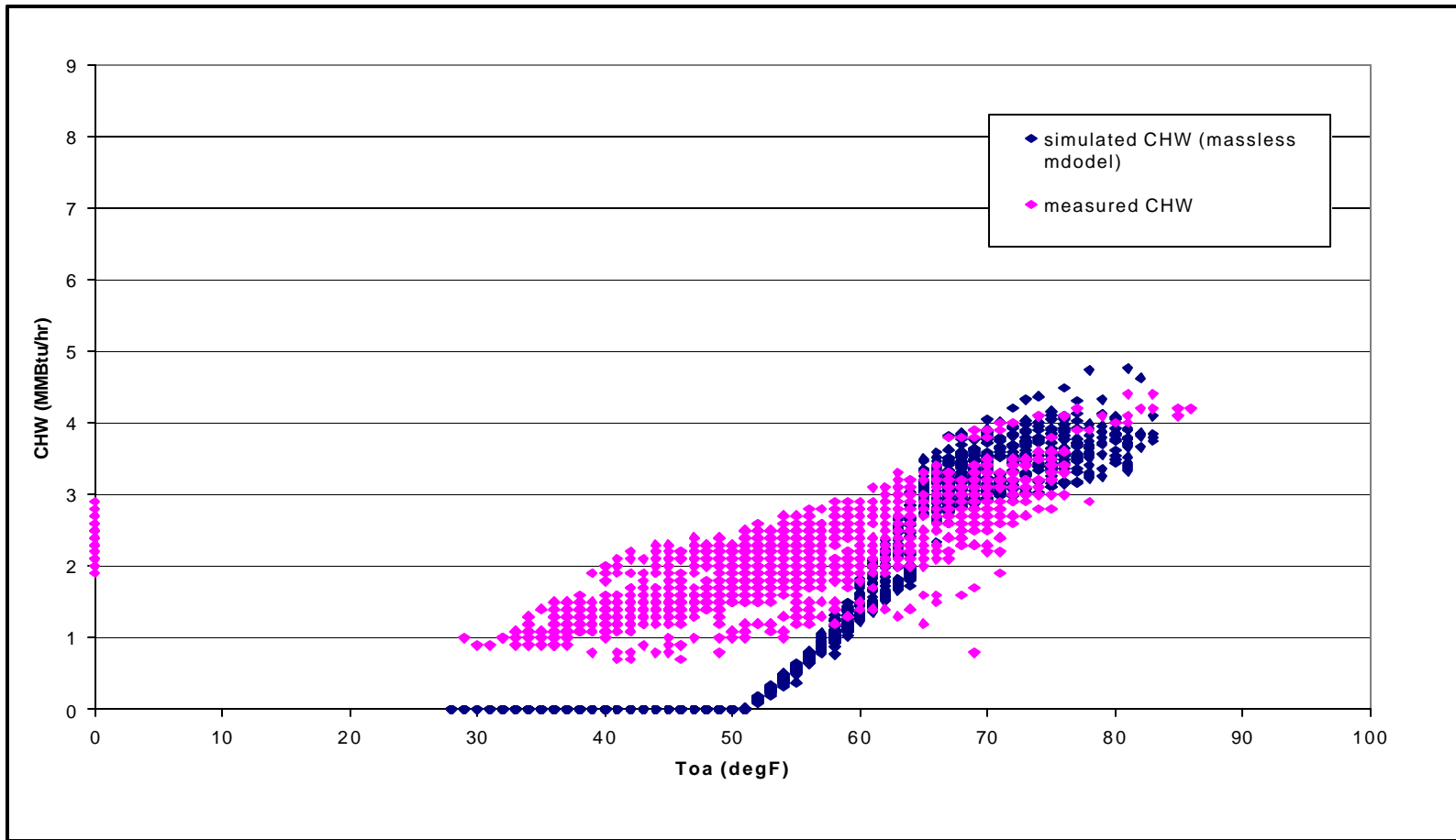
Fig 5.3 Hourly comparison of the post commissioning measured chilled water consumption with the simulated values (massless model)
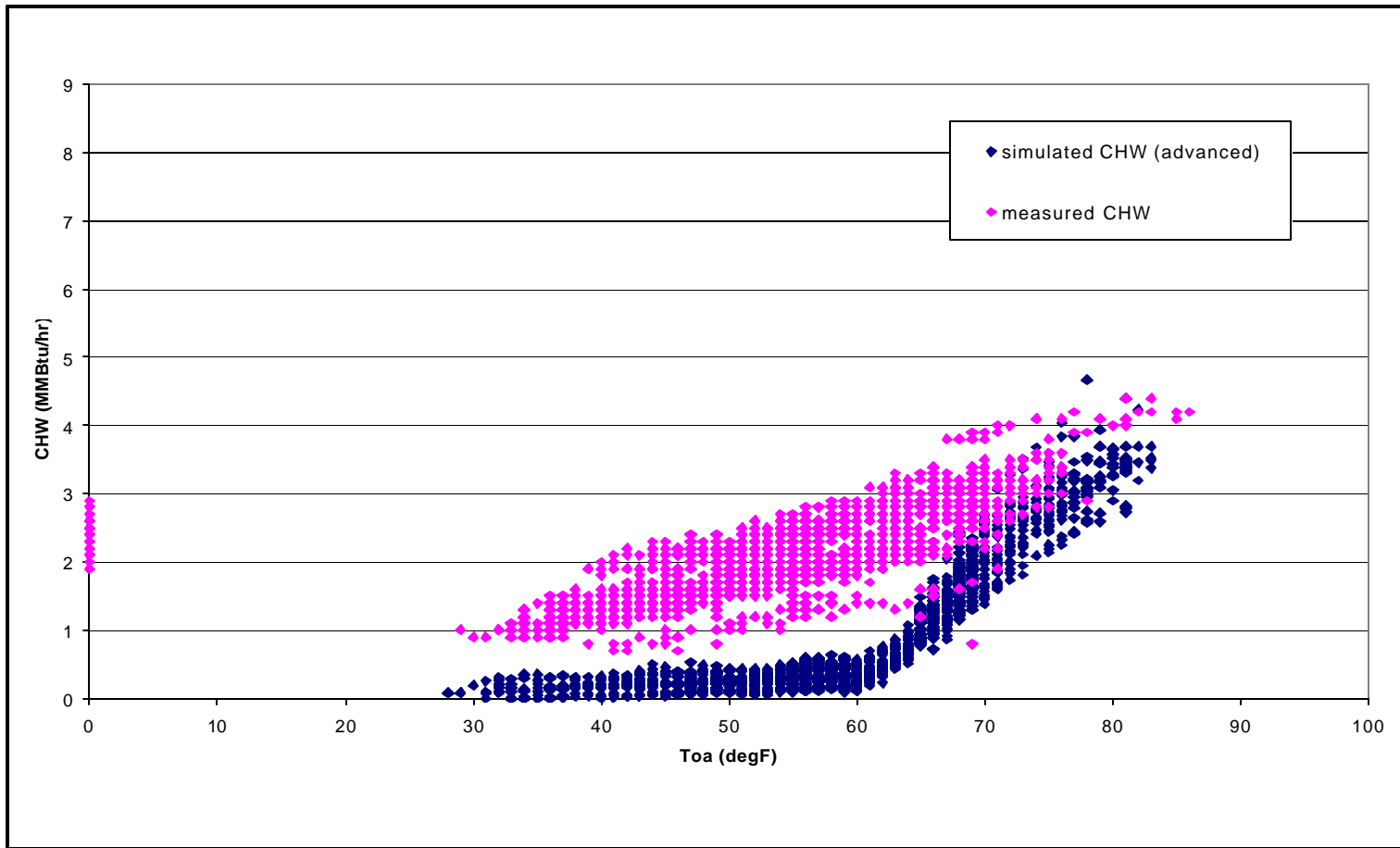
Fig. 5.4 Hourly comparison of the post commissioning measured chilled water consumption with the simulated values (advanced model)
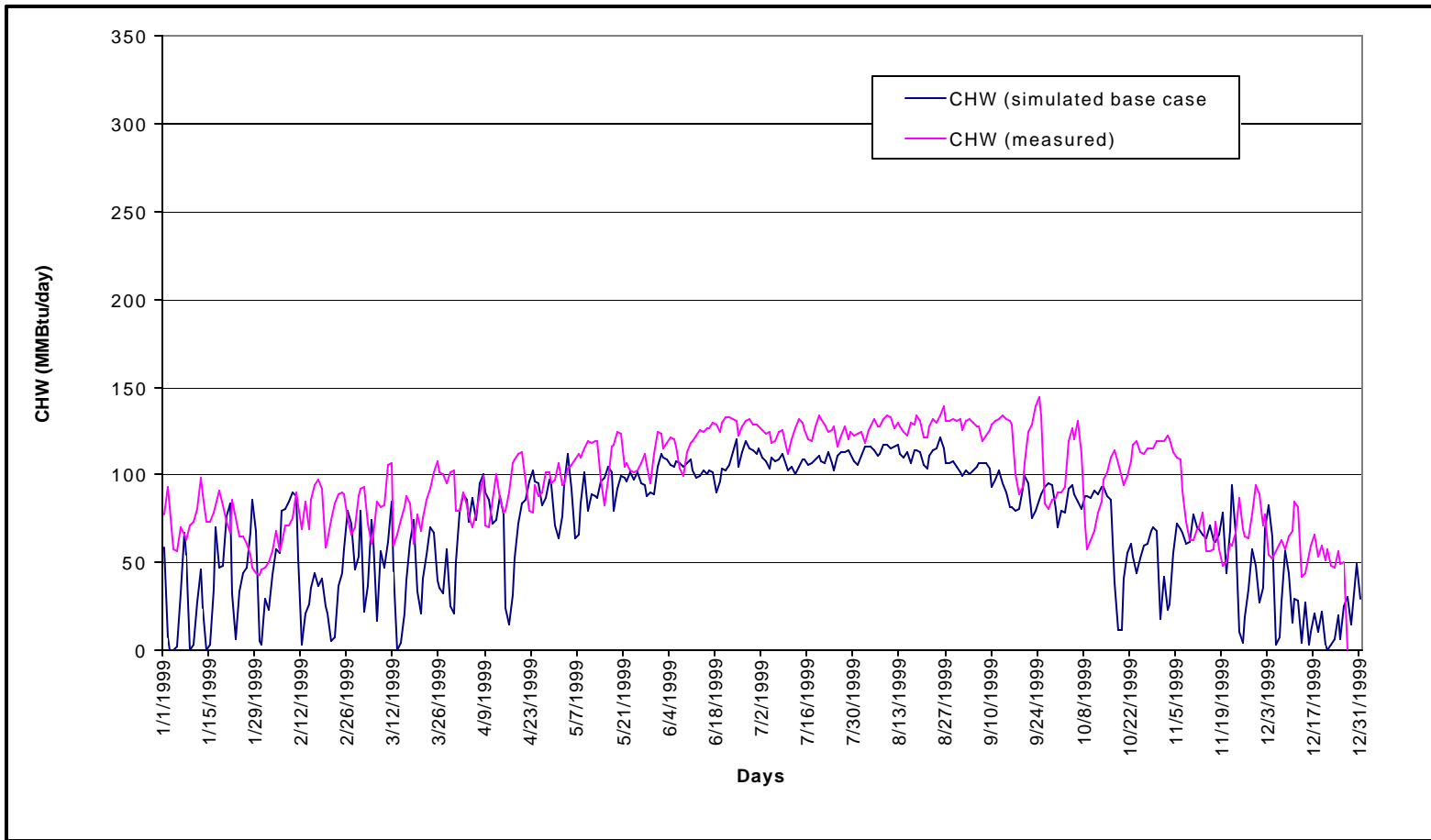
Fig 5.5 Time series of measured and simulated (massless model) for chilled water consumption (MMBtu/day)
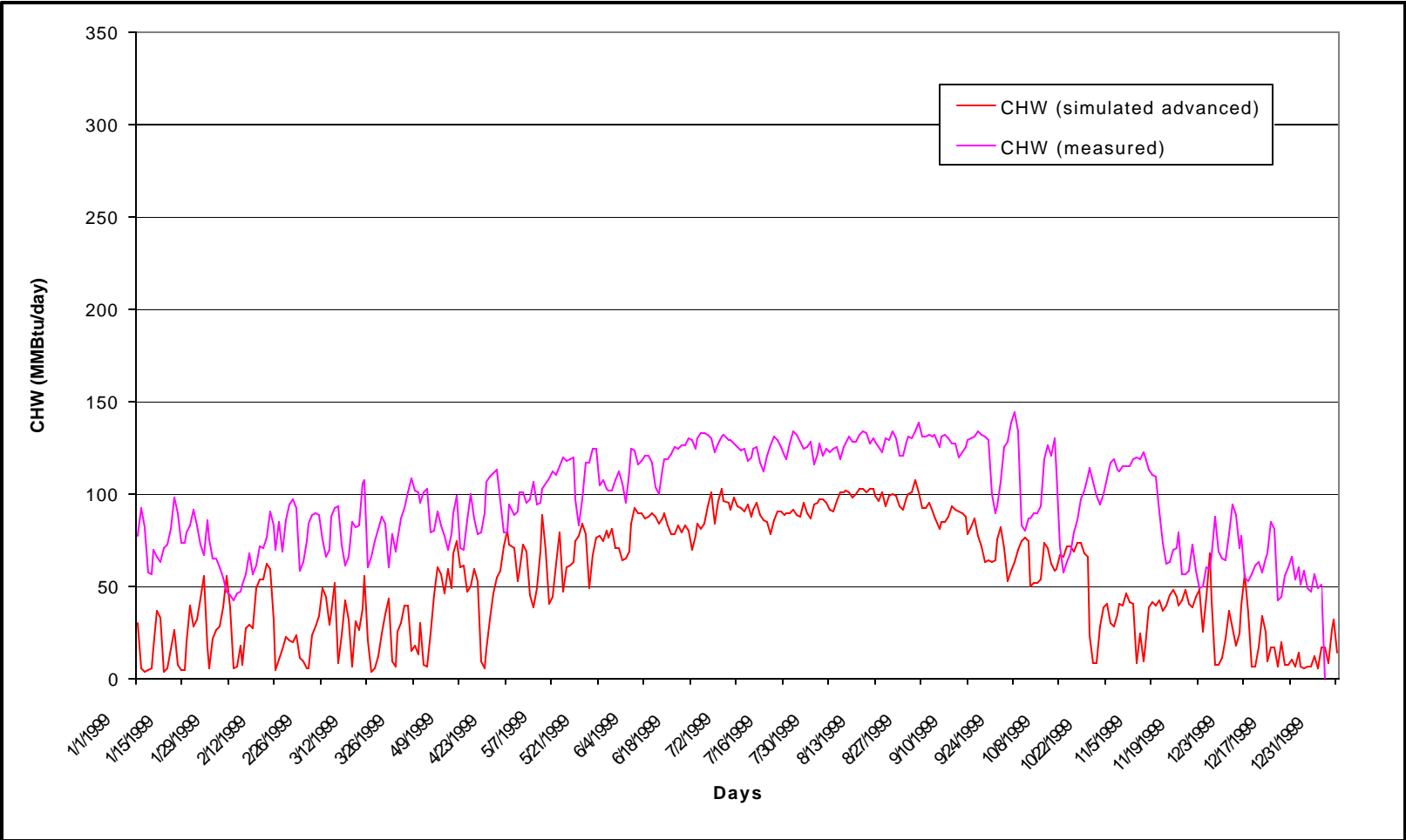
Fig 5.6 Time series of measured and simulated (advanced model) for chilled water consumption (MMBtu/day)

5.2.2 Hot Water Usage

Figures 5.7 to 5.10 show the comparison between simulated and measured hot water usage for the massless and the advanced model respectively. The measured data is for the year 2000. For hot water consumption, the simulated values for both the massless and the advanced models are less than the measured values. The following conclusions can be drawn from the comparison:

- The measured hot water data shows very high consumption between the temperatures 60°F and 80°F. The simulated data for both the models shows more reasonable values of around 17MMBtu/day in contrast with 40 MMBtu/day, which is being used.
- The leaking valves associated with a number of terminal units can be the cause of the high values for hot water consumption.
- Since the advanced model is using as-built values for all the airflows, the model may be depicting better operating conditions as compared to the measured data.
- The time series comparison of hot water consumption show that from the 2000 measured data, the building is using a high amount of hot water. The advanced model is using less than the massless model and it is better depicting the actual conditions as the hot water consumption is almost going down to zero for the summer months.

As with the cooling loads, the simulated values for both the massless case and the advanced case do not coincide with the measured values. The RMSE and MBE for hot water consumption in case of the massless model is 94.5% and –72.9% respectively. For the advanced case it is 113.5% and –92.68%. This does not provide any conclusive evidence about the quality of the simulation models or the quality of the data.
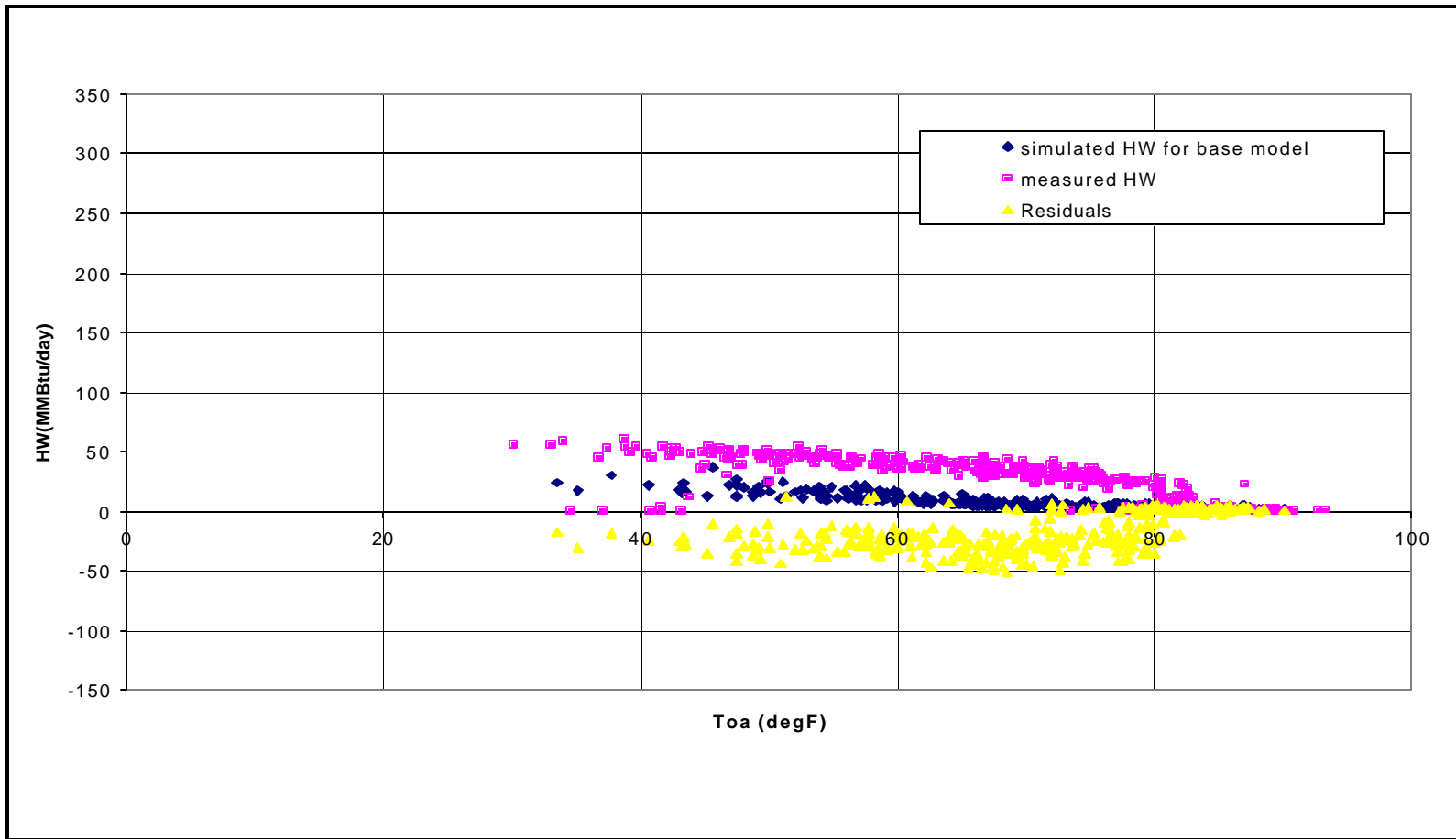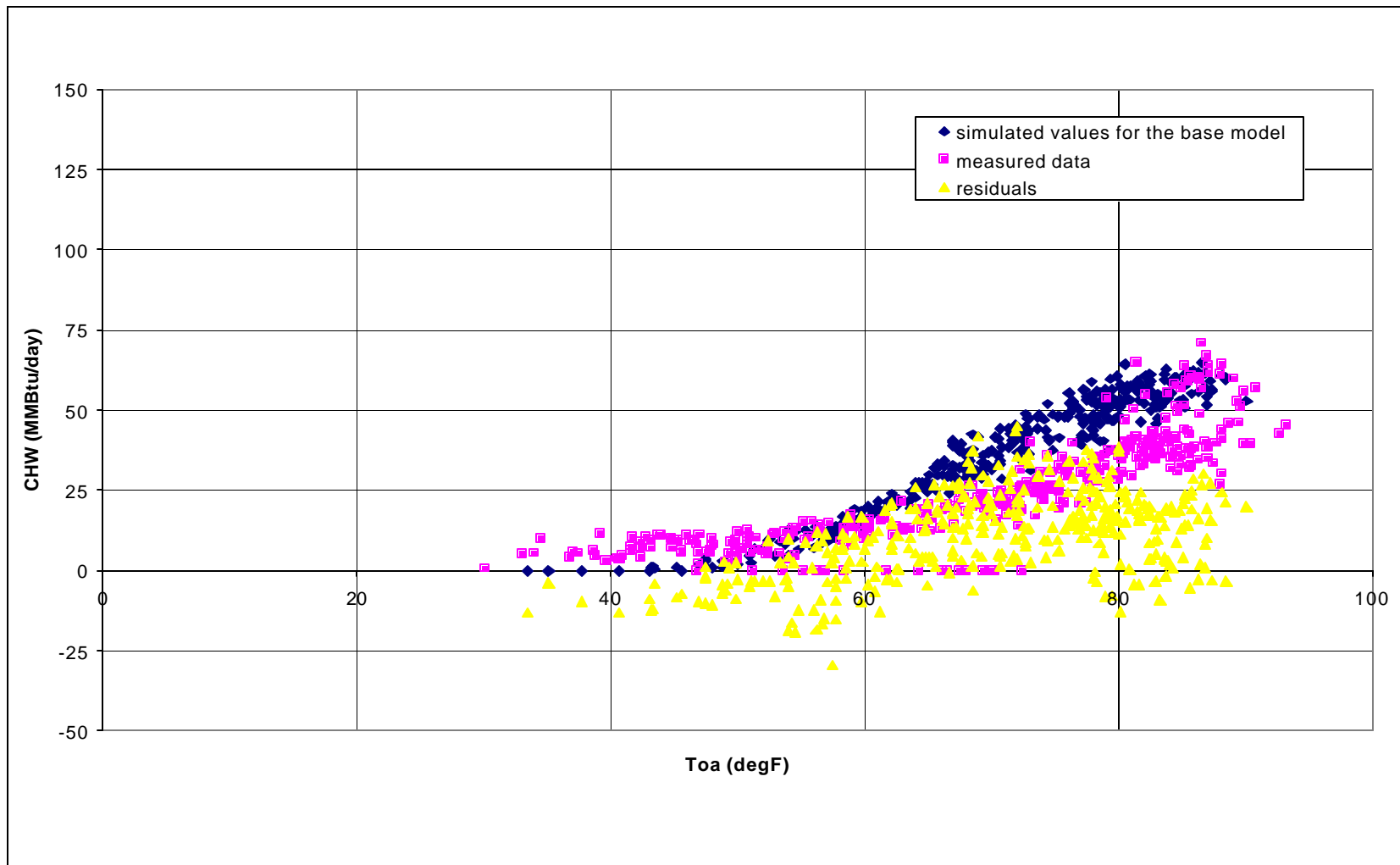
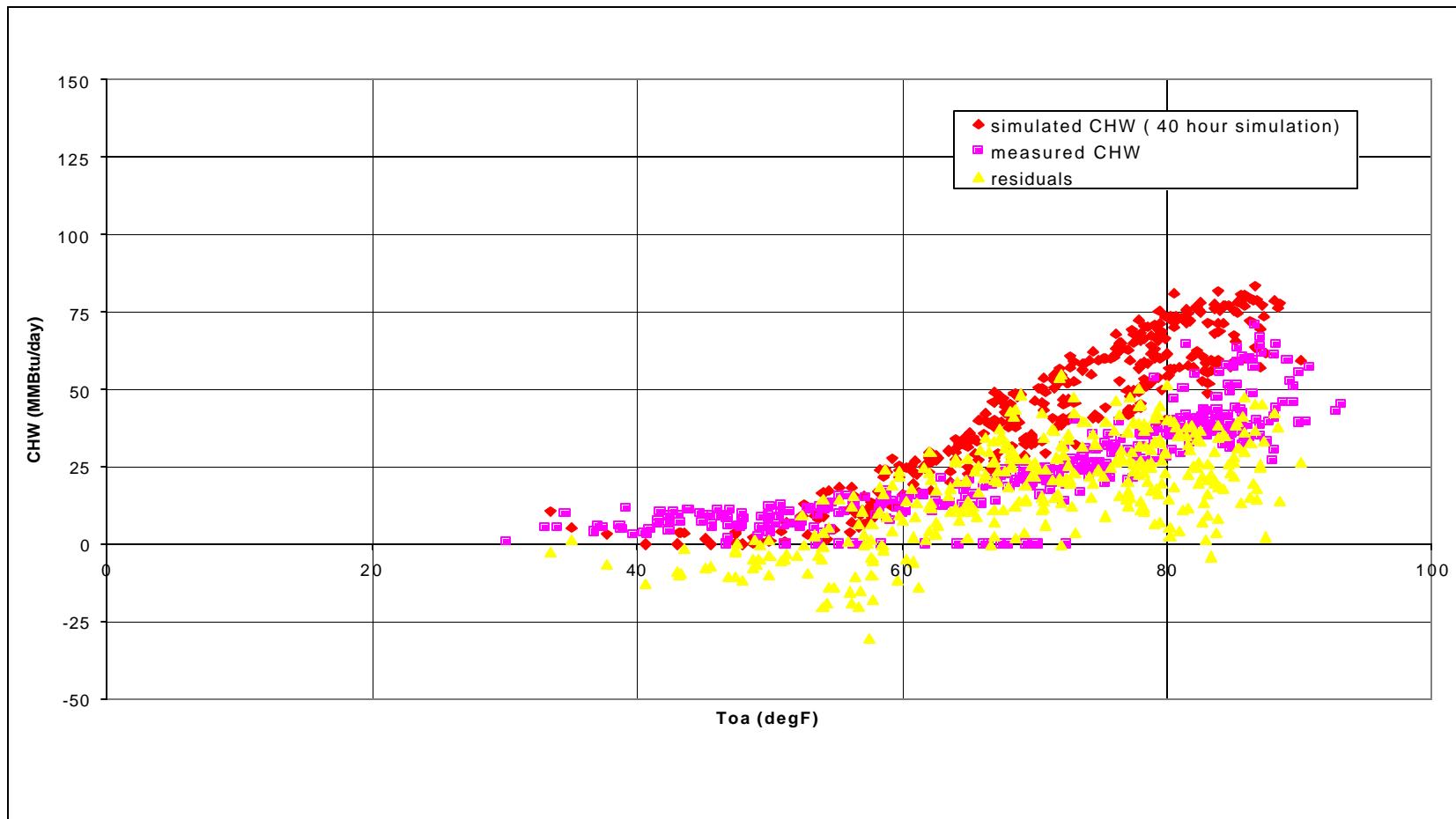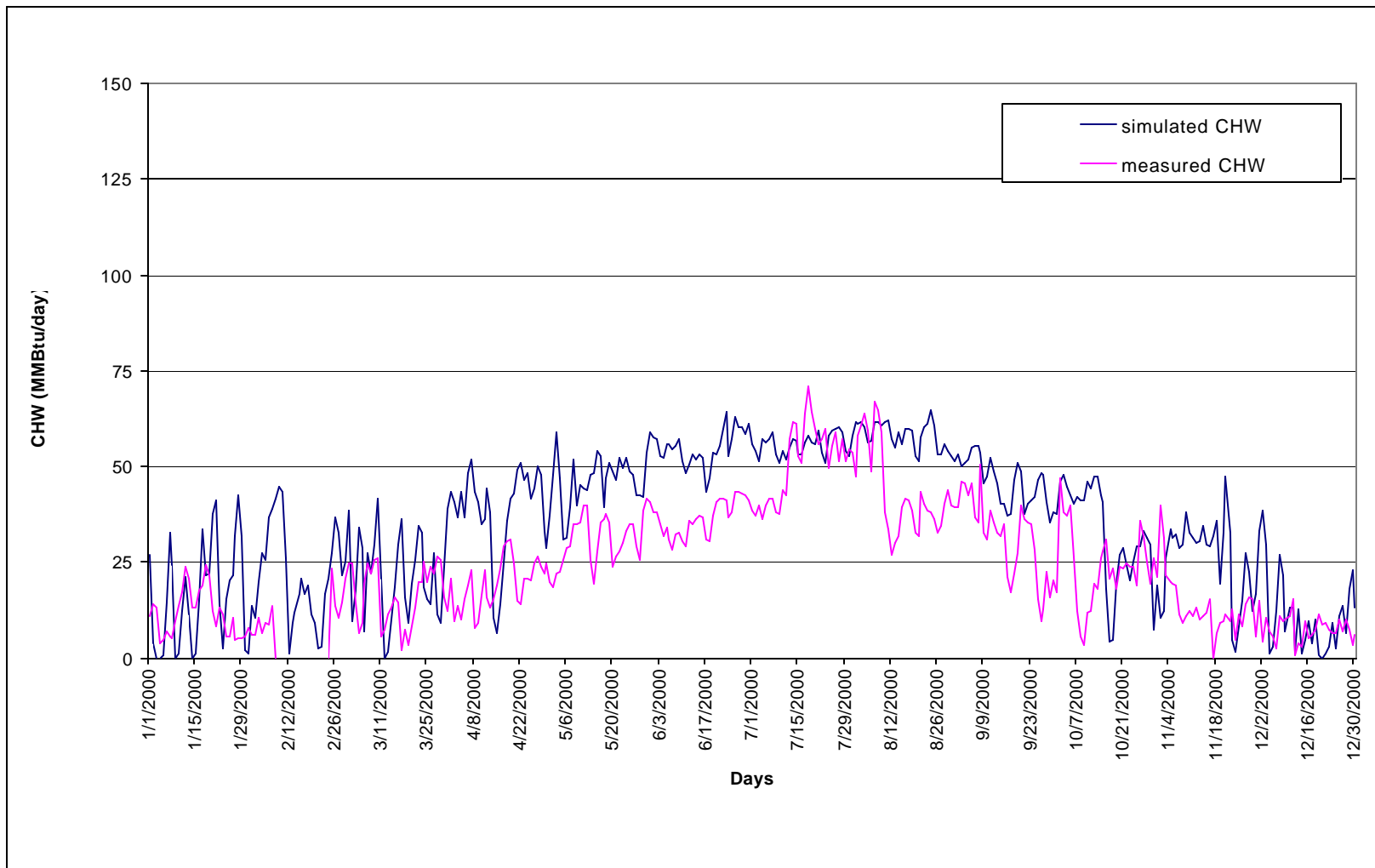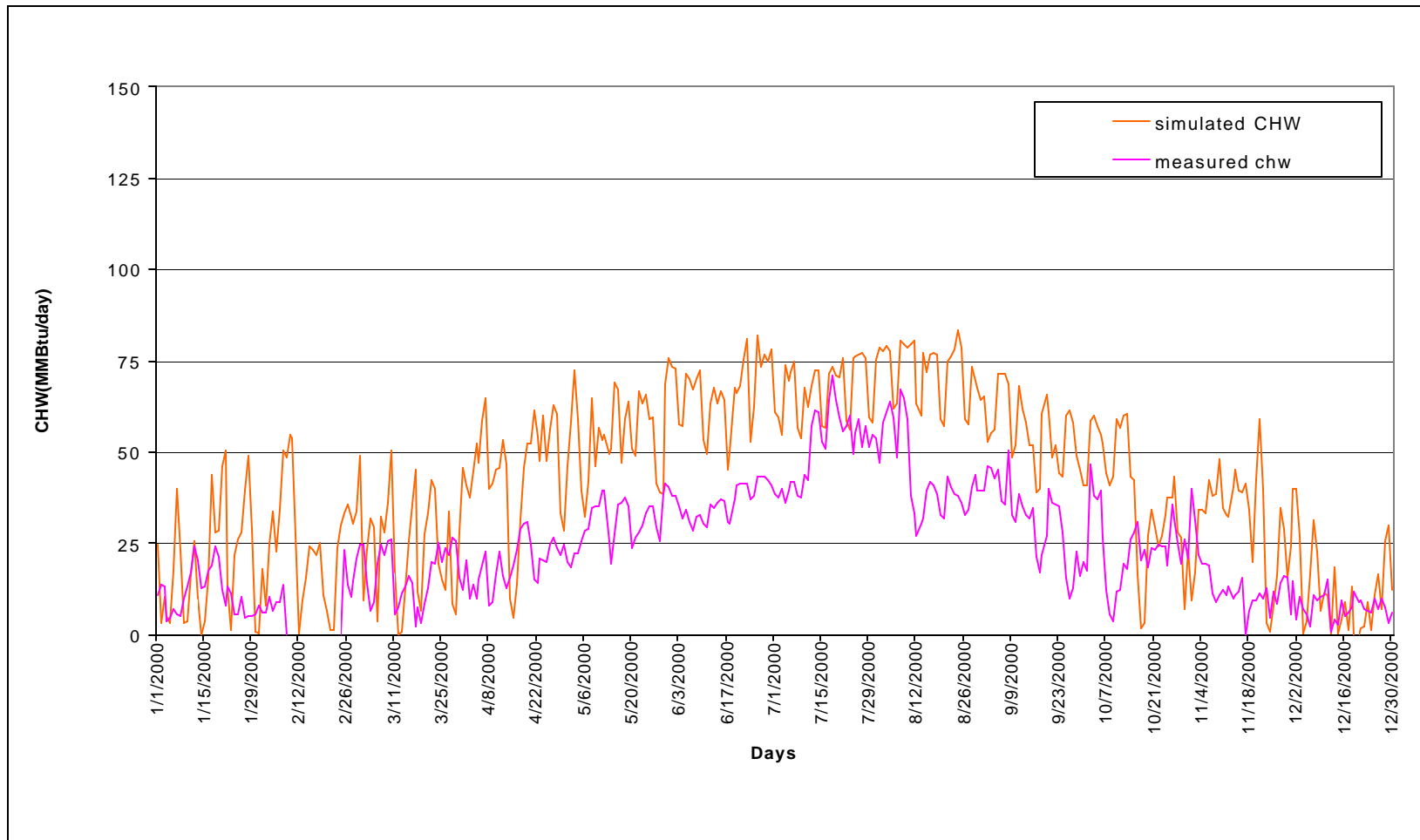**Fig 5.7 Comparison between the measured and simulated (massless model) hot water consumption (MMBtu/day)**
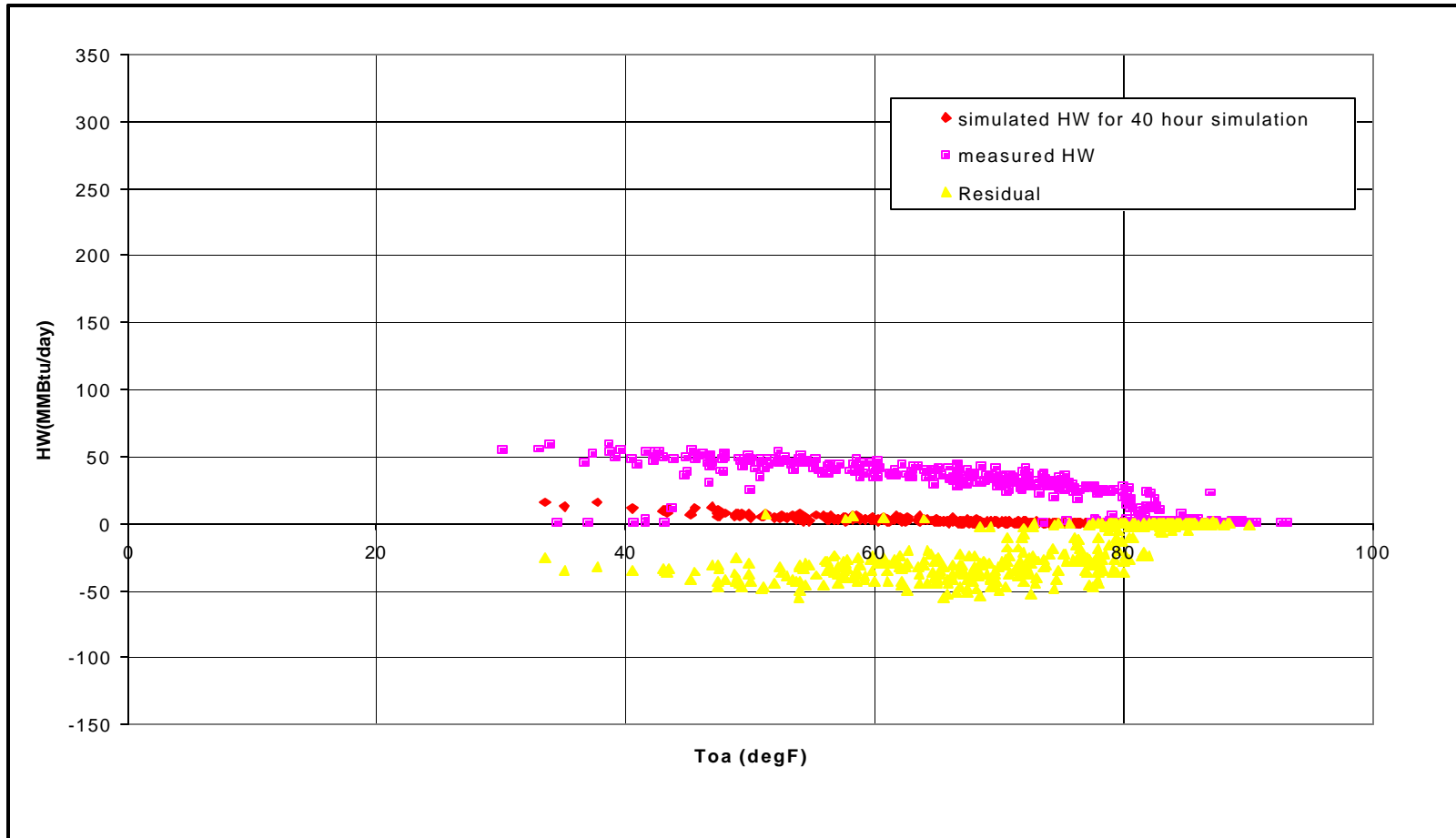
Fig 5.8 Comparison between the measured and simulated (advanced model) hot water consumption (MMBtu/day)
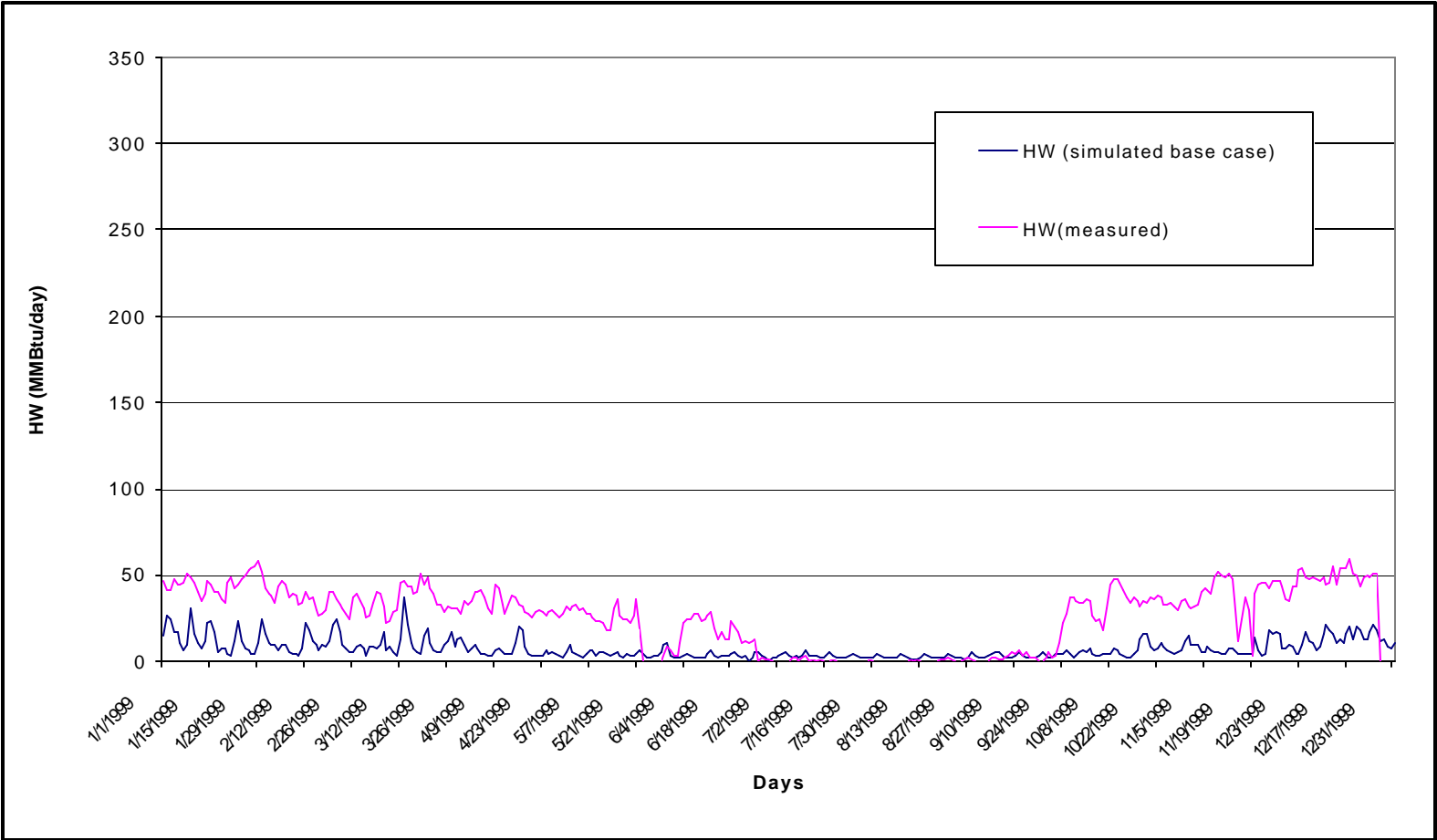
Fig 5.9 Time series of measured and simulated (massless model) hot water consumption (MMBtu/day)
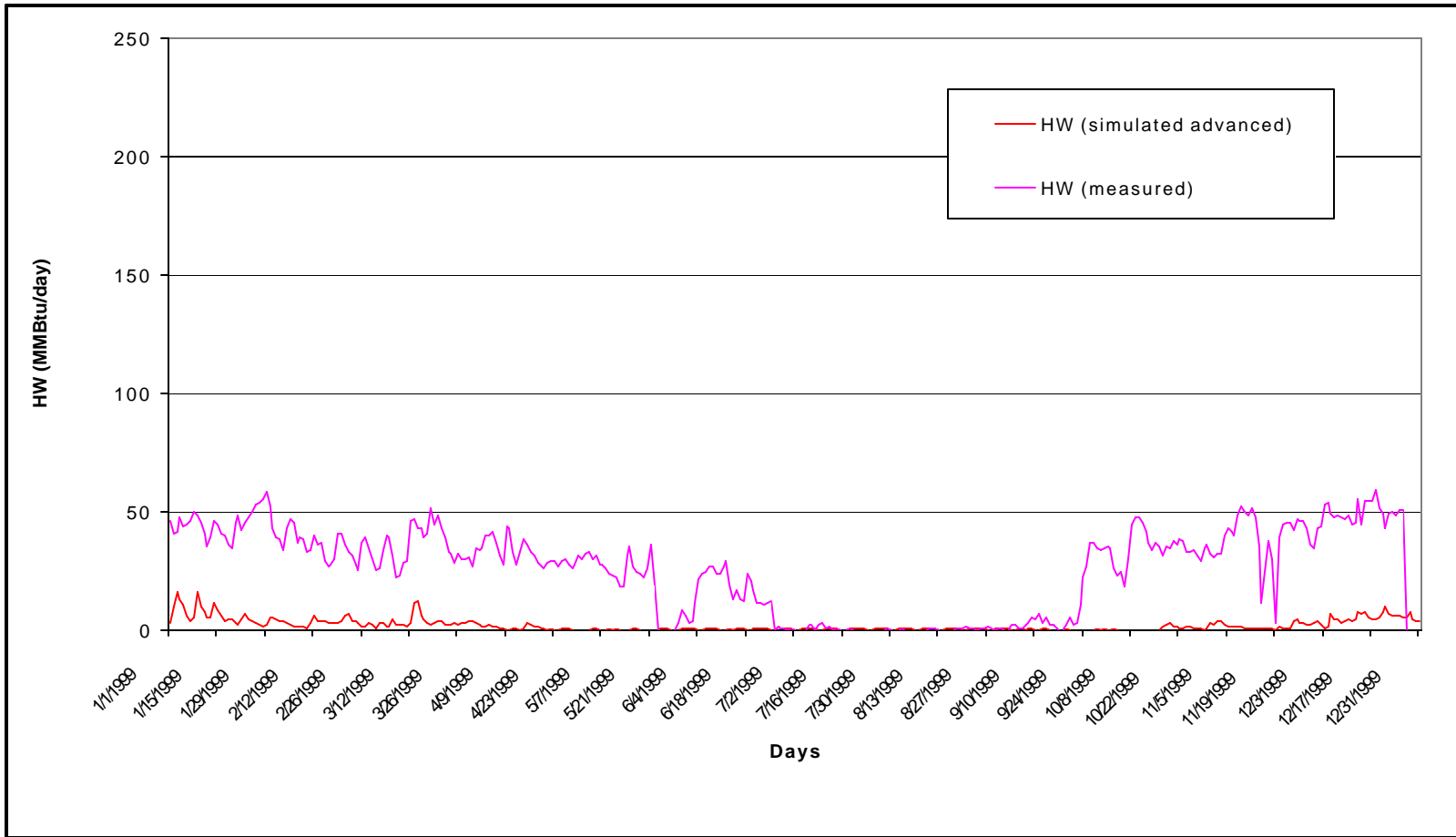
Fig 5.10 Time series of measured and simulated (advanced model) hot water consumption (MMBtu/day)

5.3 Harrington Tower

  Harrington Tower is a 130,844 sq. ft building located on the main campus of the Texas A&M University, College Station, Texas. It is eight stories high plus the basement. It mainly consists of offices and other meeting rooms.

  The same procedure was followed for Harrington Tower as for the Wisenbaker building. The same variables and graphs have been used to analyze the differences between the energy usage of the massless and the advance simulation models.

5.3.1 Chilled Water Usage

  Figures 5.11 to 5.14 show the comparison between simulated and measured chilled water usage for the massless and the advanced model respectively. The measured data is for the year 2000. For the simulated result, the consumption of the advanced model is higher then the massless model. The following conclusions can be drawn from the scatter plot:

- For low temperatures, the measured values and the simulated values from the massless model are similar, however for higher temperatures the measured consumption is 30% to 40% less than the simulated.

- The chilled water consumption for advanced case is higher than measured values for summer. The difference in this region is almost 50%. This behavior of the chilled water consumption is not clear since design values for the airflow and the outside air were taken. The measured values depict reasonable chilled water consumption for the Harrington Tower.

  From the graphs, it can be concluded that the current operation of the building is more efficient than the operation depicted by the advance simulation, which is based on parameters provided by the commissioning engineer for the post-retrofit period.
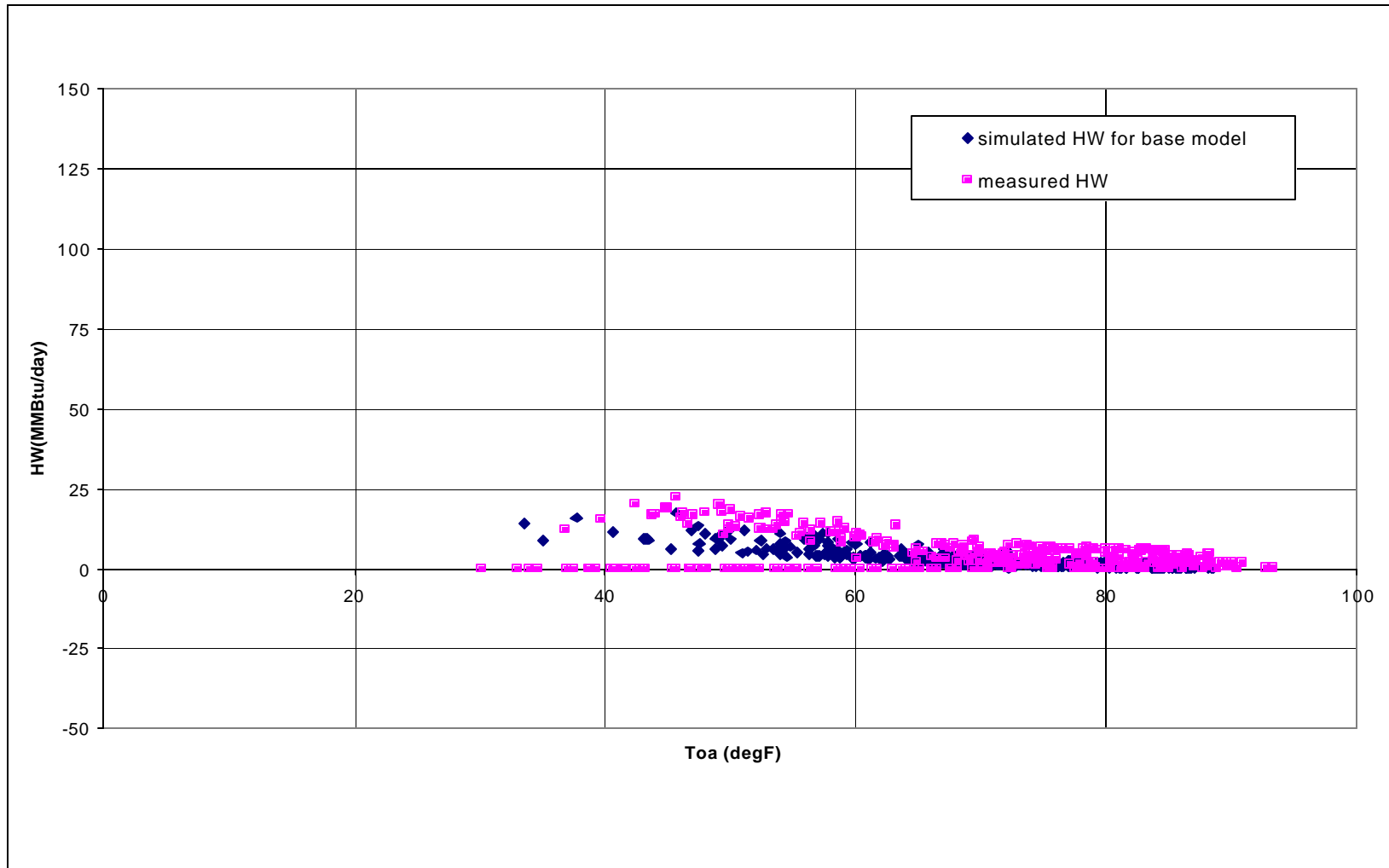
Fig 5.11 Comparison between measured and simulated (massless model) chilled water consumption values (MMBtu/day)
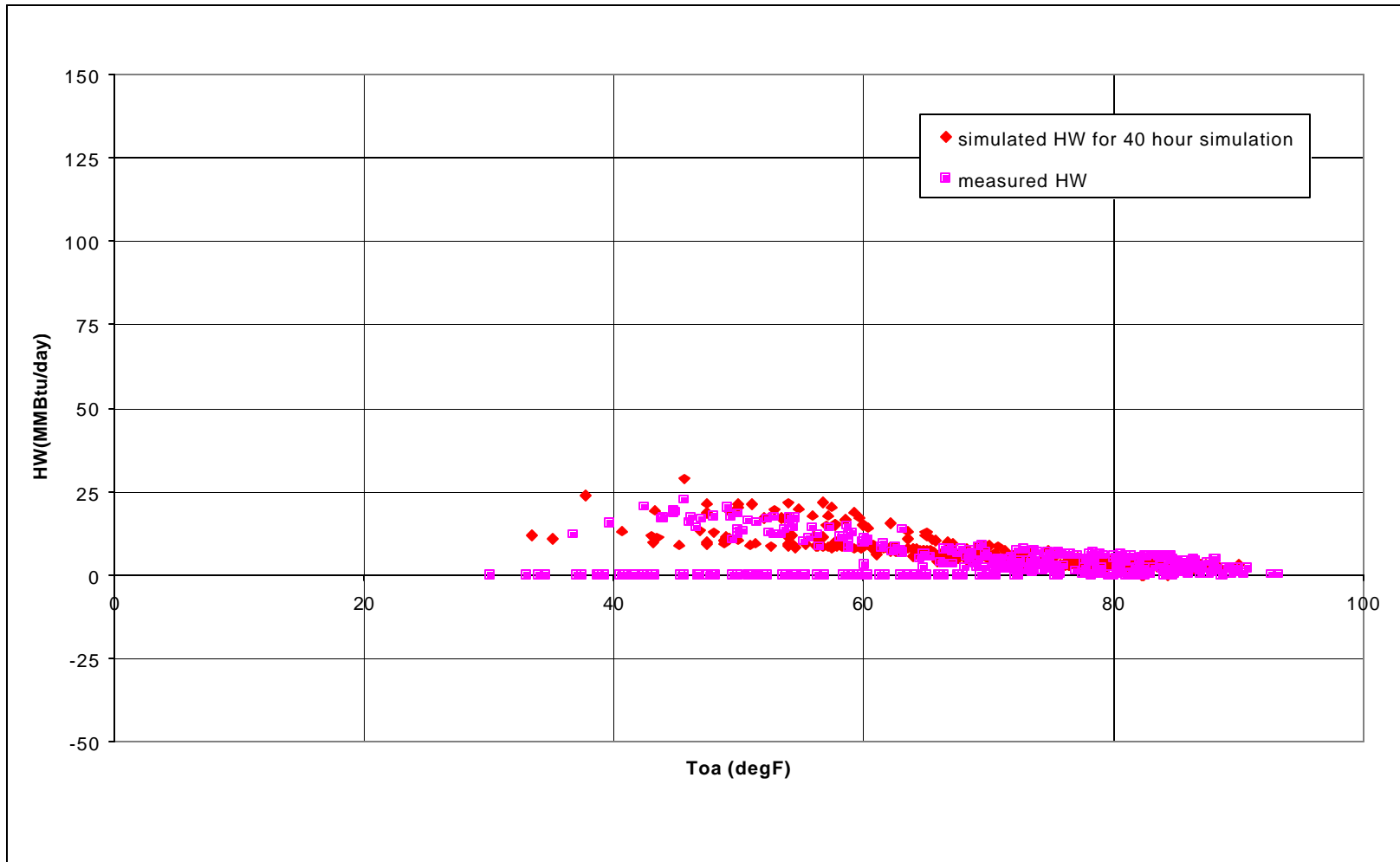
Fig 5.12 Comparison between measured and simulated (advanced model) chilled water consumption values (MMBtu/day)
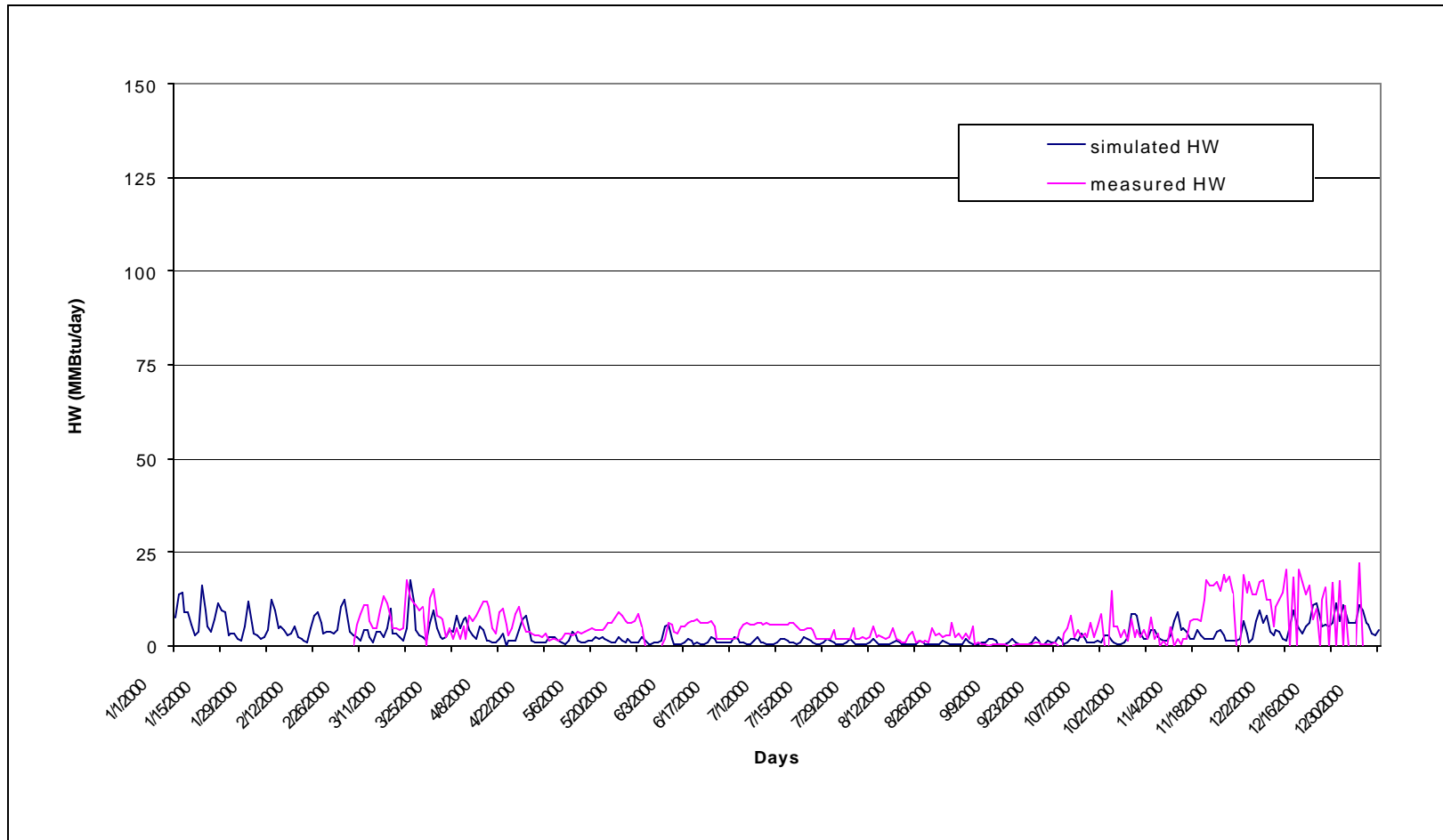
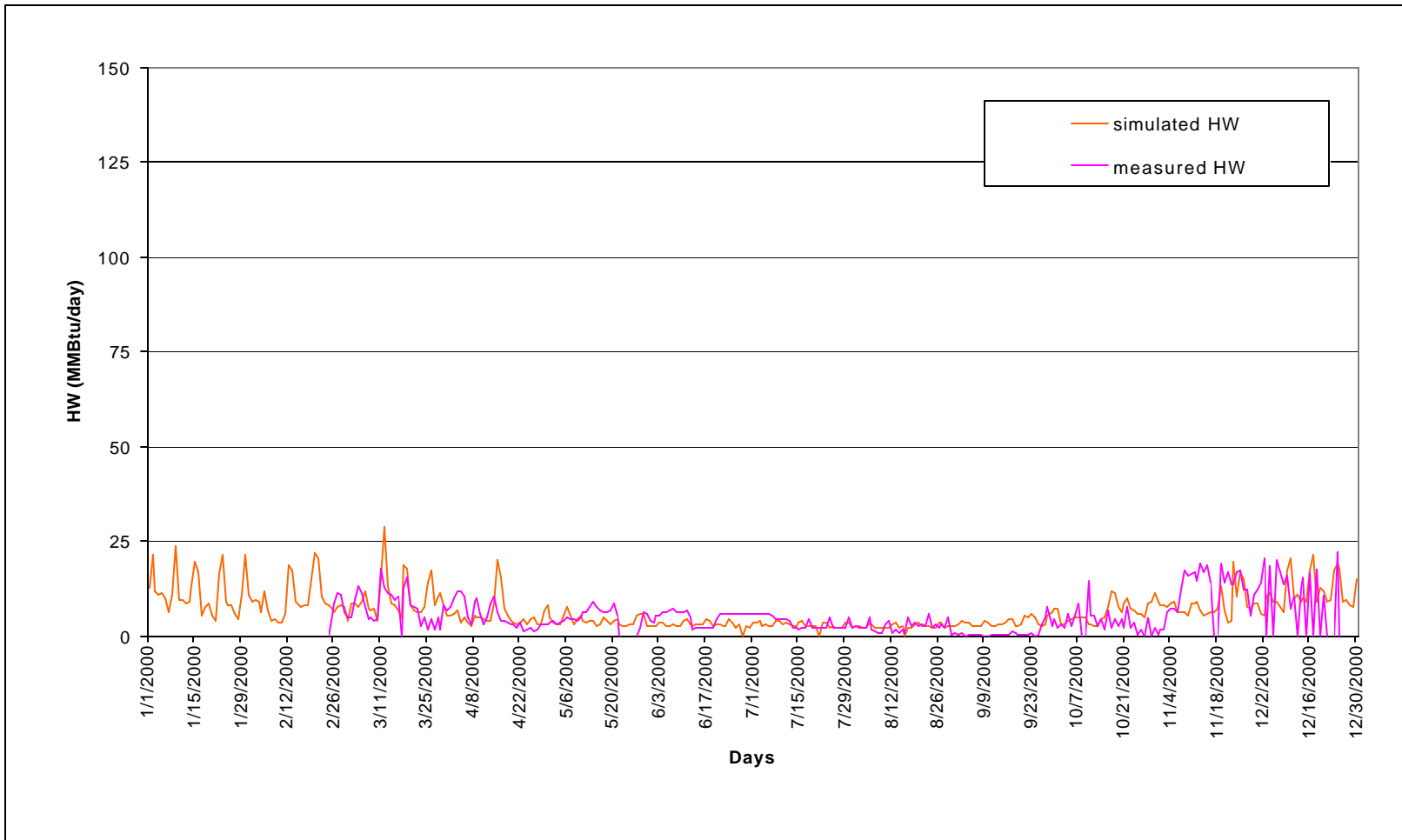**Fig 5.13 Time series of measured and simulated (massless model) for chilled water consumption (MMBtu/day)**

Fig 5.14 Time series of measured and simulated (advanced model) for chilled water consumption (MMBtu/day)

5.3.2 Hot Water Usage

Figures 5.15 to 5.18 depict the comparison of the hot water usage for the Harrington Tower. The consumption of the massless model is less than the measured data. However the advanced model has a better fit for all temperatures.

- The measured values show that even for higher temperatures the hot water consumption is 5 to 7 MMBtu/day. This might be indicating a leaking valve. The massless model values are less than the advanced model. This can be due to the use of post-retrofit parameter values.
- The advanced model shows a good fit with the measured data, except for summer months where the measured hot water consumption attains a constant value, which may indicate a problem in the hot water supply.

However the same parameter values do not provide a reasonable fit with the measured chilled water suggesting that it is not necessary that the building is currently working on the assigned post retrofit values. For chilled water, the CV (RMSE) and MBE for the massless model are 71.5% and 47.8%. For the advanced model the values are 100.9% and 76.6%. The advanced case is clearly worse than the massless model in depicting the operating conditions. For hot water, the CV (RMSE) and MBE for the massless model are 129.7% and –32.4%. For the advanced case the values are 149.8% and 47%. From these values, it looks that the massless model is better in depicting hot water usage as well. However just by observing the following graphs, the advanced model provides a better fit. The conclusion from these values and graphs is that both these models cannot predict the current operating conditions of the building. In the following graphs the residuals have not been plotted to clarify the visual difference s between the measured and the simulated.

Fig 5.15 Comparison between measured and simulated (massless model) hot water consumption values (MMBtu/day)
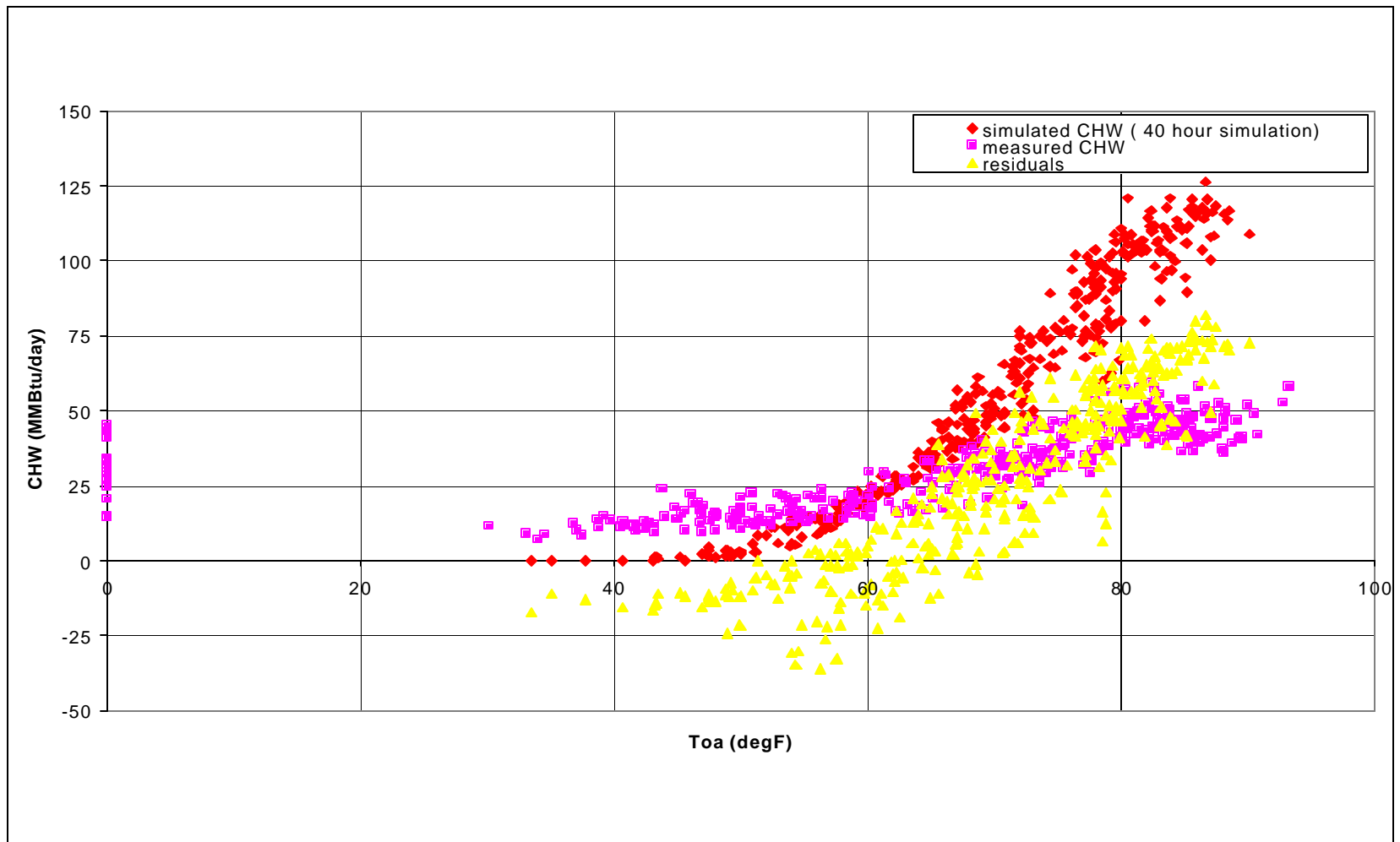
Fig 5.16 Comparison between measured and simulated (advanced model) hot water consumption values (MMBtu/day)
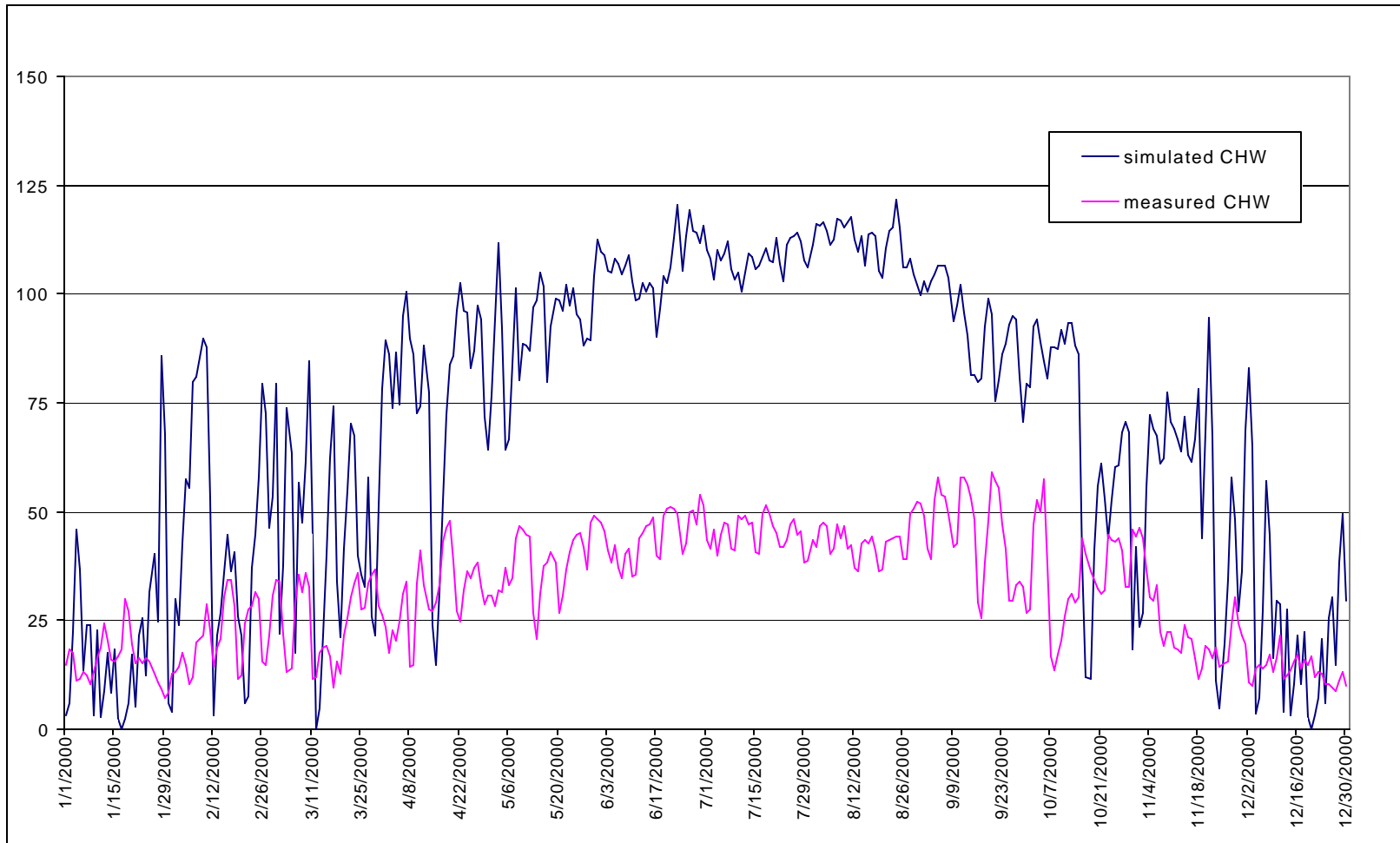
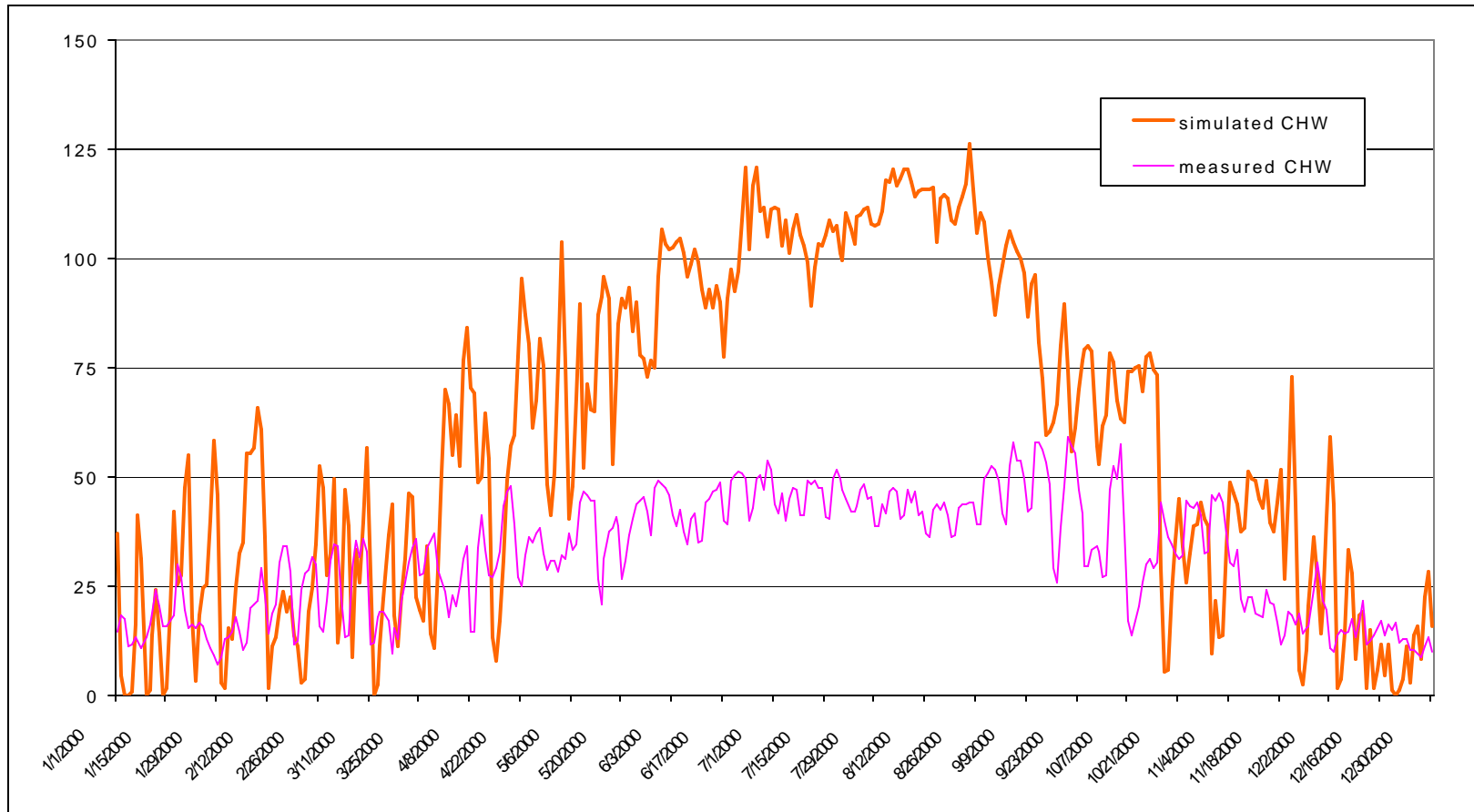**Fig 5.17 Time series of measured and simulated (massless model) for hot water consumption (MMBtu/day)**

Fig 5.18 Time series of measured and simulated (advanced model) for hot water consumption (MMBtu/day)

5.4 Wehner Business Administration Building

The E. L. Wehner Building at Texas A&M University is a 4-story 192,000-ft^2 academic building catering to the different needs of students, faculty and staff of the Lowry Mays College & Graduate School of Business. It is located on the west campus of Texas A&M University, College Station.

The measured data from the building consisted of chilled water consumption, hot water consumption and whole building electric. The conclusions drawn from the comparison of the simulation model with the measured data are as follows:

5.4.1 Chilled Water Consumption

Figures 5.19 to 5.22 show the comparison between simulated and measured chilled water usage for the massless and the advanced model respectively. The measured data is for the year 2000. For the simulated result, the consumption of the advanced model is higher then the massless model. The following conclusions can be drawn from the scatter plot:

- The chilled water consumption of both the massless and the advanced model is 50% to 60% more than the measured for summer. For the massless model it can be said that this high consumption can be a result of wrong assumption on the outside air fraction. However for the advanced case the outside air fraction values were taken from as- built design spec sheets. This step did not provide a better fit with the measured data.

- From the measured data, the chilled water consumption looks to be quite constant throughout the year. It can be inferred from the graph that the outside air, which is to be supplied to the building as per design is not coming in. The design values range from 27% to 45% of the total supply air for different air handlers. However it looks that less than 15% of the total supply cfm is outside air. This may suggest that the outside air

valves are completely shut and whatever outside air is coming in is
through the leaks.

This building was recently surveyed by the Energy Systems Laboratory (ESL) for the commissioning process. Quite a few problems were detected with the current operation of the building. According to the engineer, the chilled water valve is independent of the control pressure. This explains the chilled water usage for low temperatures. But at the same time, the engineer thinks that the building is getting more outside air than required. The measured data does not depicts this, the data shows that the outside air fraction is minimal. Leaks are also present in the main hot water valves. There are also other problems associated with thermostat control, VFDs and damper controls. This problems have been identified but there is not update whether they have been rectified or not. So until now, no post maintenance data is available.

5.4.2 Hot Water Consumption

Figures 5.23 to 5.26 show the comparison of the measured hot water consumption with the massless and advance simulation models. The measured hot water consumption is more than both the simulated models. The hot water consumption by the massless model is greater than the advanced model. Following conclusions can be drawn from the graphs:

- The match between the simulated and measured values is better than that for the chilled water usage, however both the massless and advanced model predictions are 20 to 60% less than the measured values.
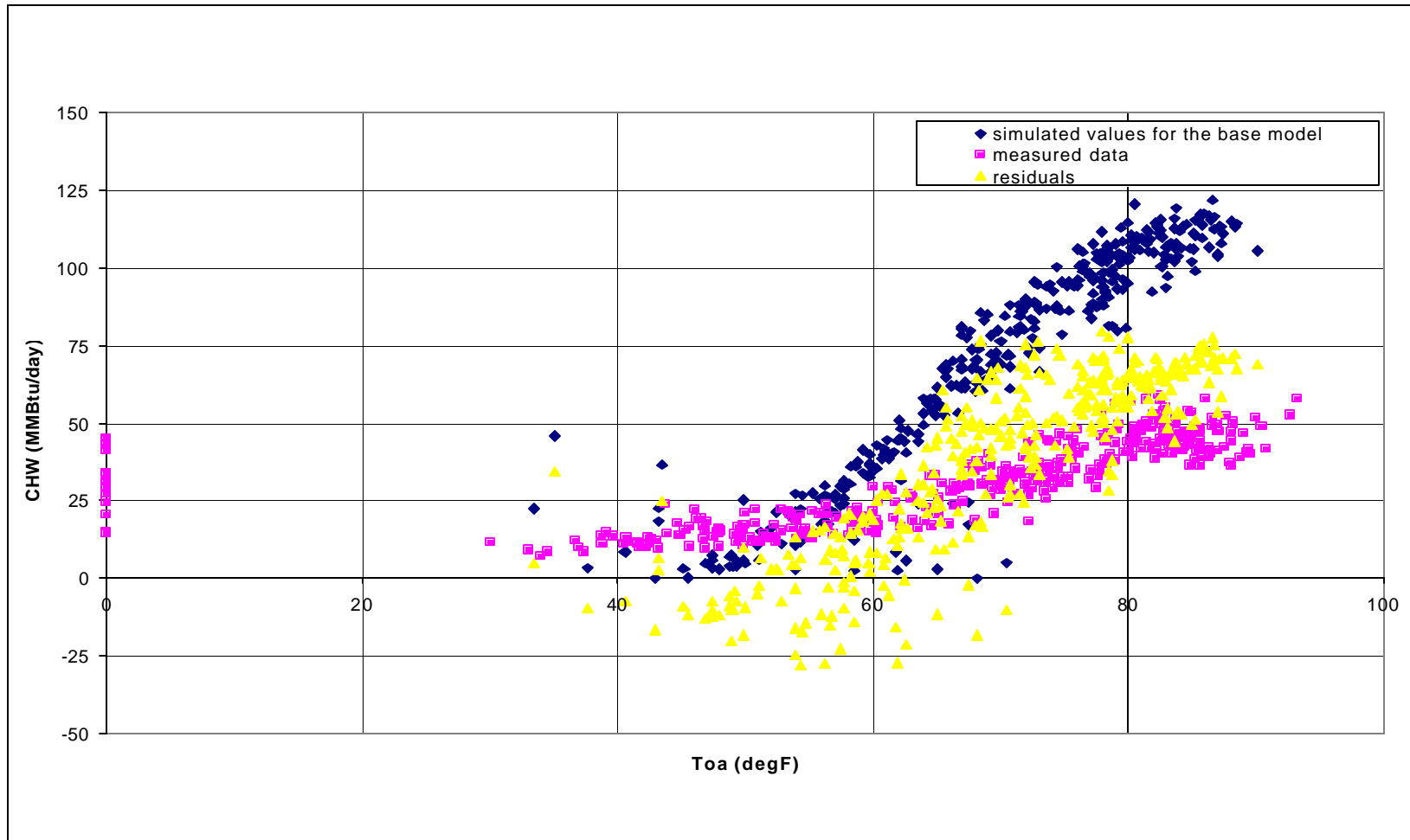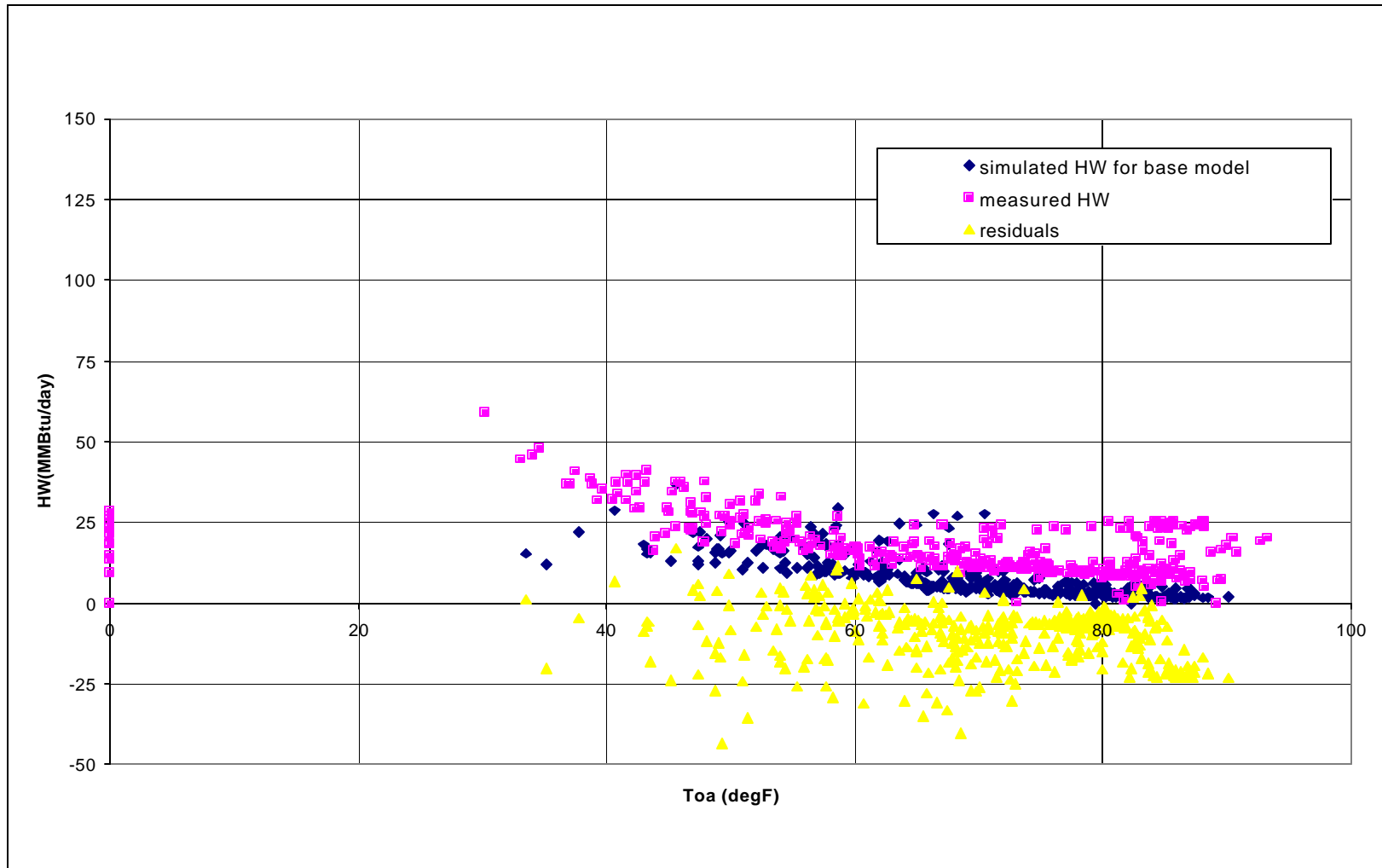
Fig 5.19 Comparison between measured and simulated (massless model) chilled water consumption values (MMBtu/day)
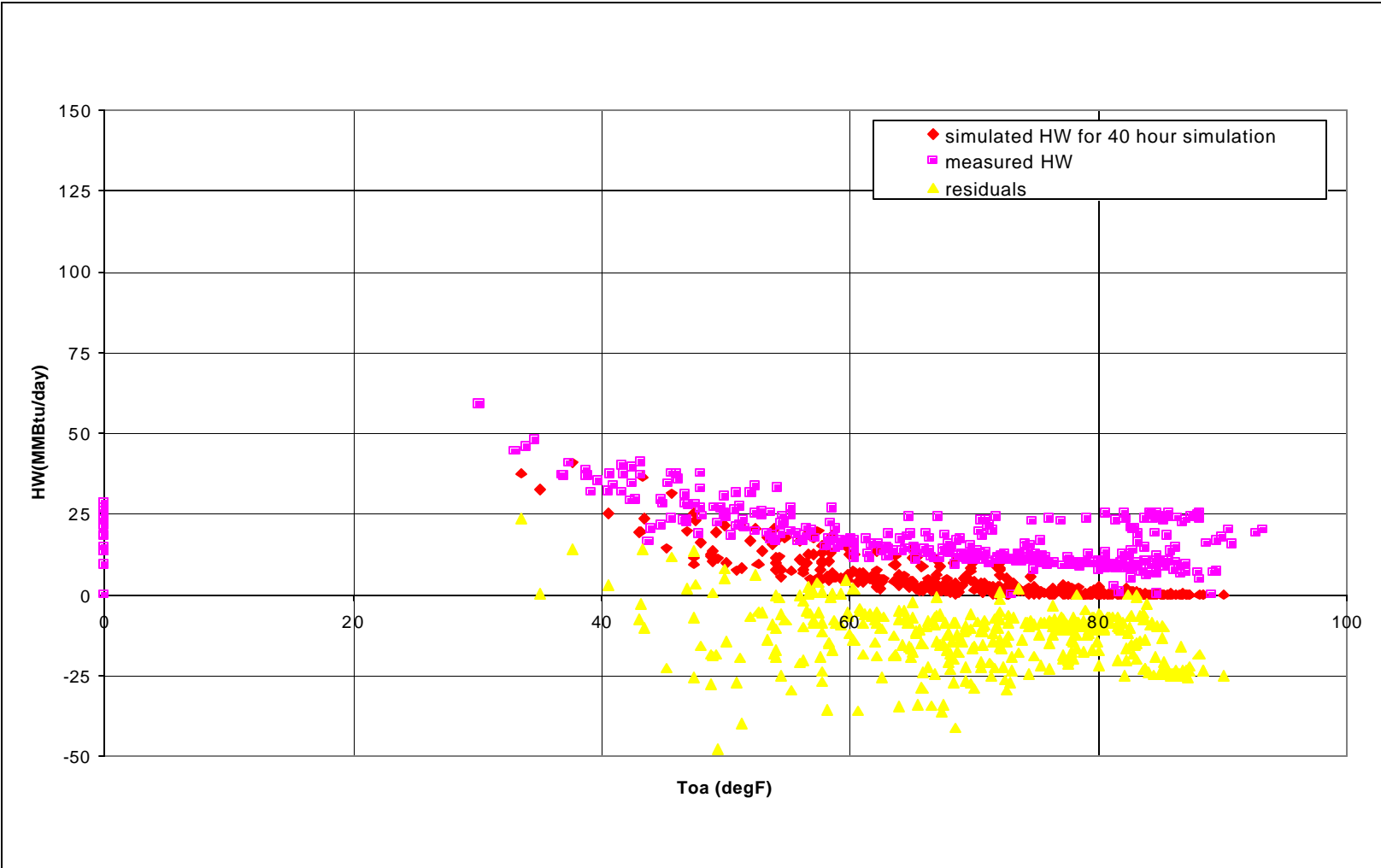
Fig 5.20 Comparison between measured and simulated (advanced model) chilled water consumption values (MMBtu/day)
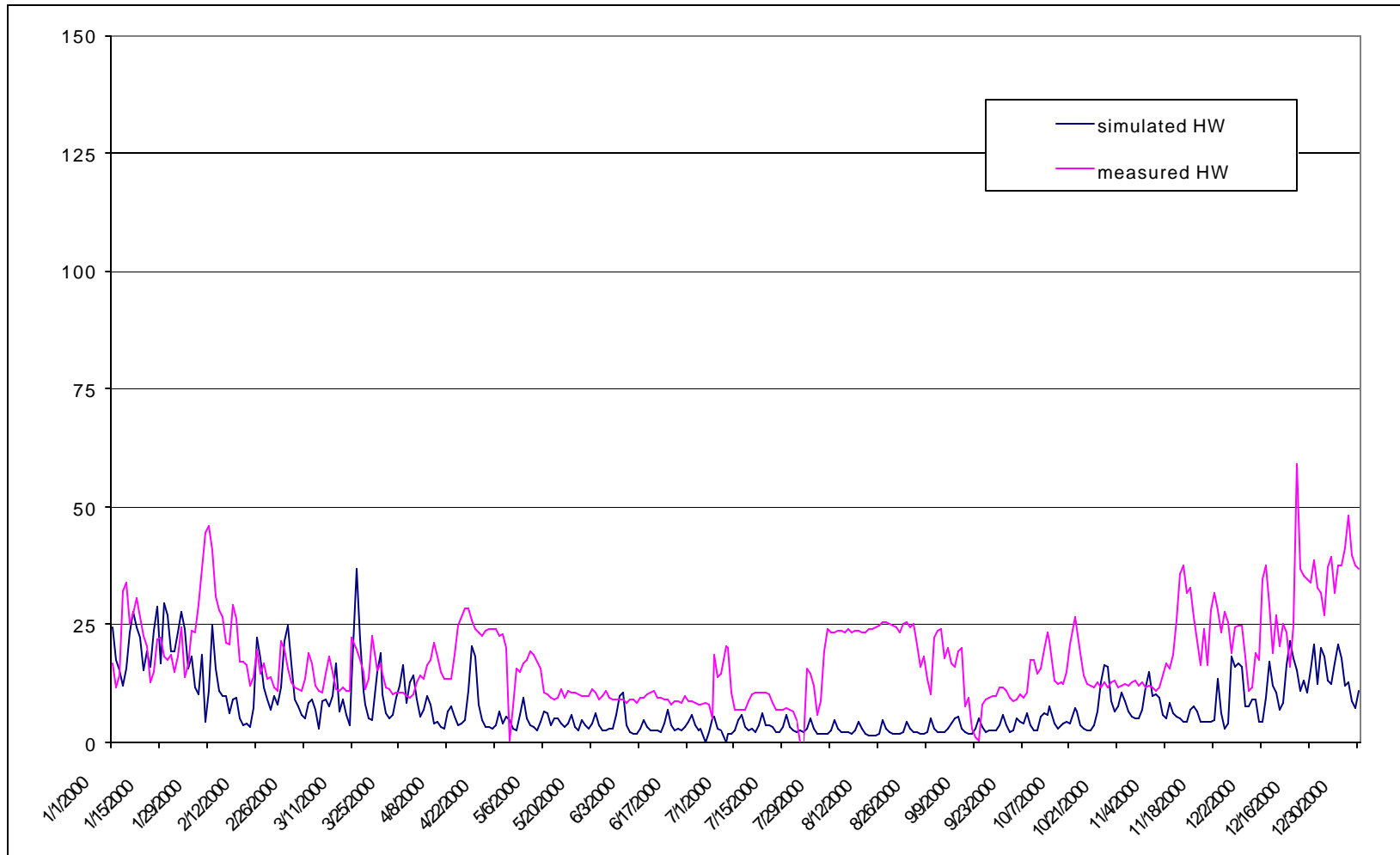
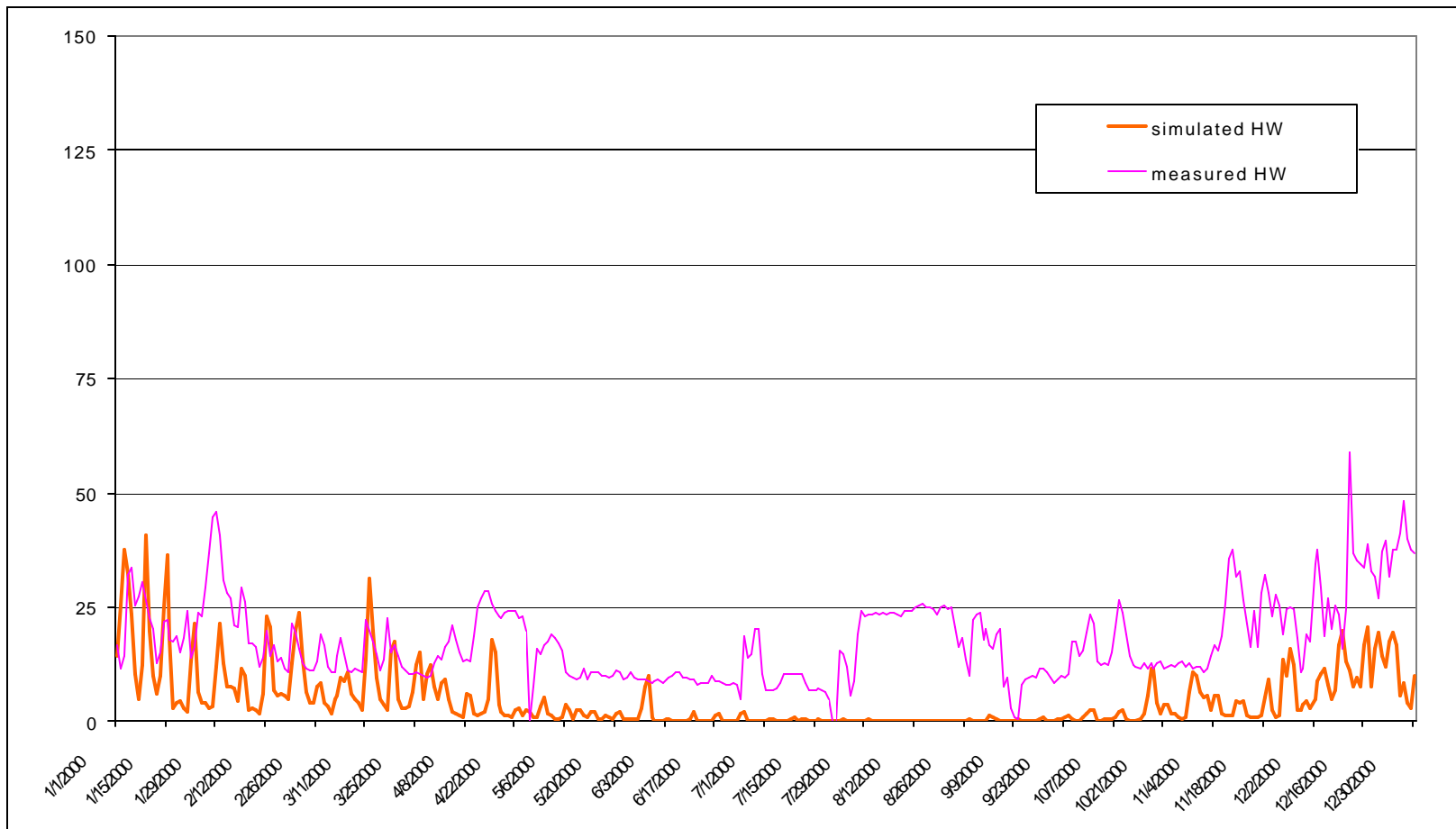**Fig 5.21 Time series of measured and simulated (massless model) for chilled water consumption (MMBtu/day)**

Fig 5.22 Time series of measured and simulated (advanced model) for chilled water consumption (MMBtu/day)

- Another thing to note is that the measured chilled water and hot water consumption has approximately the same magnitude. For an internally load dominated building this is not the usual case. The chilled water consumption is usually 3 to 4 times more than hot water consumption.

- The measured data shows hot water consumption of around 25 MMBtu/day even for temperatures reaching 90°F. This can be due to the leak in the main hot water valve reported by the commissioning engineer.

The statistical parameters calculated depict that the uncalibrated models created for this building does not reflect the current operating conditions. For chilled water, the CV (RMSE) and MBE for the massless model are 152.4% and 123.8%. For the advanced model the values are 128% and 88%. The advanced case for this building is better than the massless model. For hot water, the CV (RMSE) and MBE for the massless model are 77% and –56.9%. For the advanced case the values are 93.4% and –73.4%.

5.5 John B. Connally Building (State Headquarters)

John B. Connally Building houses the administrative offices of the whole Texas A&M system. This building is supplied by a captive HVAC plant consisting of three chillers and two hot water boilers. The gross area is approximately 124,000 square feet. This is a typical office building housing only offices and conference rooms.

The measured data from the building consistd of just whole building electric and chiller electric. No data for hot water consumption was available. The comparison is between the measured and simulated chiller electric. For the summer months the measured chiller electric is less than the simulated one for both the massless and the advanced model.

Fig 5.23 Comparison between measured and simulated (massless model) hot water consumption values (MMBtu/day)

Fig 5.24 Comparison between measured and simulated (advanced model) hot water consumption values (MMBtu/day)

Fig 5.25 Time series of measured and simulated (massless model) for chilled water consumption (MMBtu/day)

Fig 5.26 Time series of measured and simulated (advanced model) for chilled water consumption (MMBtu/day)

5.5.1 Chiller Electric

Figures 5.27 and 5.28 show the comparison between measured and simulated values for the chiller electric consumption.

- The measured and simulated values match quite well except for the summer months where the difference between the measured and simulated (both cases) is around 20%.
- The differences between the massless model and the advanced model are minute and for the summer months they are less than 5%.

The CV (RMSE) and MBE for the massless model are 74% and 48.21% respectively. For the advanced model the values are 52.3% and 76.7%.

5.6 The Habitat House

The Habitat House is a low budget single-family house being built under the Habitat for Humanity project. The gross square footage is 1170 and it is located in the city of Bryan.

The measured data available from the house include the whole building electric and the gas consumption. However the gas consumption data does not seem to be correct since the values are more than 10 times higher than the simulated values.
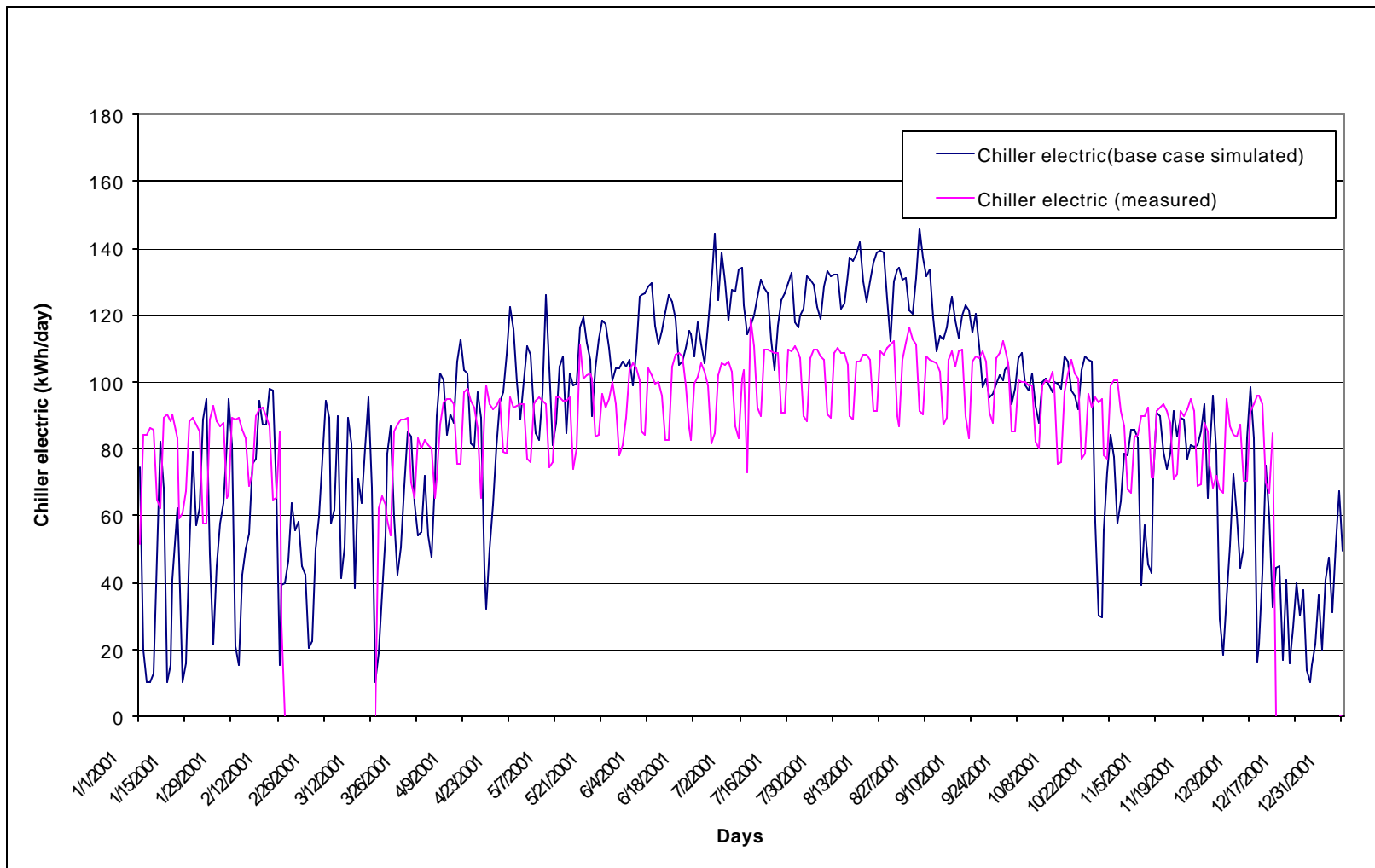
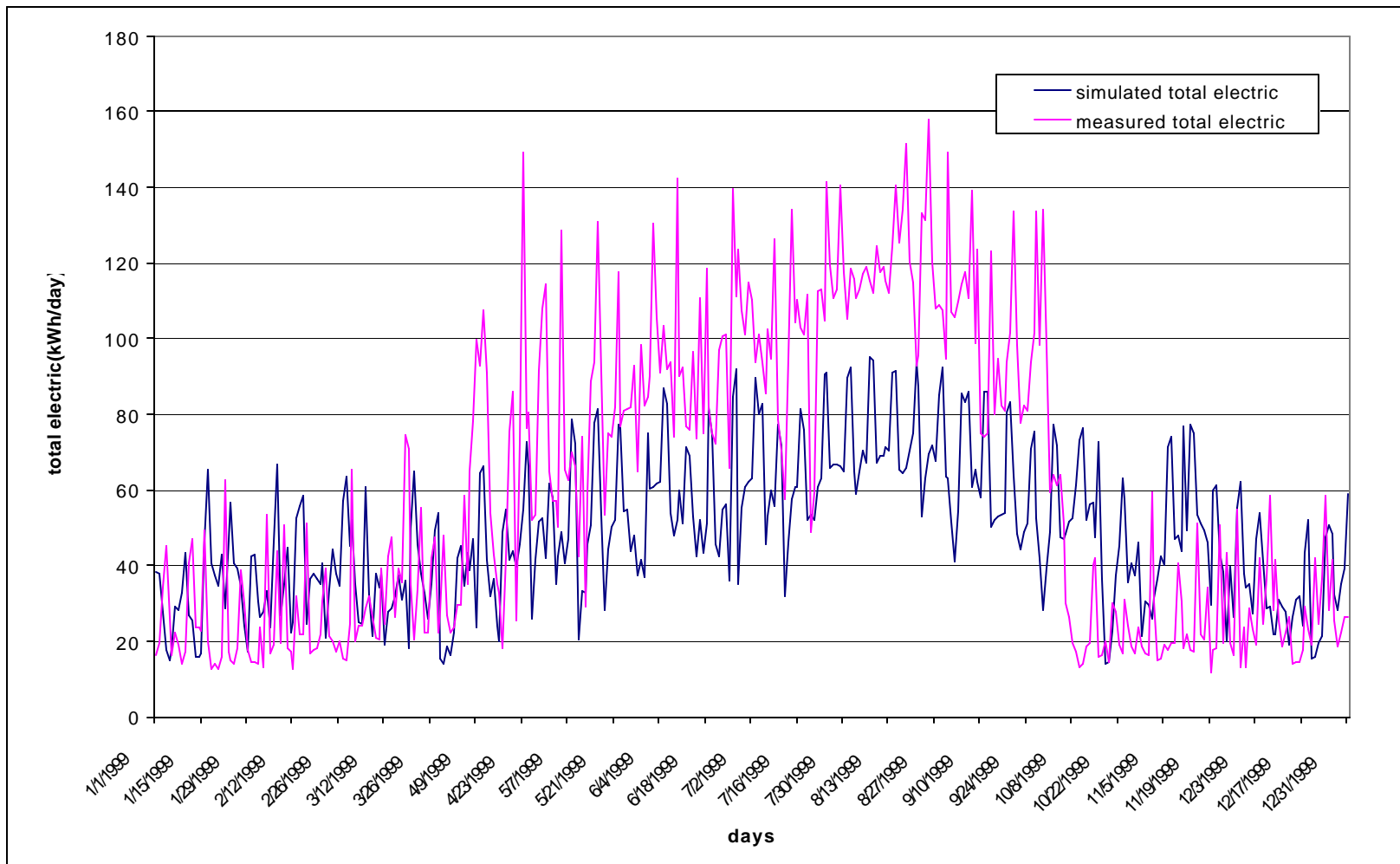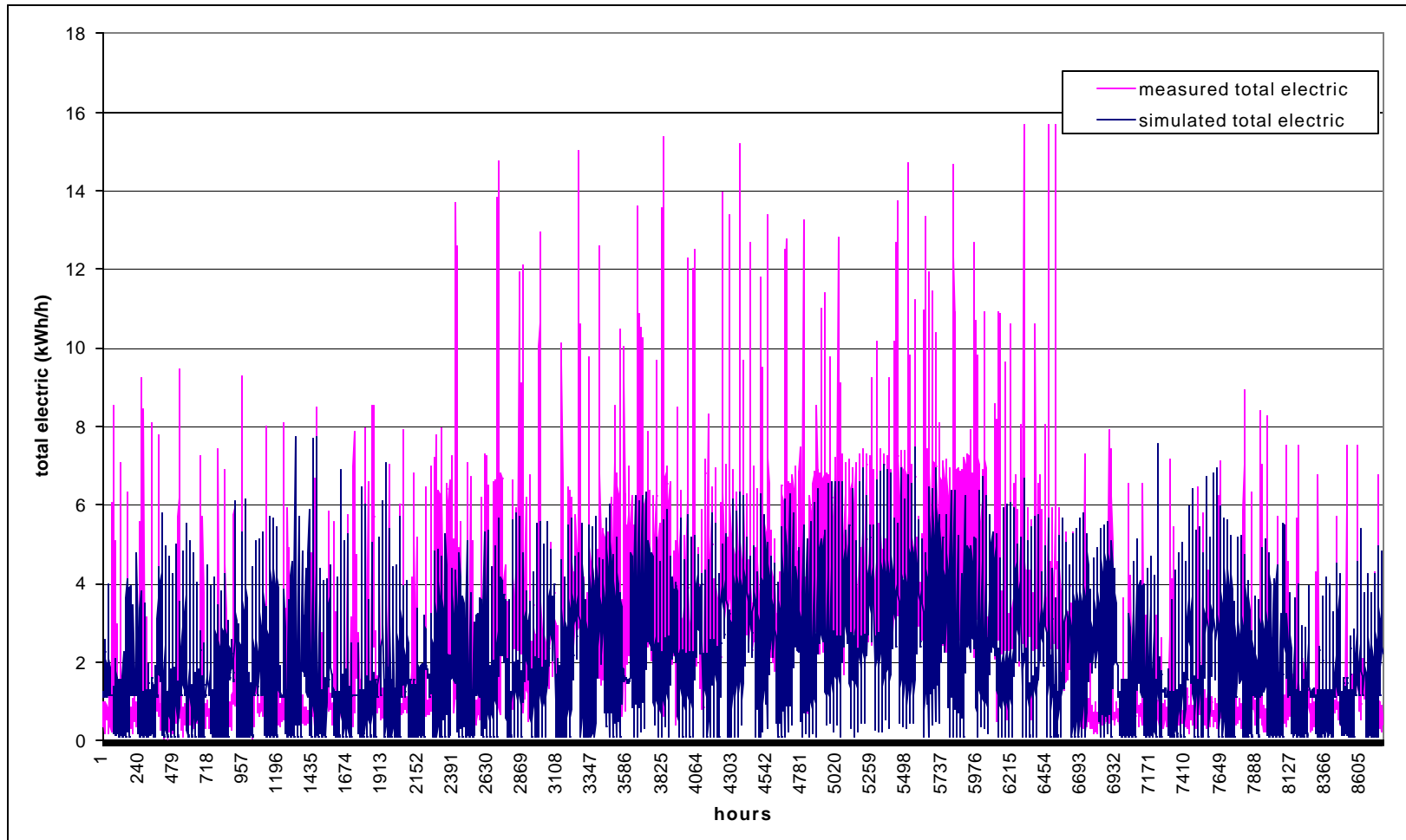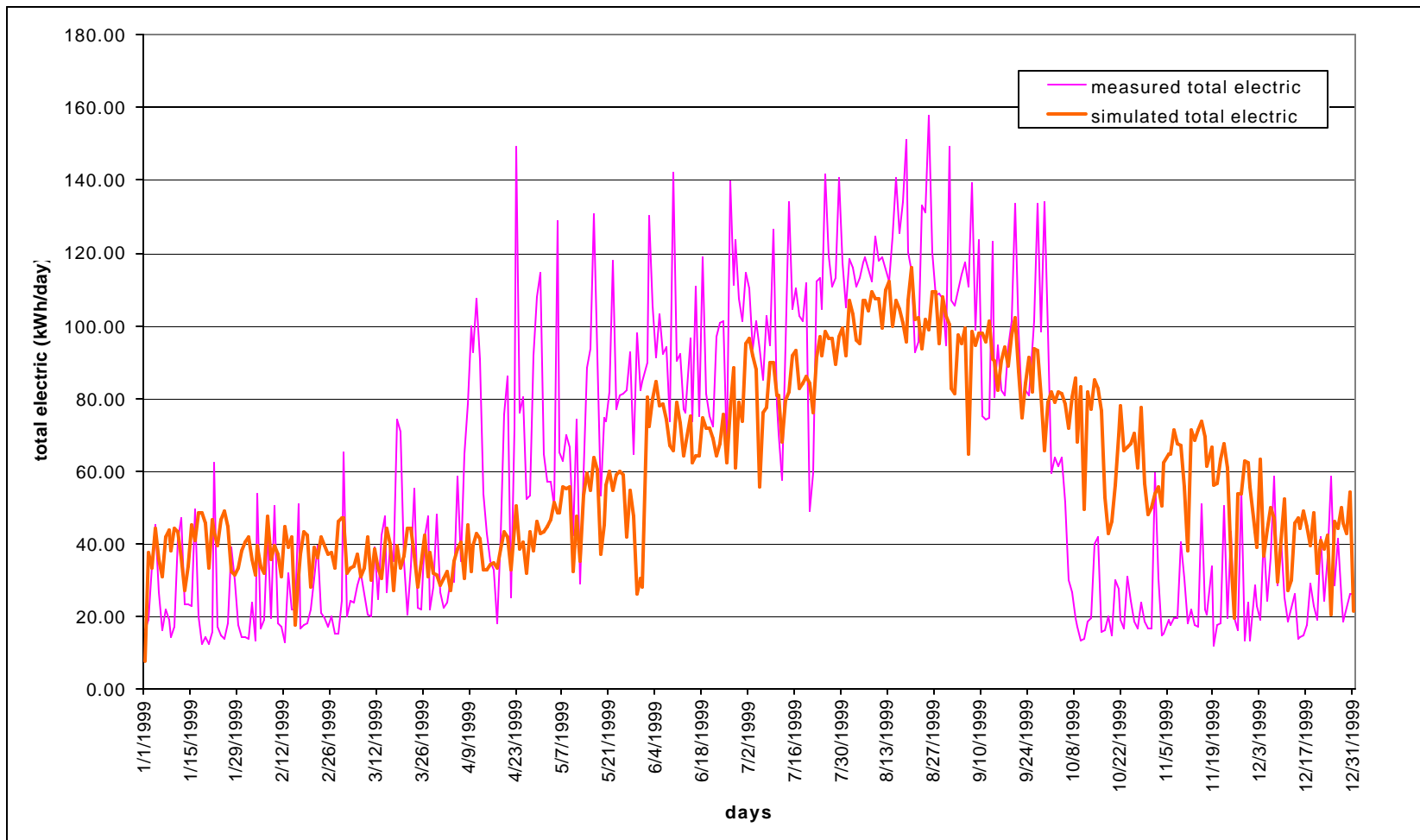**Fig 5.27 Time series of measured and simulated (massless model) for chiller electric (kW)**
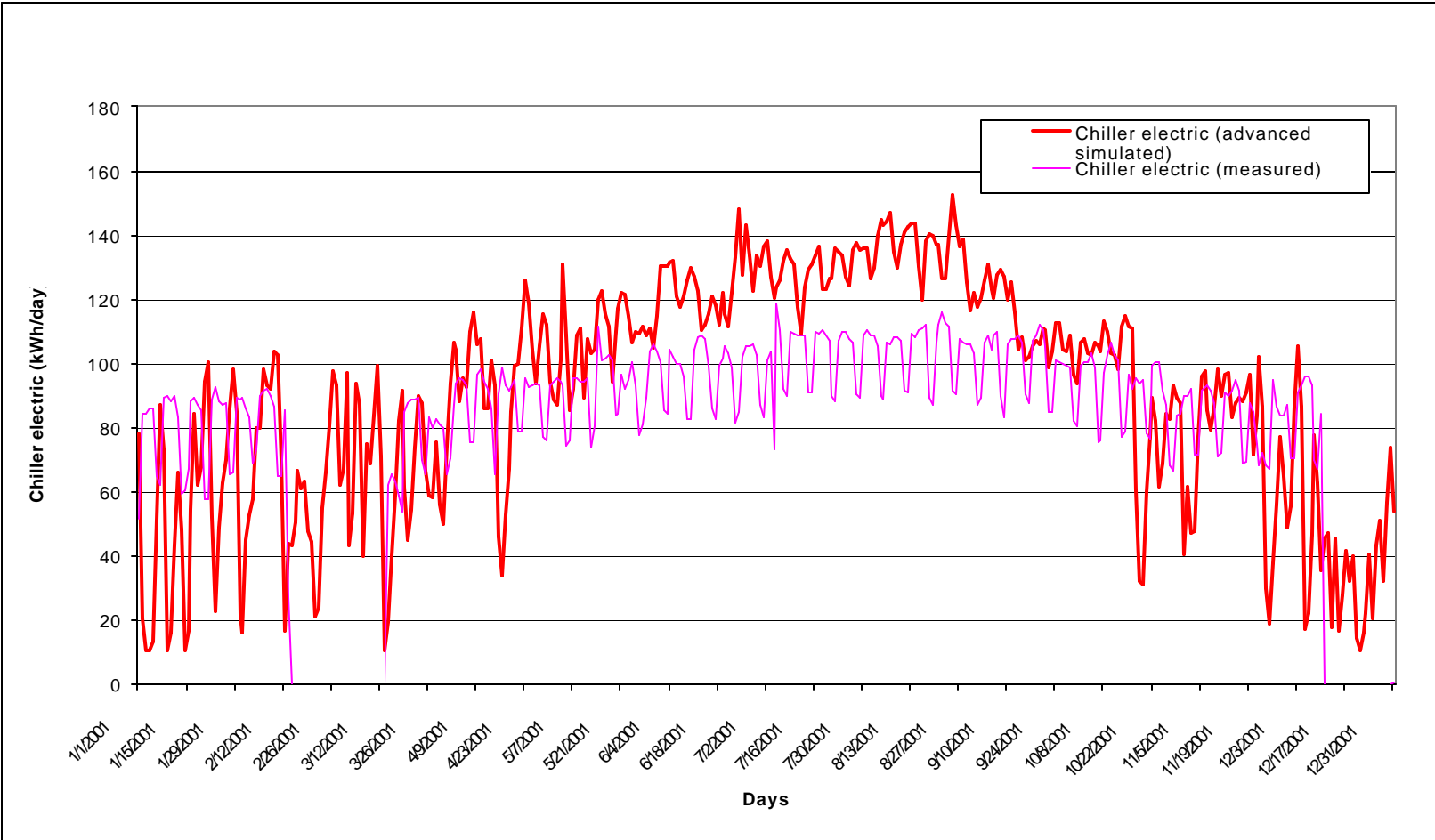
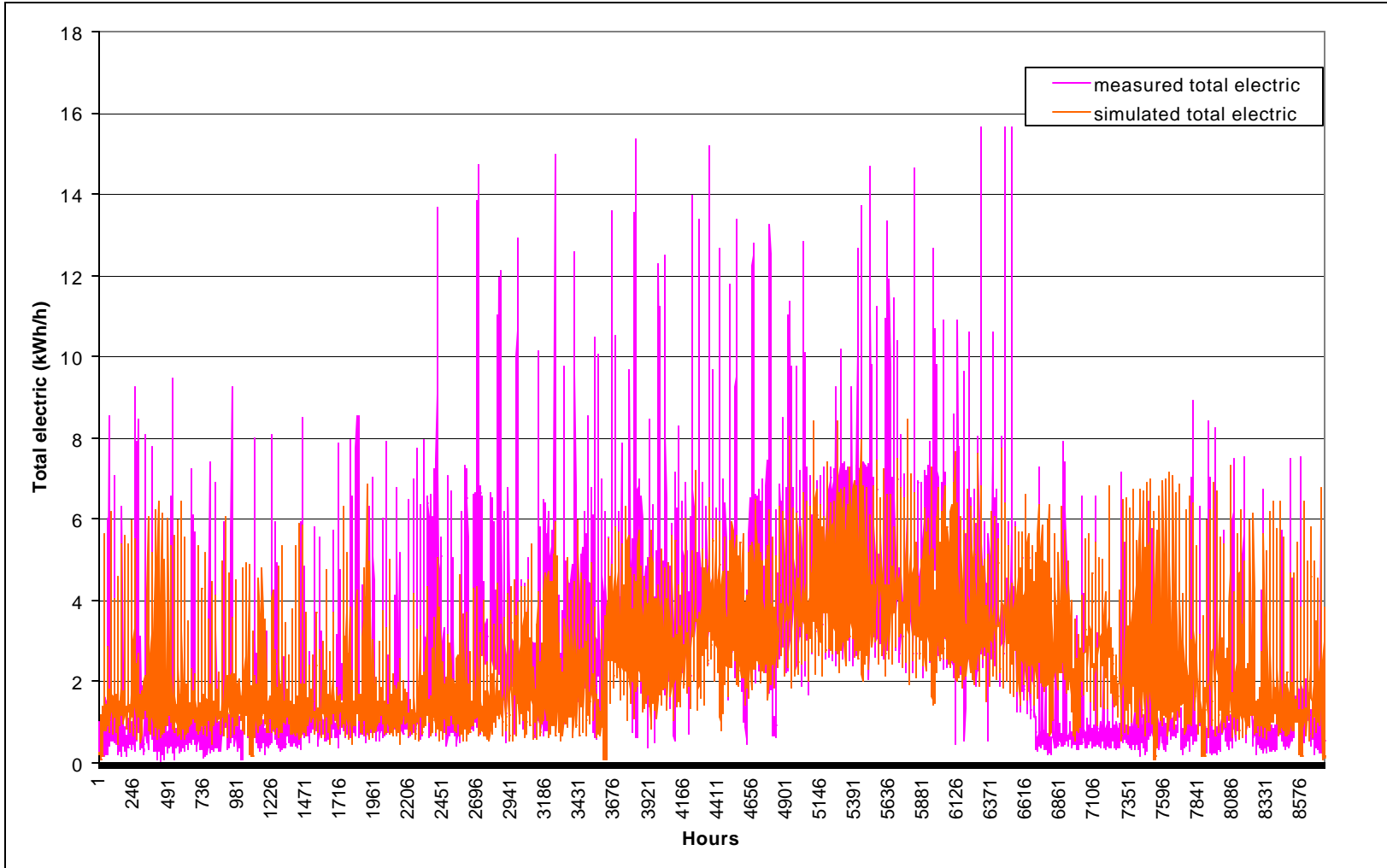**Fig 5.28 Time series of measured and simulated (advanced model) for chiller electric (kW)**

5.6.1 Total Electric Consumption

Figures 5.29 to 5.32 show the comparison between the measured and simulated total electric of the Habitat House. The simulated data for both the models is less than the measured data for the summer months. Following conclusions can be drawn from the graphs:

- For both the models the simulated values match quite well with the measured data, except for the summer months where the difference for the massless model is about 30%. The advanced model matches well with the measured data all round the year except for the month of October where it shows higher consumption. According to the researcher (Victor Kootin Sanwu) working on the house, the spikes in the measured data depict the operation of the dryer. The advanced model matches better with the measured data because the schedules used for lighting and equipment were measured by Victor.
- The effect of thermal mass is quite visible by comparing massless and advanced models. The massless model shows sudden surges and drops in the total electric use showing that the energy addition and removal is sudden. However in the advanced case the energy increase and decrease is subtle due to the thermal storage effect. And in summer months the cooling use goes up by 25% for the advanced model when compared with the massless model.

5.6.2 Gas Consumption

The measured data for gas consumption is almost 10 times higher than the simulated data for both the models. The comparison between the simulated and measured has no graphical significance. However the comparison between the massless model and the advanced model show that the thermal mass and the measured schedules have a significant impact on the heating load. The gas consumption increased by 40 to

80% for the winter months. Figure 5.33 depicts the comparison. The constant minimum value for both cases show the pilot light of the furnace, which is assumed to be rated, at 800 Btu/hr.

5.7 Comparison Between the Massless Model and the Simplistic Model

In order to quantify the impact of correct envelope details, comparison between the simplistic model and the massless model was analyzed. This comparison was performed for different weather location, Houston and Chicago. These weather stations were chosen because of the completely different weather conditions. All the four buildings were analyzed.

A study by Hepting and Jones (2001) analyzed the importance of defining the correct physical shape of building in the DOE-2 simulation software. They found out the using the detailed approach to define the building as it looks architecturally has a relatively small impact on the simulation output. The major impact was on cooling load, which decreased by 14% on the average for the two buildings. However these buildings were located in a climate with very high heating degree-days. So the overall impact of cooling load is negligible.

Fig 5.29 Time series of measured and simulated (massless model) for total electric (kWh/day)

Fig 5.30 Time series of measured and simulated (massless model) for total electric (kWh/hr)

Fig 5.31 Time series of measured and simulated (advanced model) for total electric (kWh/day)

Fig 5.32 Time series of measured and simulated (advanced model) for total electric (kWh/hr)
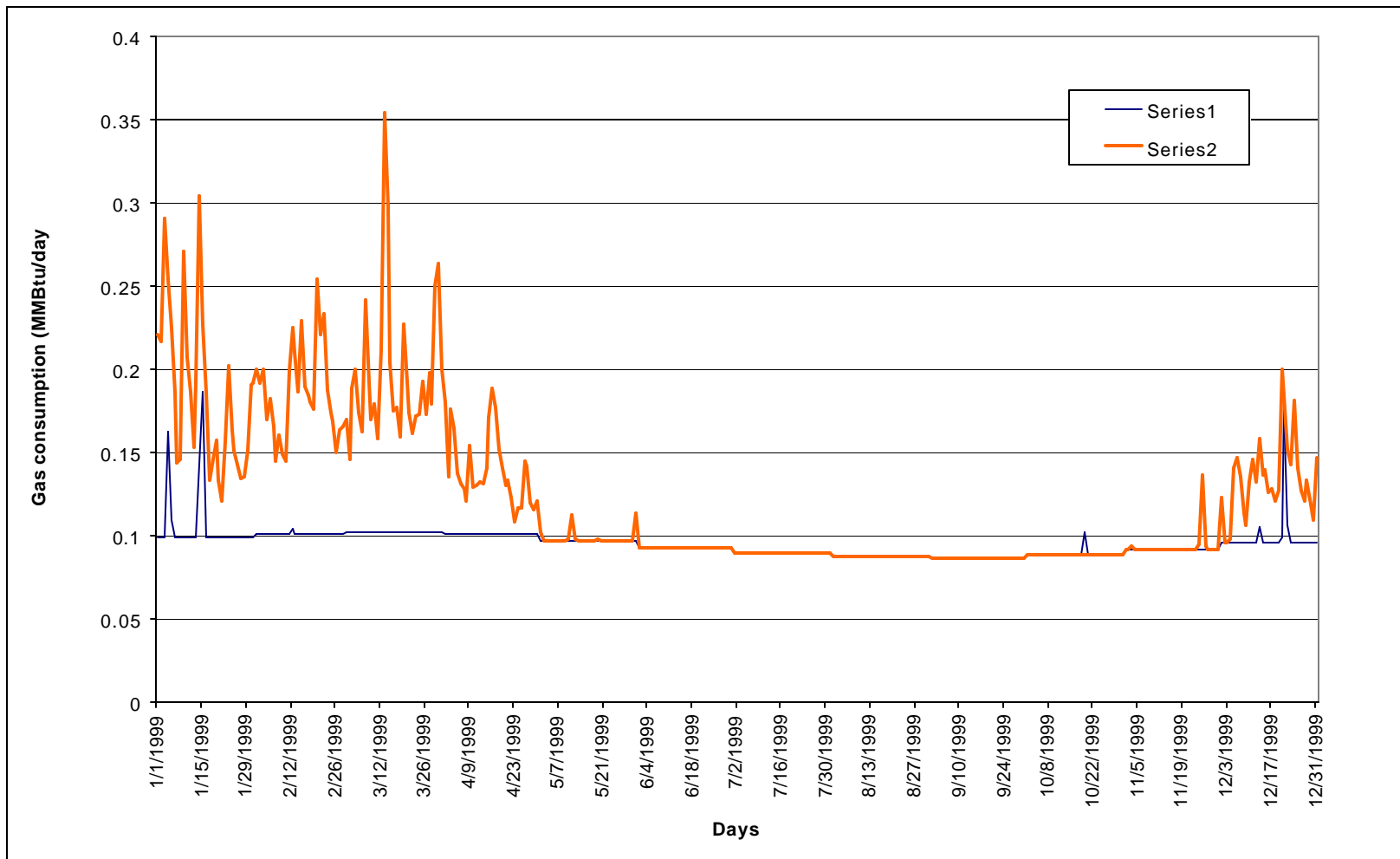
Fig 5.33 Time series of gas consumption for the comparison between the massless and advanced simulation models (MMBtu/day)

For the scope of this current research, instead of making a disjointed model, the building was simplified to a single floor two-zone model for all the four cases. This model has the area equivalent to the complete building. The two weather conditions chosen are very different from each other, Chicago with 6549 65°F heating degree-days (HDD) and Houston with 1548 65°F HDDs. The analysis has been divided by the weather data.

5.7.1 Chicago Weather File

5.7.1.1 Cooling Loads

Figures 5.34 to 5.37 compare the chilled water consumption between the simplistic model and the advanced model. The comparison indicates that there is hardly any difference for chilled water consumption for the Chicago weather file. All the buildings show similar results irrespective of the layout. The average percentage difference for all the buildings is between 0.5 to 3.5%.

5.7.1.2 Heating Load

Figures 5.38 to 5.41 compare the heating load for the two models. The comparison shows that hot water consumption for the two models is not similar. The consumption of the simplistic model is greater than the massless model. This is mainly because that the simplistic model for all the building has very large roof and floor area. The heat gains due to the internal loads are being lost to the ground and the outside through the floor and the roof. This is causing the hot water consumption to go up. However for WERC and John B. Connally Building, the hot water consumption is identical to the massless model. For WERC it can be said that since the material laboratory at the back of the building has a high heating load and it is not being simulated in the simple model, so the increase in heating load due to the increase in roof and floor area is being compensated. For John B. Connally Building the explanation may

be the high percentage of window to wall ratio, because solar heat gain helps to reduce hot water usage in winter.

5.7.2 Houston Weather File

5.7.2.1 Cooling Load

Figures 5.42 to 5.45 show the cooling load comparison between the simplistic and massless model for the four buildings. For John B. Connally Building and Wehner Building, the chilled water consumption is almost identical. The average percentage difference is from 0.5 to 1.7% for the two buildings. For WERC the simplistic model consumption is lower than the massless model. This may be because the materials lab is not being simulated for the simplistic model. This lab has a significant cooling and heating load. So even if the cooling load increases for the simplistic model because of the large roof area, it is being compensated by the removal of the materials laboratory.

5.7.2.2 Heating Load

Figures 5.46 to 5.49 compare heating load for the massless model and the simplistic model. For WERC the heating loads are almost same for both models. The average percentage difference is around 5%. However for the rest of the buildings the heating load goes up significantly for the simplistic model. Main reason is the increased roof and floor area, which is dissipating a large fraction of the heat gain due to internal loads. For WERC, the material-testing laboratory again nullifies the effect of the increased floor and roof area.
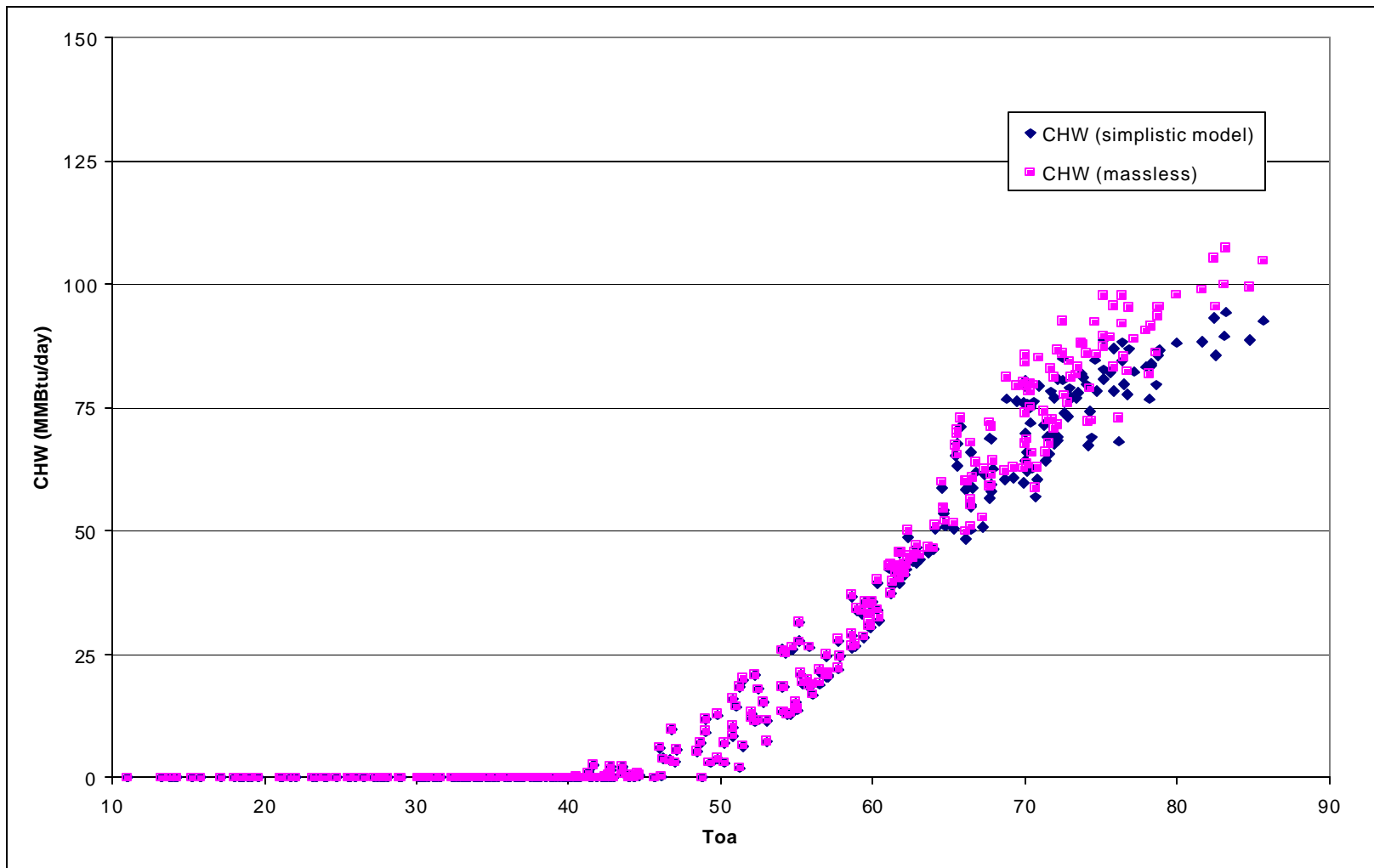
Fig 5.34 Comparison between simplistic and massless models for cooling loads, WERC (MMBtu/day)
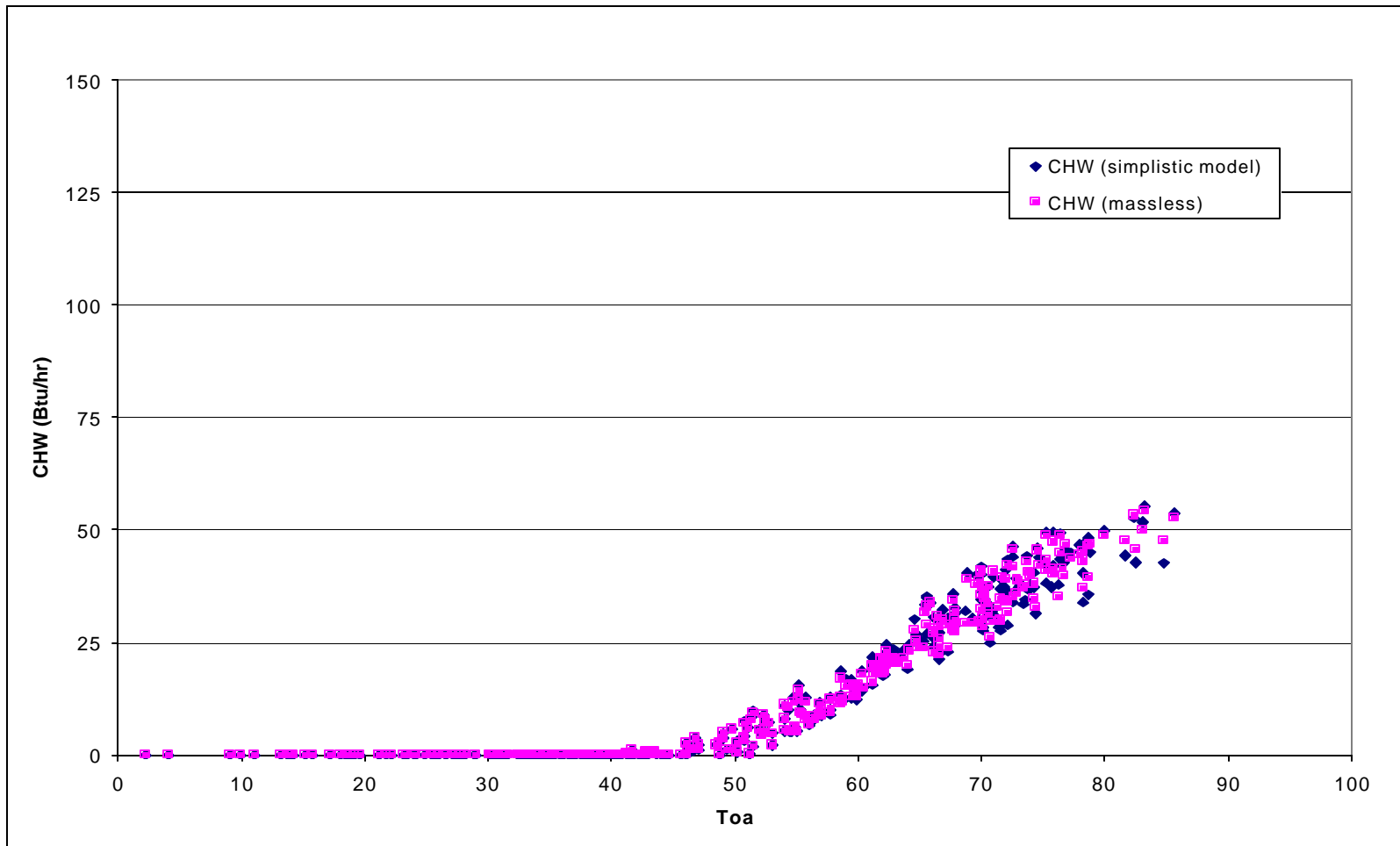
Fig 5.35 Comparison between simplistic and massless models for cooling loads, Wehner Building (MMBtu/day)
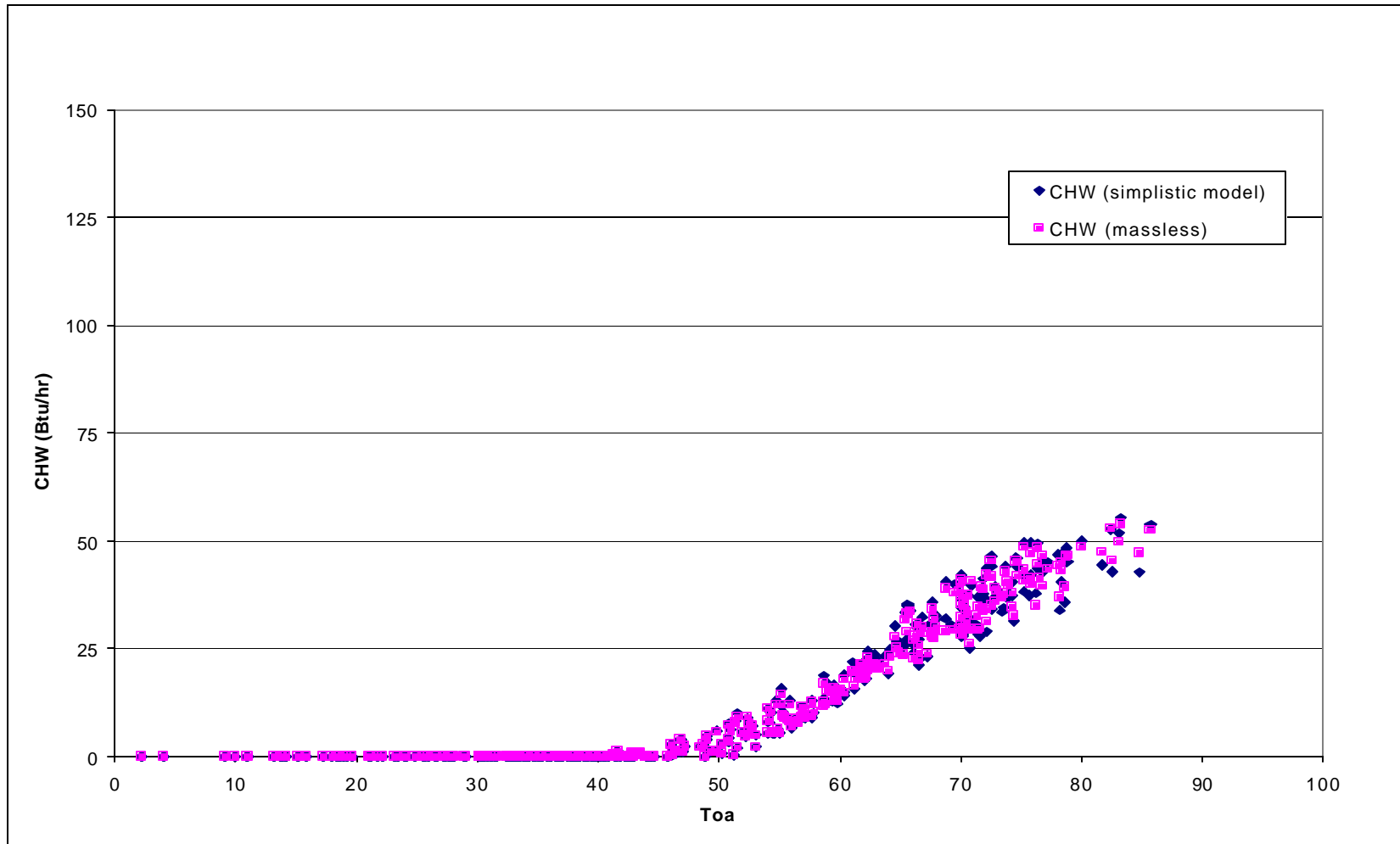
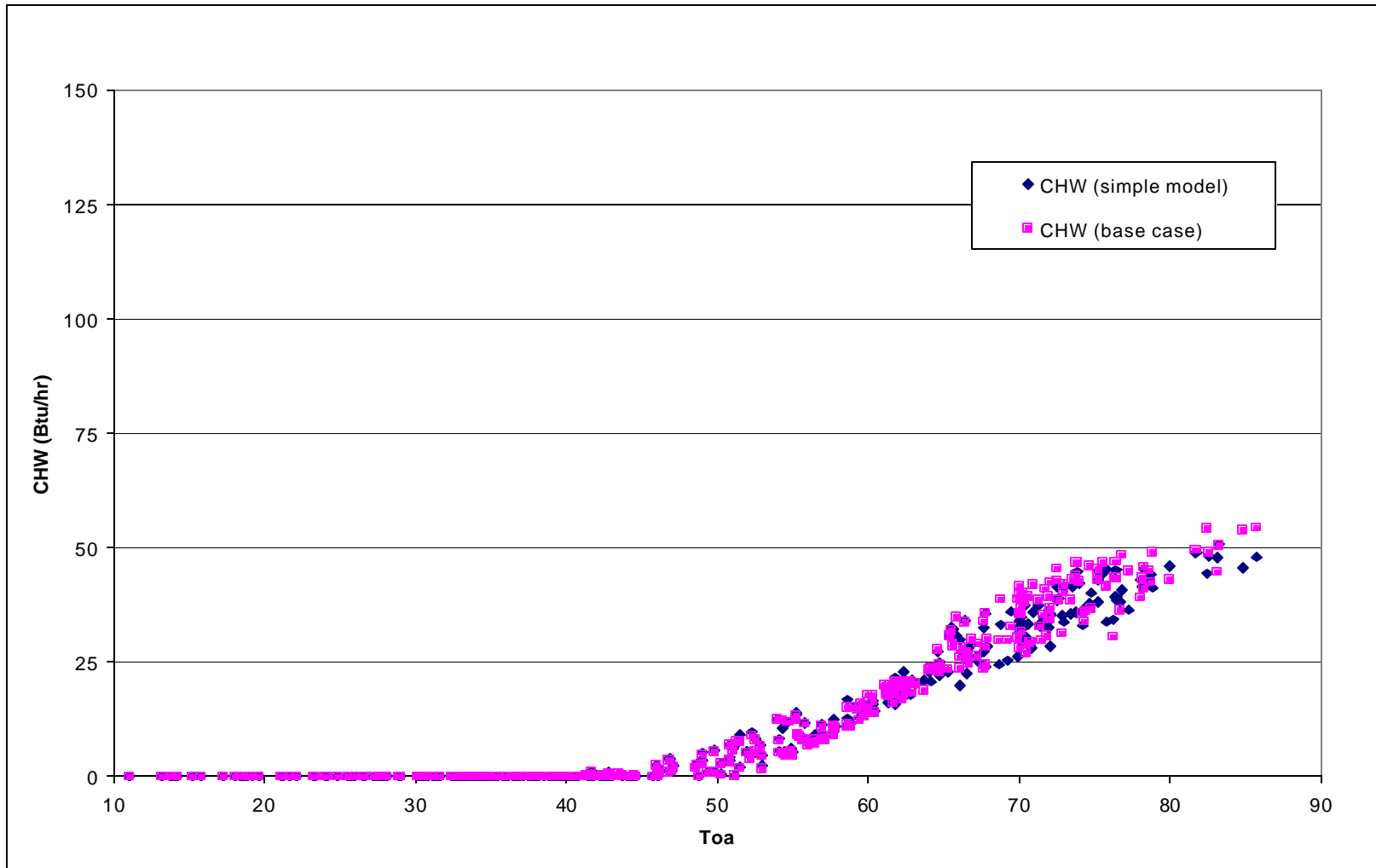**Fig 5.36 Comparison between simplistic and massless models for cooling loads, Harrington Tower (MMBtu/day)**

Fig 5.37 Comparison between simplistic and massless models for cooling loads, John B. Connally Building (MMBtu/day)
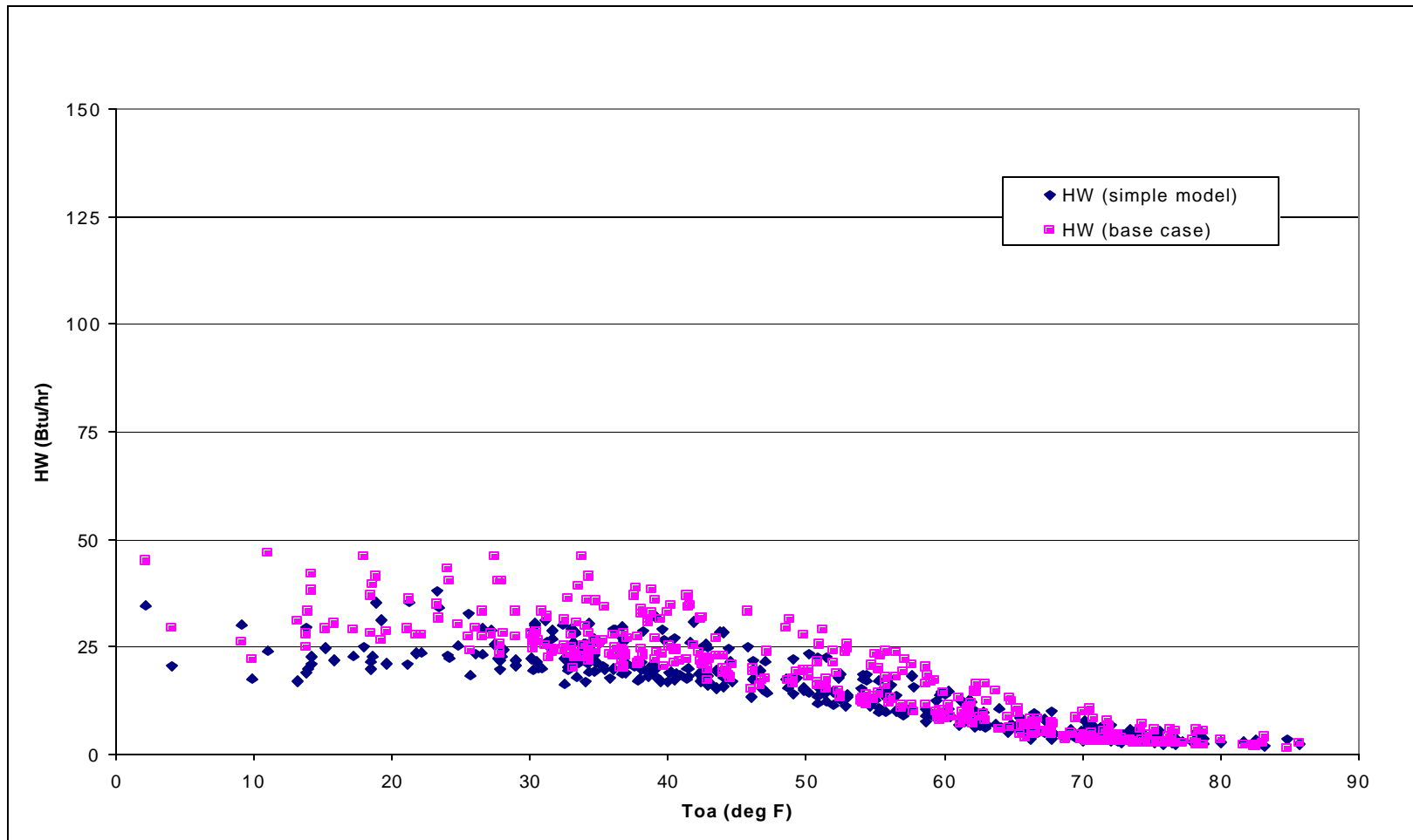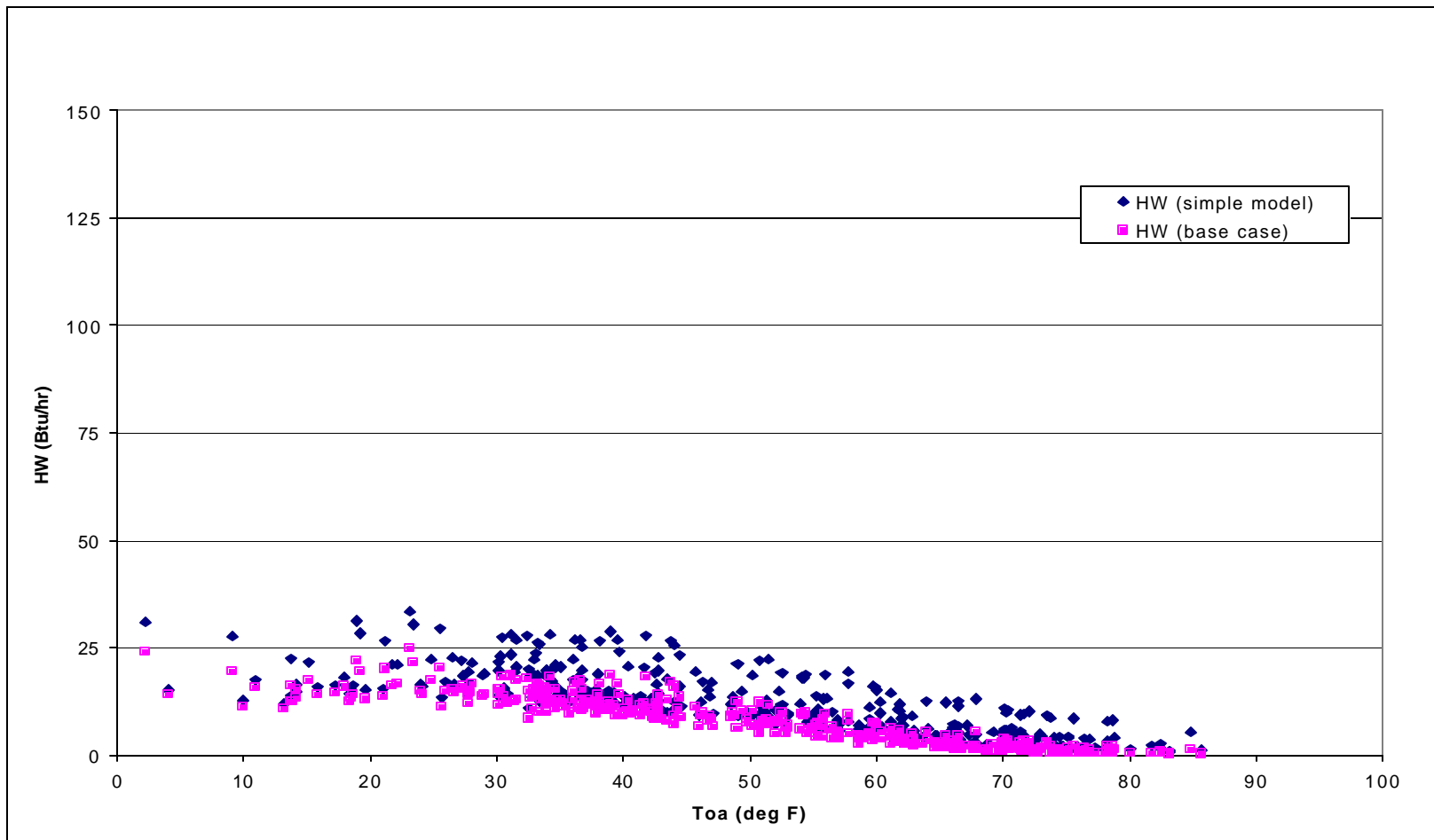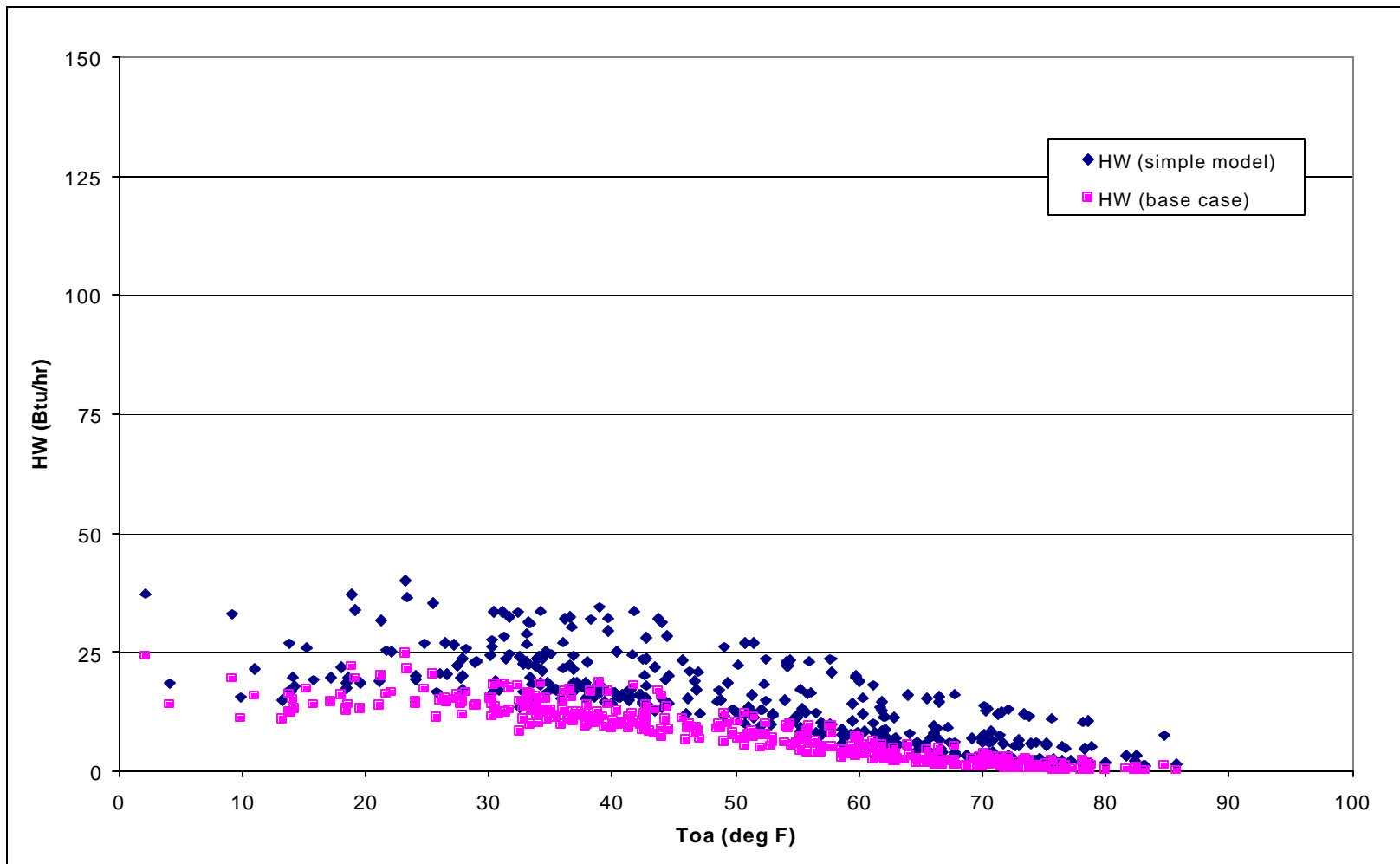
Fig 5.38 Comparison between simplistic and massless models for heating loads, WERC (MMBtu/day)

Fig 5.39 Comparison between simplistic and massless models for heating loads, Wehner Building (MMBtu/day)

Fig 5.40 Comparison between simplistic and massless models for heating loads, Harrington Tower (MMBtu/day)
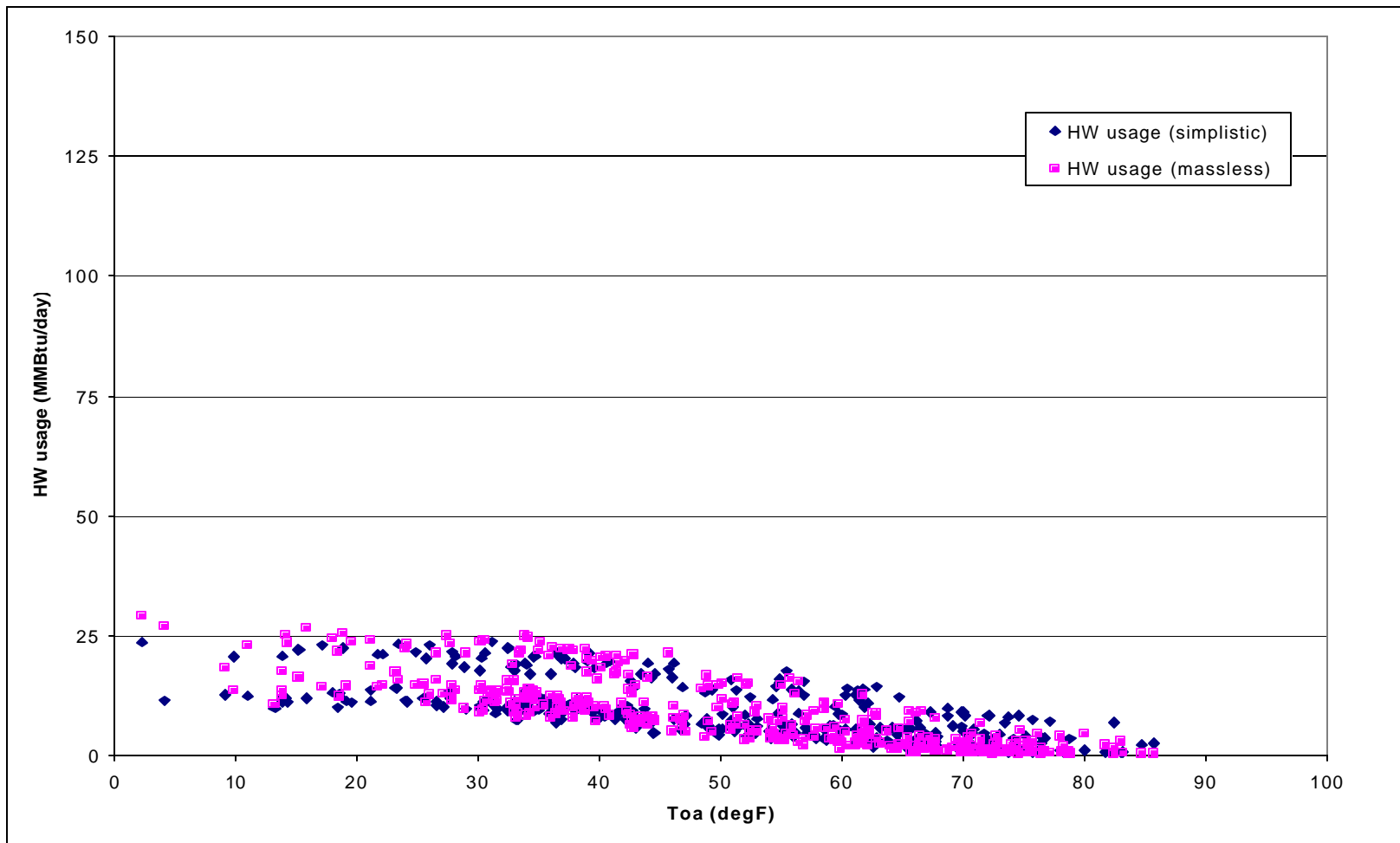
Fig 5.41 Comparison between simplistic and massless models for heating loads, John B. Connally Building (MMBtu/day)
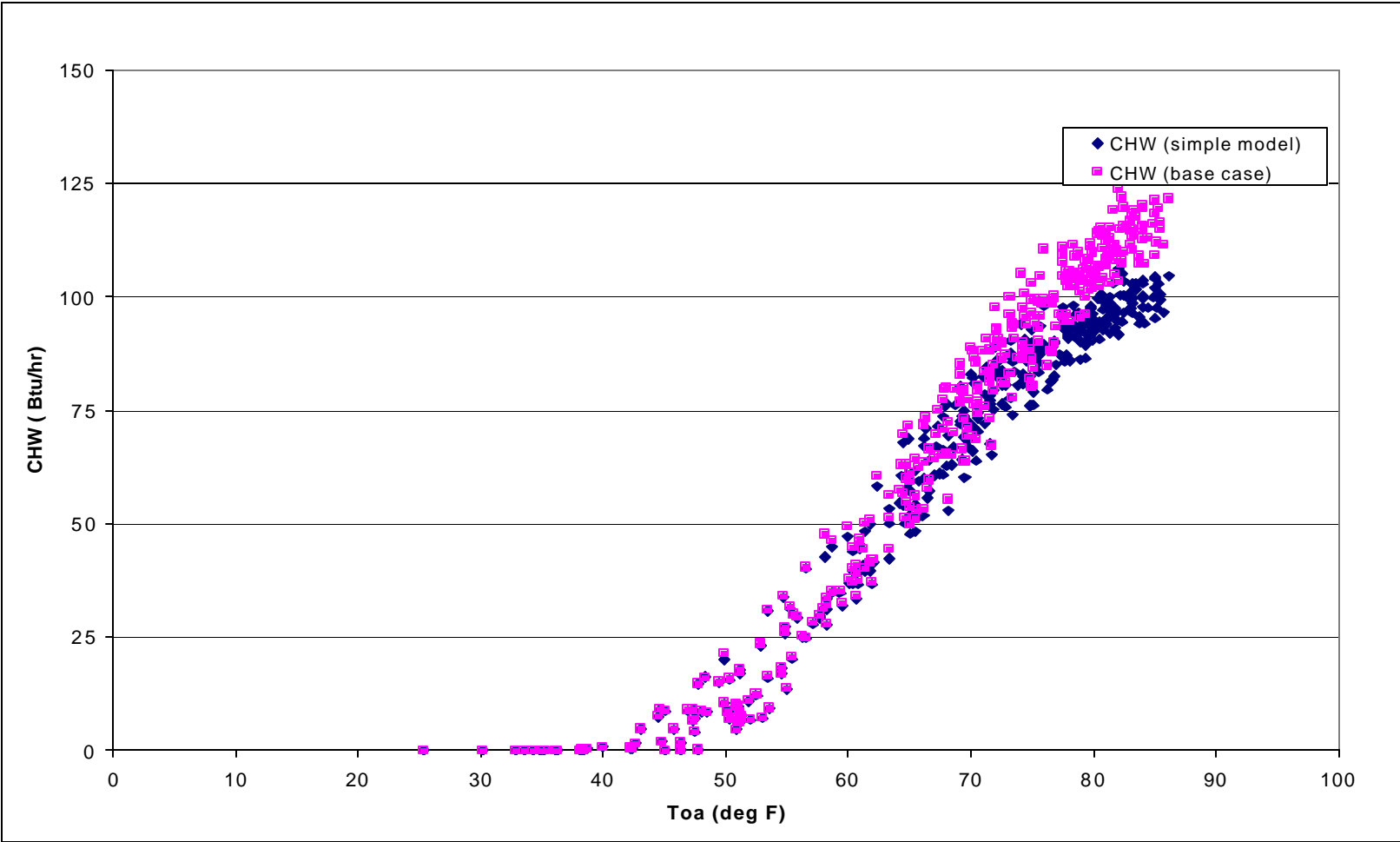
Fig 5.42 Comparison between simplistic and massless models for cooling loads, WERC (MMBtu/day)
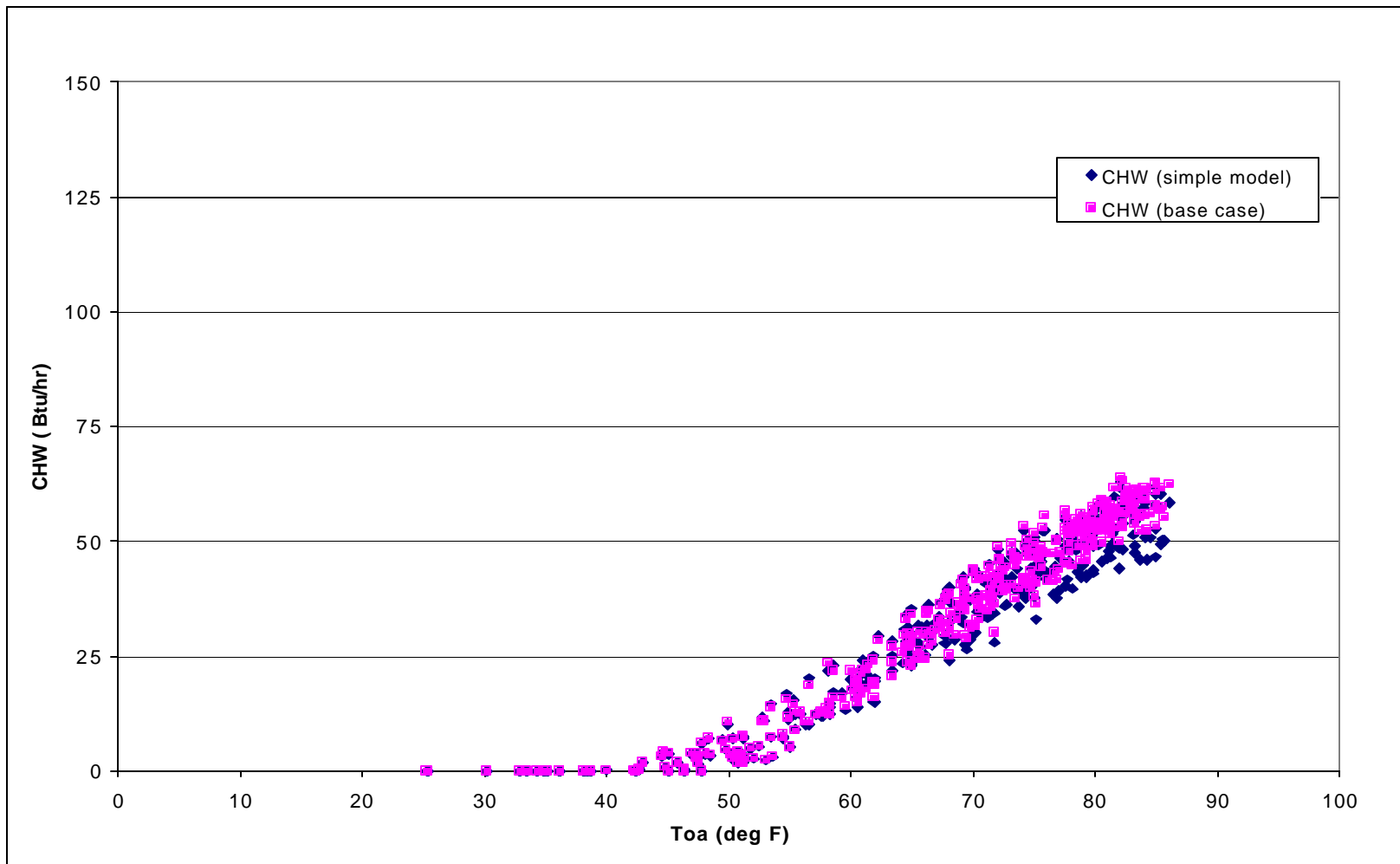
Fig 5.43 Comparison between simplistic and massless models for cooling loads, Wehner Building (MMBtu/day)
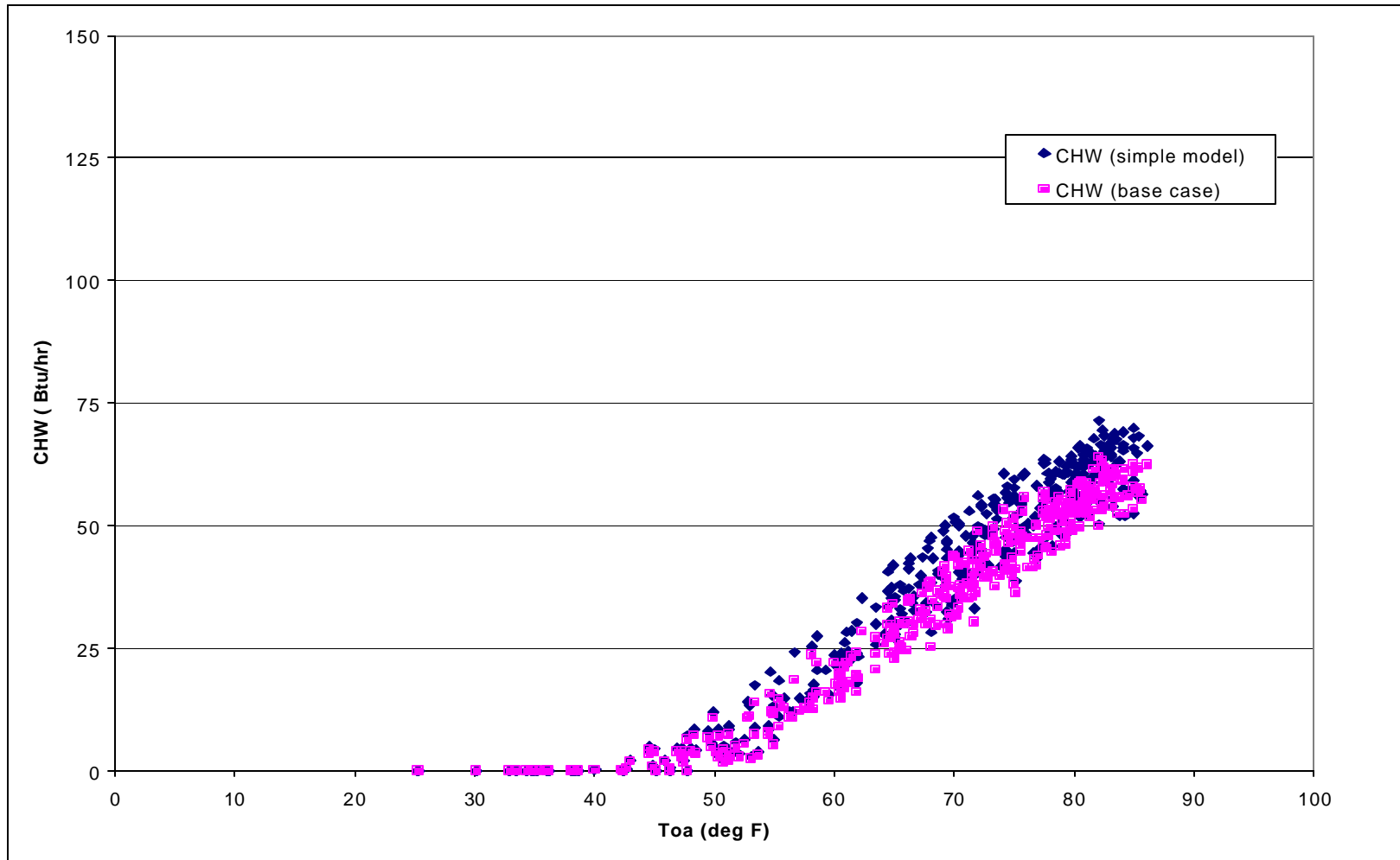
Fig 5.44 Comparison between simplistic and massless models for cooling loads, John B. Connally Building (MMBtu/day)
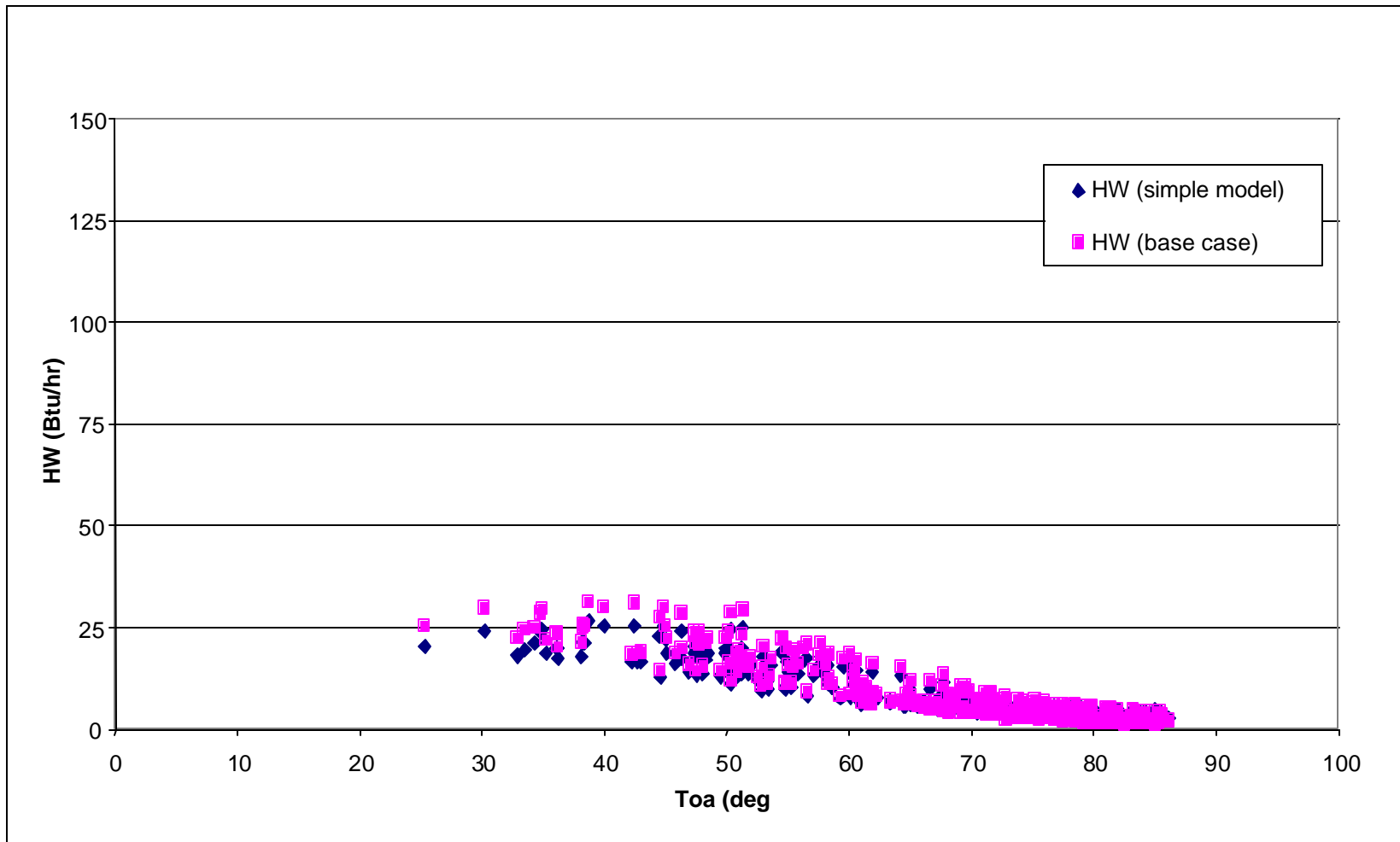
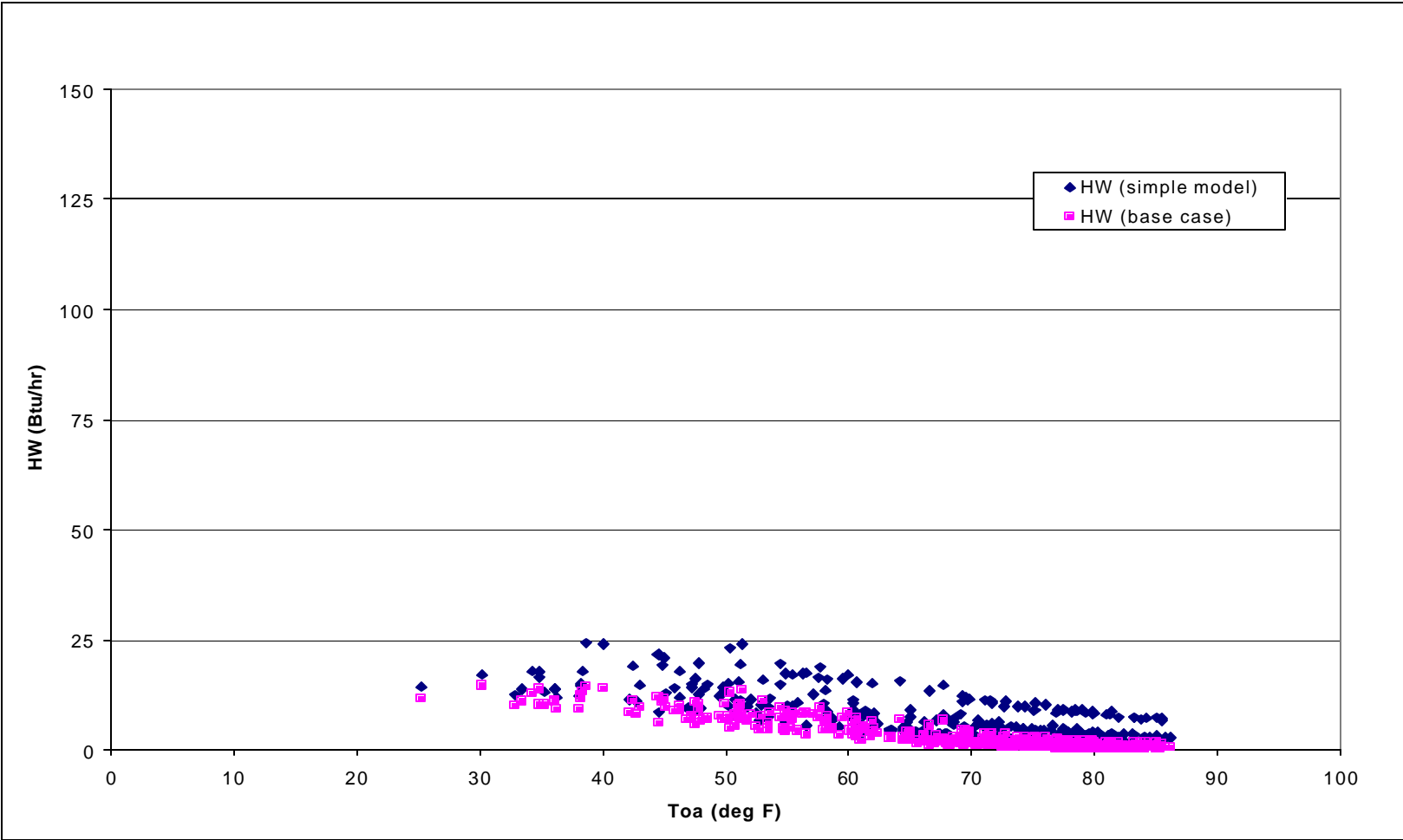**Fig 5.45 Comparison between simplistic and massless models for heating loads, WERC (MMBtu/day)**

Fig 5.46 Comparison between simplistic and massless models for heating loads, Wehner Building (MMBtu/day)
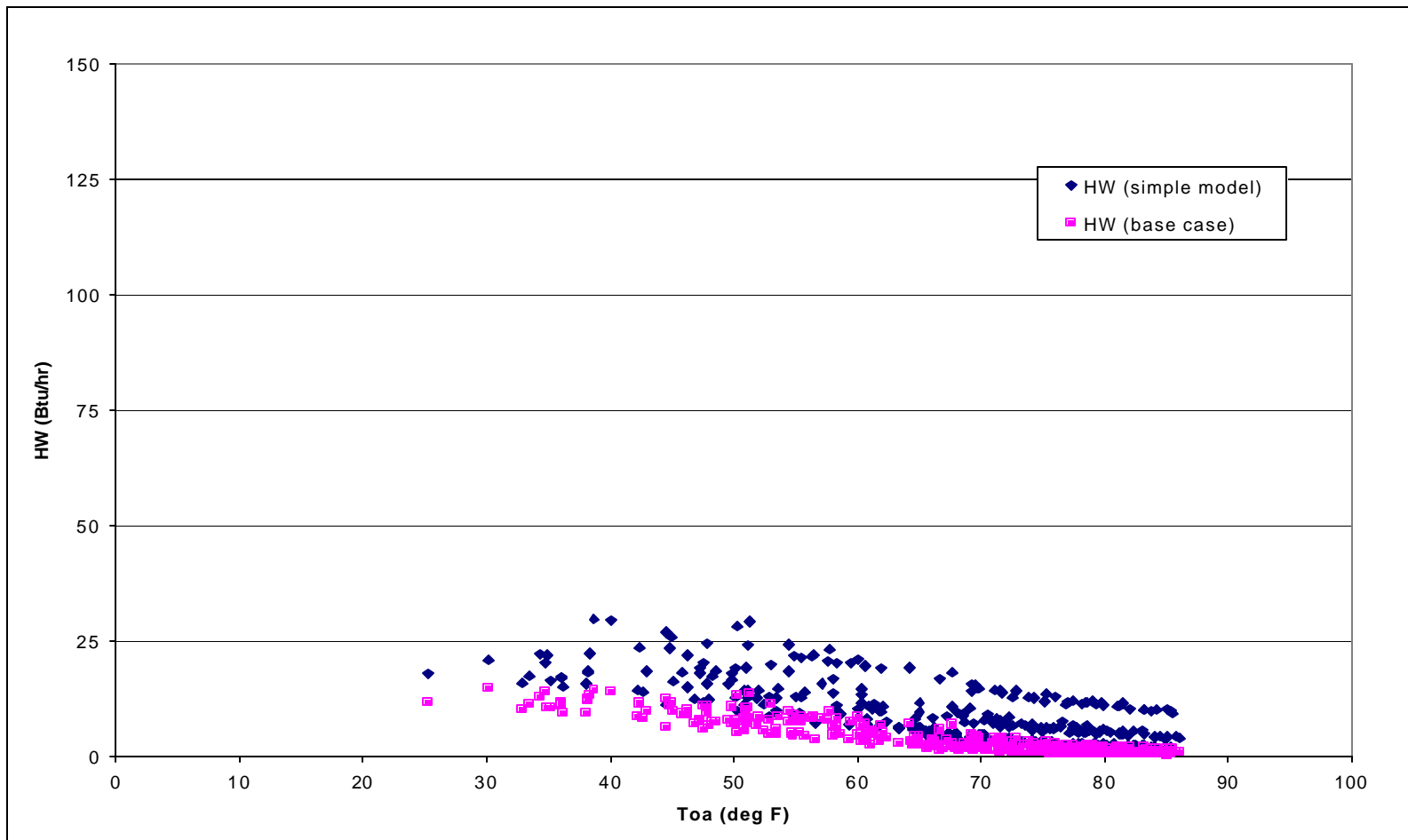
Fig 5.47 Comparison between simplistic and massless models for heating loads, Harrington Tower (MMBtu/day)
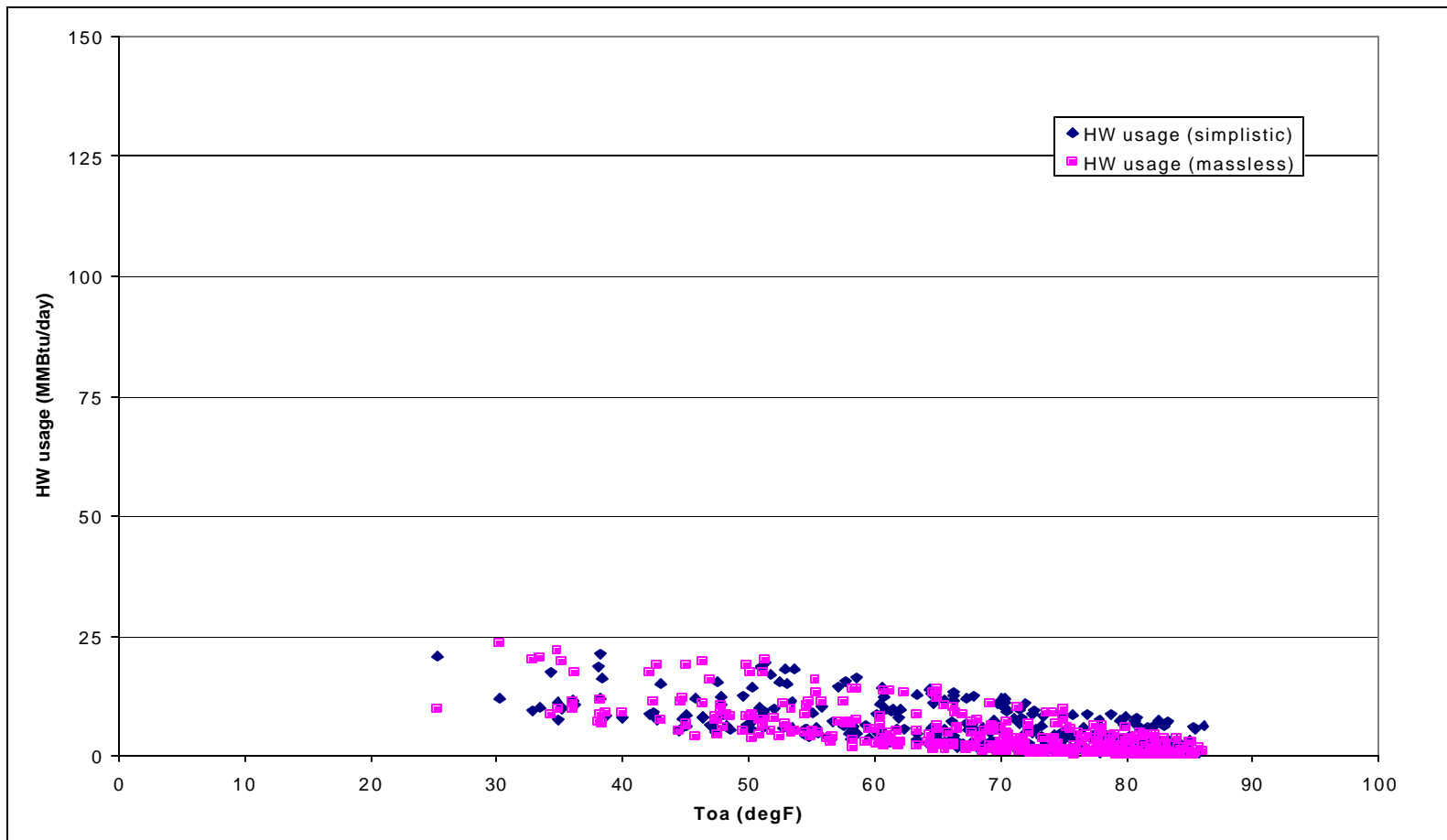
Fig 5.48 Comparison between simplistic and massless models for heating loads, John B. Connally Building (MMBtu/day)

From analyzing the above graphs, the conclusions which can be drawn is that envelope layout and exact details have an impact on the overall simulation result. However the extent of this impact does not depend on the weather condition for internally load dominated buildings. But this also depends on the layout of individual buildings. For example if a building has a specialized facility which cannot be incorporated in the simple model, then the differences will be more as compared to a normal office buildings. Same can be said for glazing area in a particular orientation, which could not be defined as the same for the simplistic model.

5.8 Sensitivity Analysis

In order to determine how an uncalibrated simulation can better depict actual operational conditions of a building, a sensitivity analysis of selected parameters was conducted. The aim of this study was to identify those parameters, which have a significant impact on the simulation output. This will help the modeler to divide the simulation time accordingly and also to assume or acquire better values for the important parameters. The following parameters have been selected for the analysis:

- Thermal mass
- Thermostat schedule
- Fan schedule
- Outside air fraction

Sensitivity was run on all the four buildings. But since all buildings are internally load dominated, the results were same. So in the following section, the sensitivity analysis done on WERC is discussed.

5.8.1 Thermal Mass

For this parameter, the massless model was run as is, i.e. without thermal mass, and then thermal mass was added. No other change was made to the input file. Figures 5.49 to 5.52 show that:

- Adding thermal mass to an internally load dominated building has a very small impact on the heating and cooling loads.
- The average yearly chilled water consumption goes down by 11%.
- The average yearly hot water consumption goes up by 28%.
- The chilled water consumption goes down since the thermal mass in the envelope is not adding all the heat from the outside to the interior.
- The hot water consumption goes up. If the building were not using a setback schedule the consumption would have gone down. But in this case, due to the morning set back, more hot water is required to achieve the zone temperature.

5.8.2 Thermostat Schedule

Three runs in addition to the massless model were performed for this parameter. The massless model is with a setback /setup schedule. Heating is 70°F for peak hours, 60-68°F for off peak hours, 68°F for weekends, cooling is 76°F for peak hours, 82-78°F off peak hours and 80°F for weekends. For the first run, the thermostat set point was made constant with no setback/setup. In the second run a 5°F setback/setup is incorporated while for the third case this value is changed to 10°F.

Fig 5.49 Comparison between the measured and simulated chilled water consumption (massless model, no thermal mass)

Fig 5.50 Comparison between the measured and simulated chilled water consumption (with thermal mass)
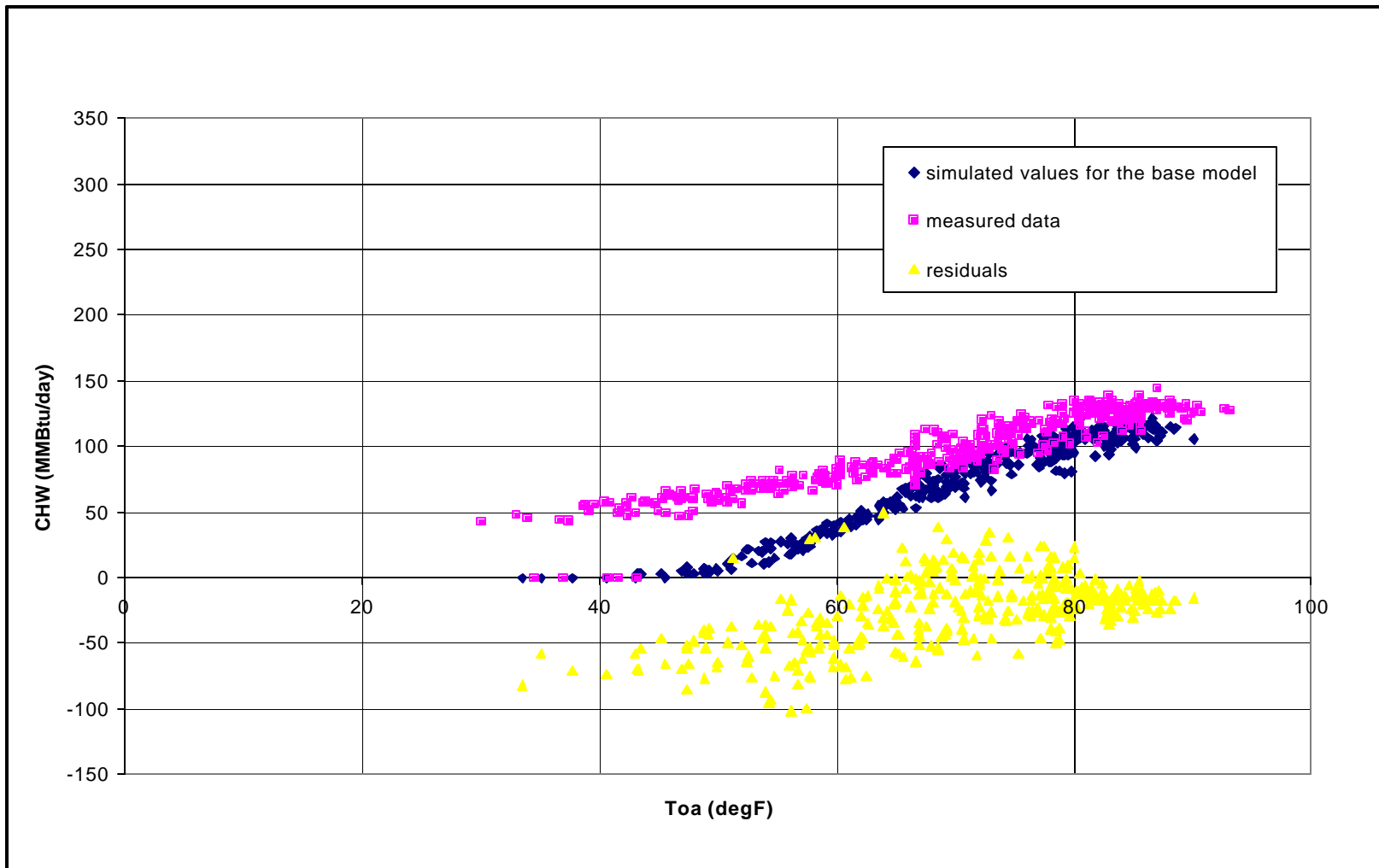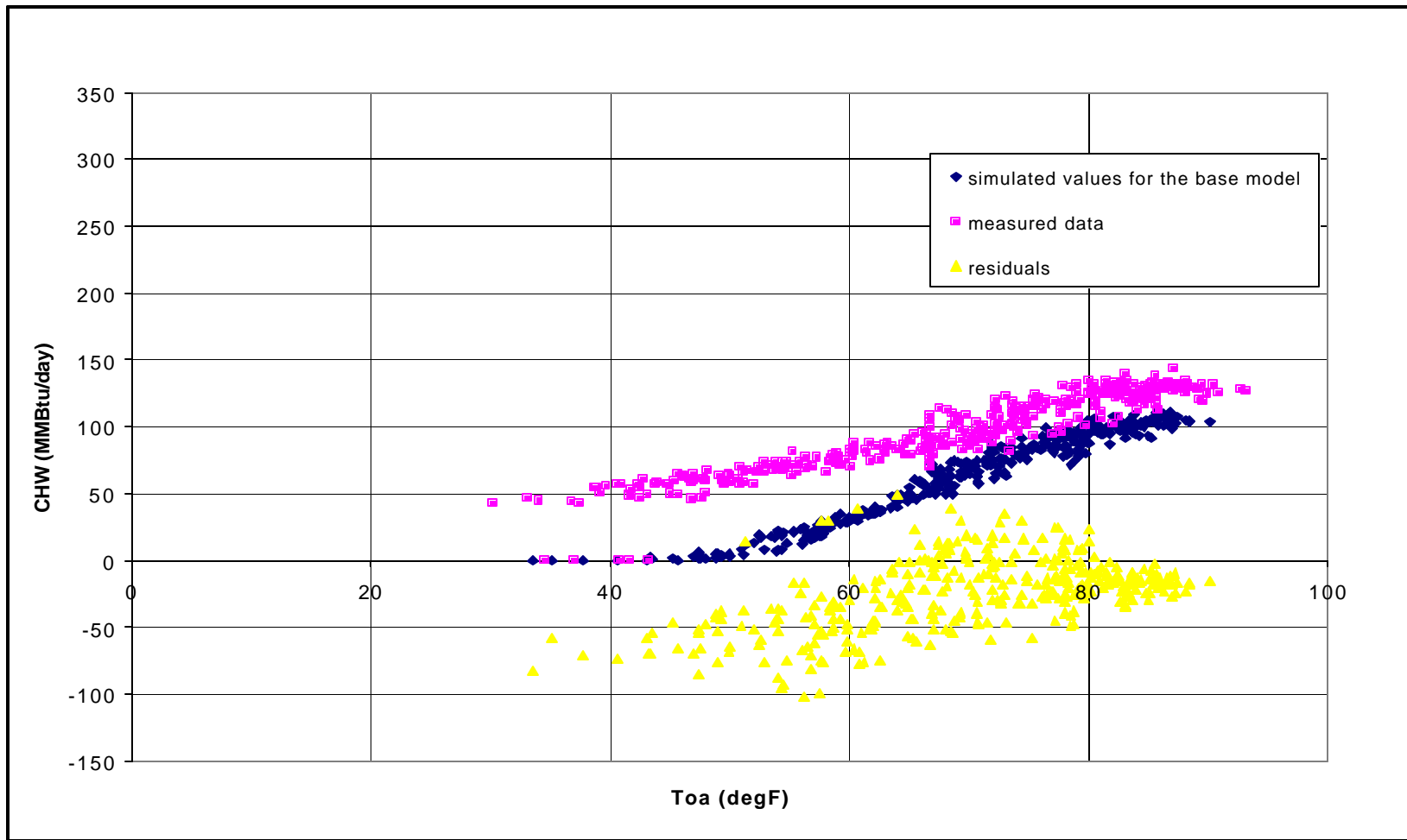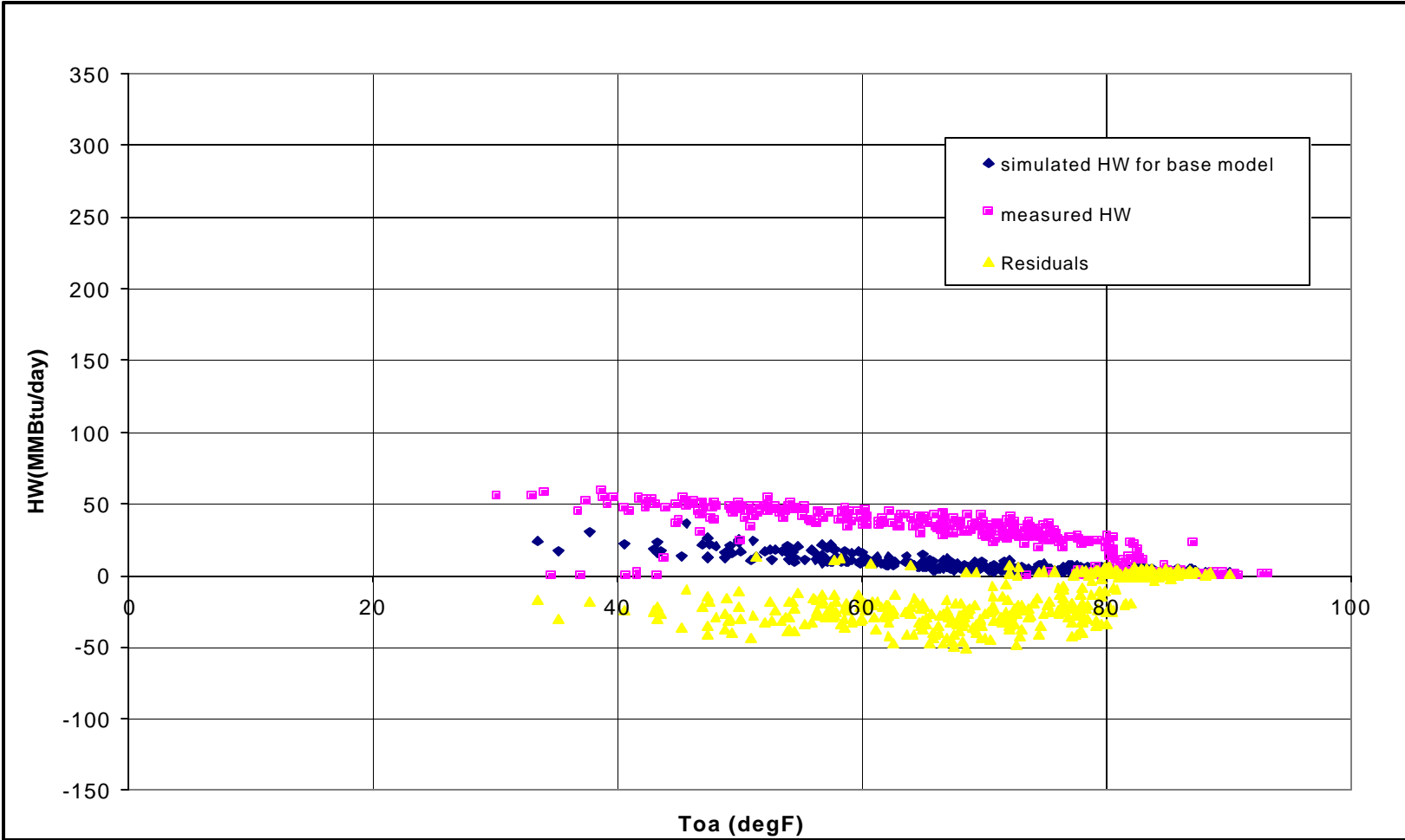
Fig 5.51 Comparison between the measured and simulated hot water consumption (massless model, no thermal mass)
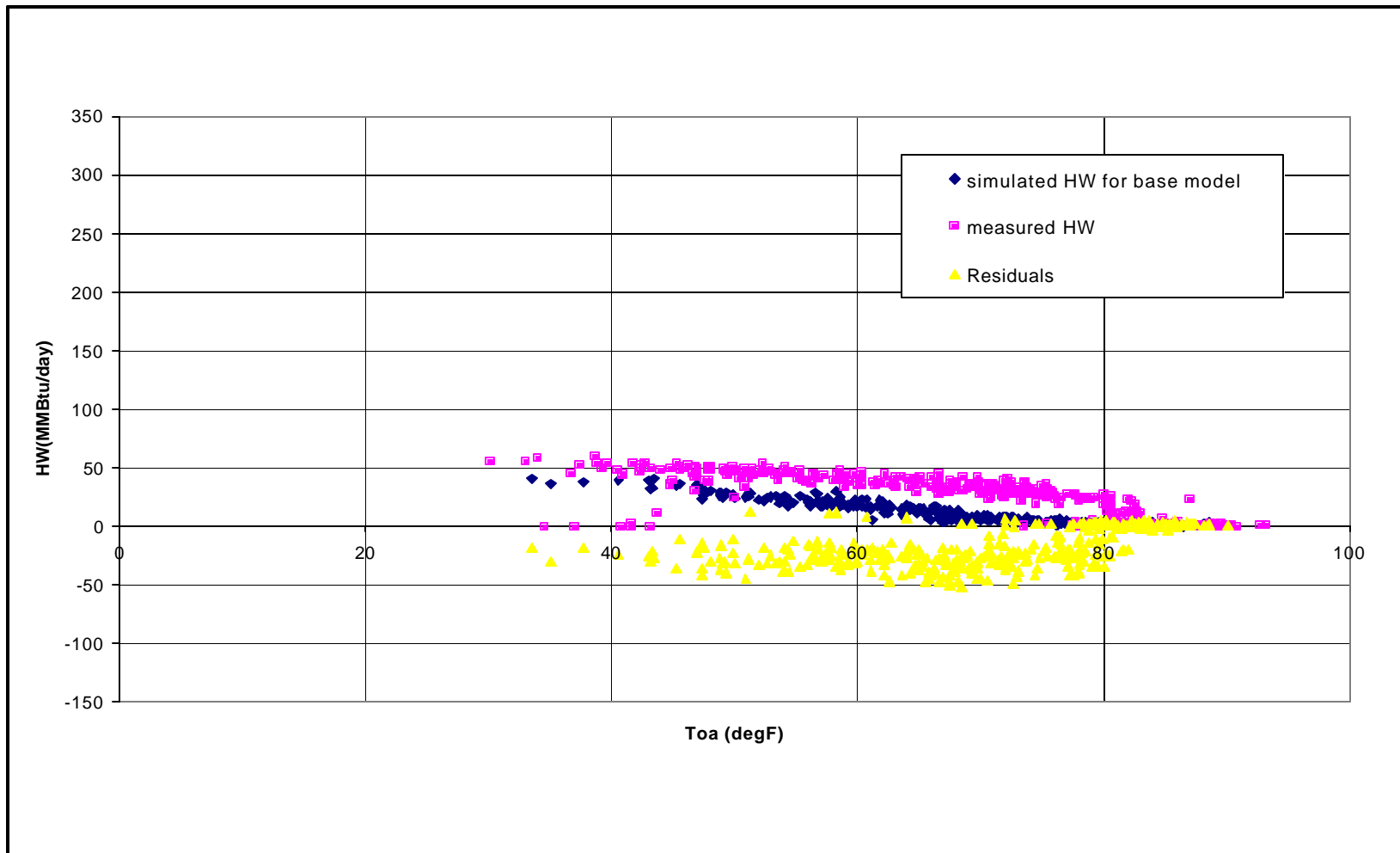
Fig 5.52 Comparison between the measured and simulated hot water consumption (with thermal mass)

The following conclusions can be drawn from figures 5.53 to 5.56:

- Chilled water consumption is independent of the thermostat schedule. How ever the hot water use goes down with the increase in setbacks.

- There is 72% reduction in the hot water consumption if the setback is increased from 0°F to 10°F.

- The reason for this decrease is that since the model is massless, the set point temperature after the night setbacks is achieved instantaneously without the any additional energy being utilized to counter the thermal storage effects.

- The chilled water is constant because the setup time during the night hours. The temperature during this time is not high and no additional energy is required to reach the set point after the morning setup.

If the advanced model were considered for analysis, the advantage due to the heating point setback would not be there. This is due to the thermal storage effects, which will require additional hot water to reach the thermostat set point after the morning setback. This is also depicted in the sensitivity analysis of thermal mass as already discussed.

Fig 5.53 Comparison between simulated and measured chilled water consumption (massless model, heating: 70° F peak, 60-68° F off peak, 68° F weekends, cooling: 76° F peak, 82-78 off peak, 80 weekends)

Fig 5.54 Comparison between simulated and measured chilled water consumption (10° F setback/setup, heating: 70° F peak, 60° F off peak/weekends, cooling: 76° F peak, 86° F off peak/weekends)

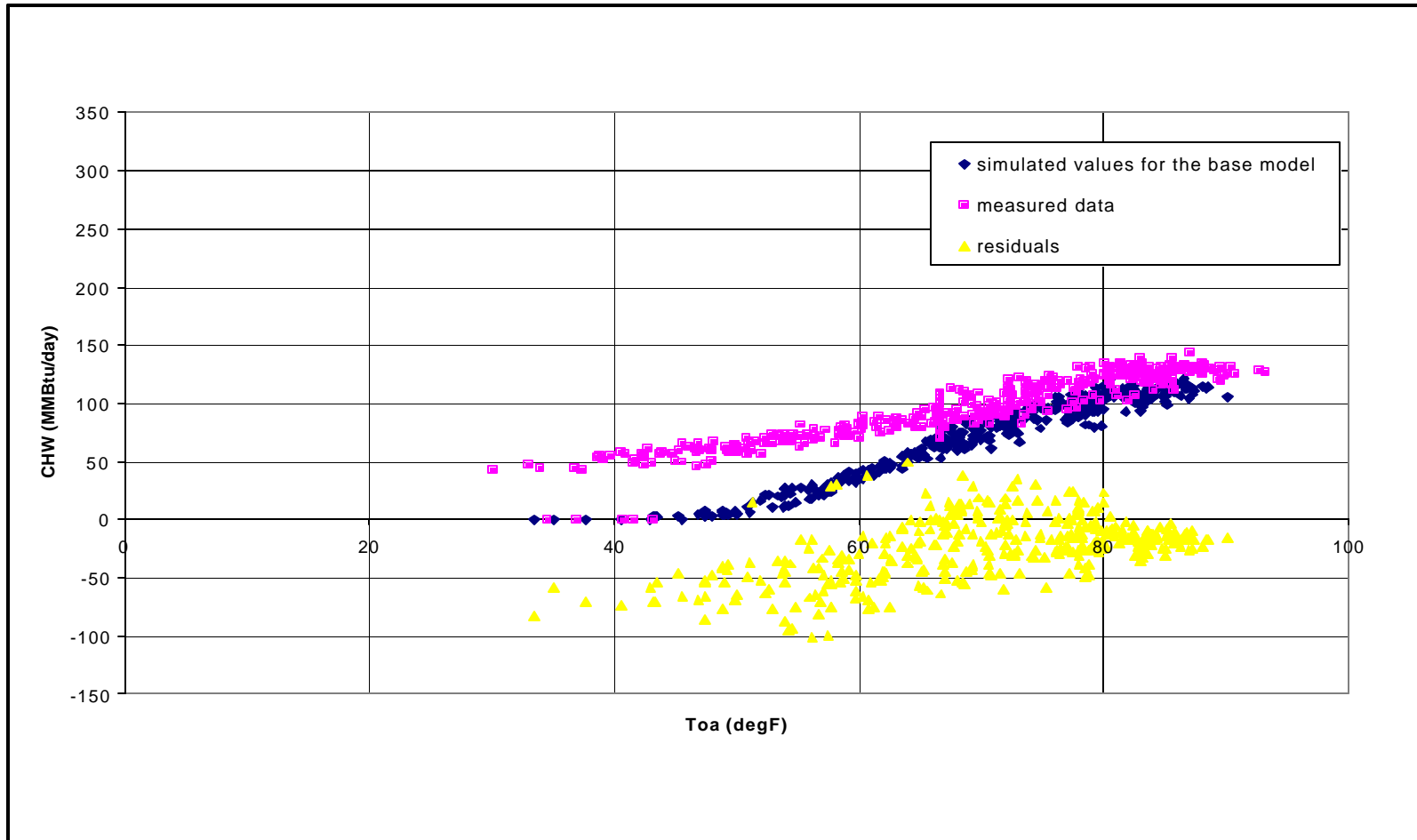**Fig 5.55 Comparison between simulated and measured hot water consumption (massless model, heating: 70°F peak, 60-68°F off peak, 68°F weekends, cooling: 76°F peak, 82-78 off peak, 80 weekends)**

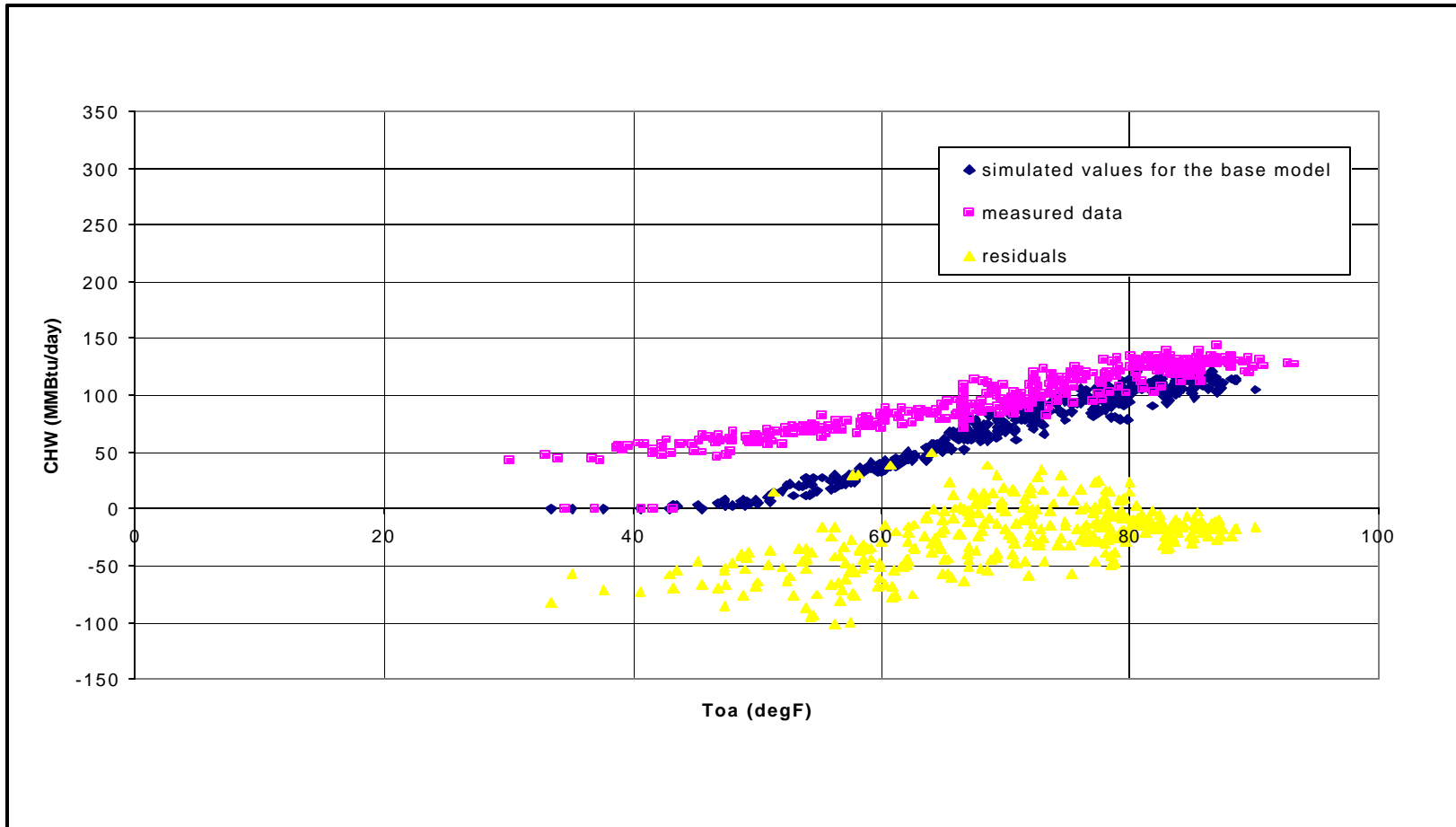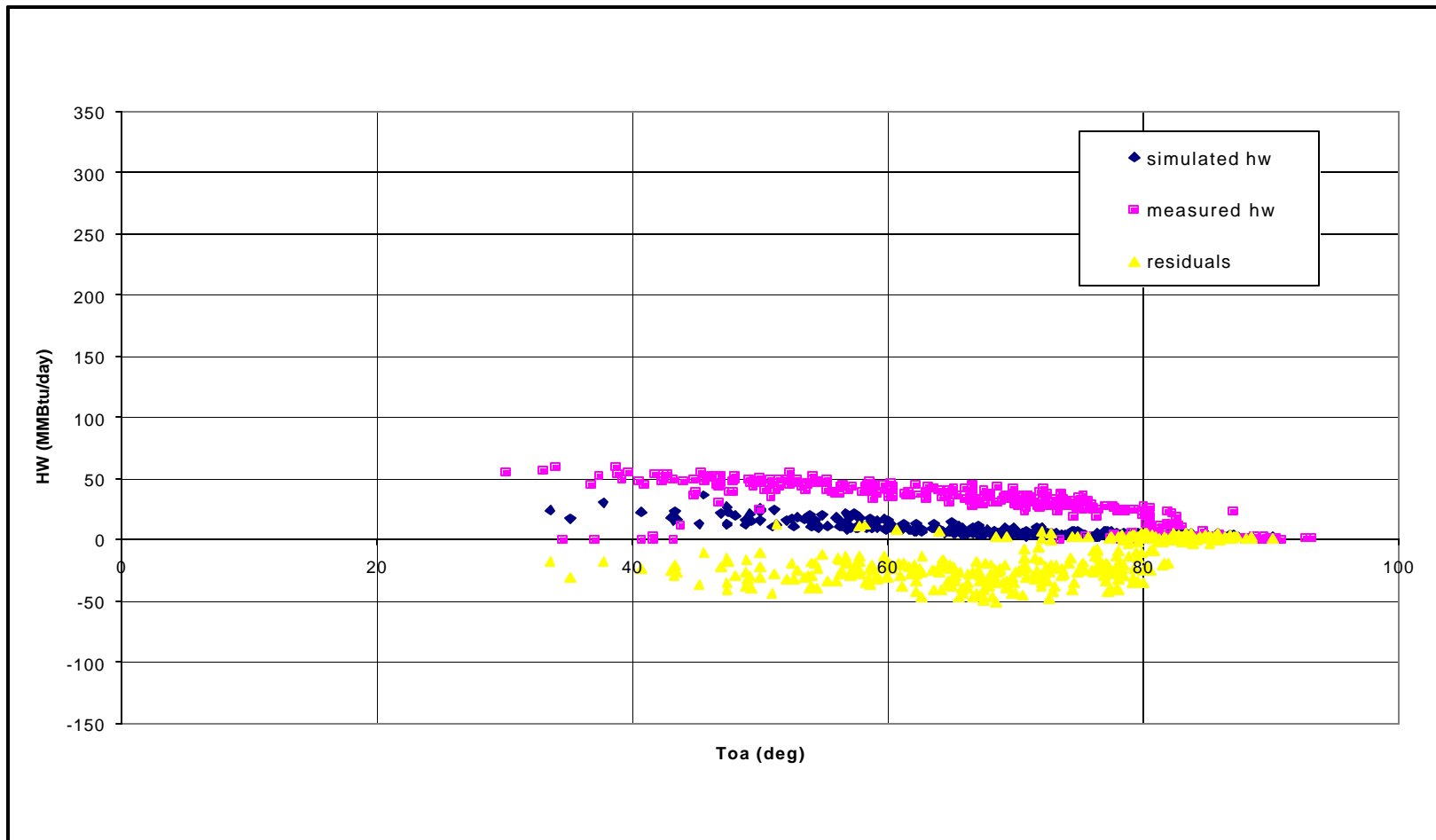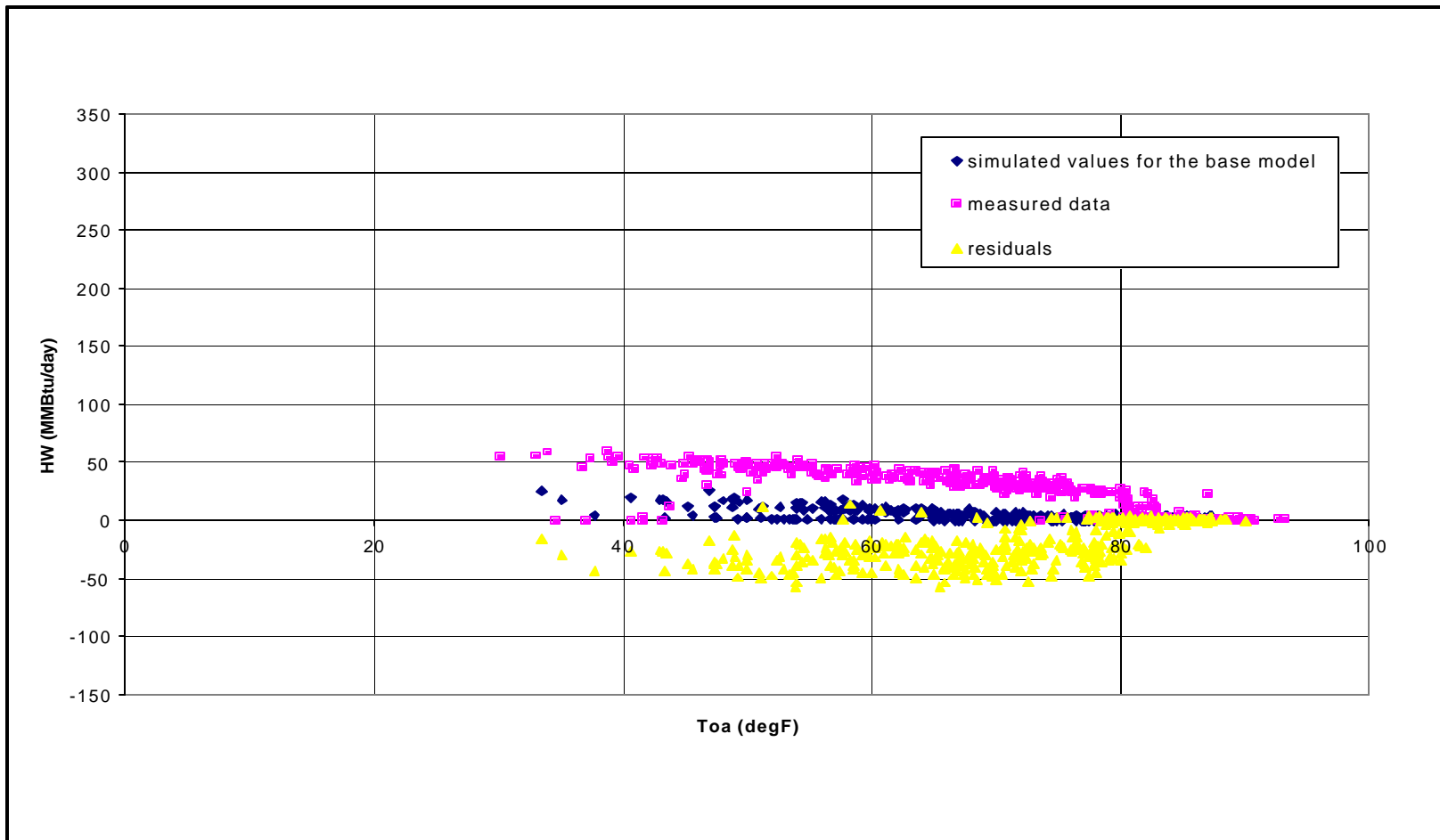**Fig 5.56 Comparison between simulated and measured hot water consumption (10° setback/setup, heating: 70° F peak, 60° F off peak/weekends, cooling: 76° F peak, 86° F off peak/weekends)**

5.8.3 Fan Schedule

Two runs in addition to the massless model were performed. The massless model considers 100% fans for the peak hours, 50-20% for off peaks hours and 50% for weekends. The first run was made with fans running 100% all year round. In the second run the fans are being completely shut off for off peak hours. From figures 5.57 to 5.60, it can be inferred that:

- Overall chilled water usage remains the same; however shutting off the fans completely increases the scatter for higher temperatures. The higher side shows that more energy is being used for morning startups while the lower end shows that energy is being conserved by shutting the fans completely during off peak hours. The total increase with fans shutting down completely is around 1%.

- For hot water, the massless model and the continuous operation of the fans is the same while the consumption drops down almost to zero when the fans are being shut off completely. This is an 80% reduction in the average annual hot water usage. This is logical because the if the fans are completely shut off during the night then even when the temperature is very low, no heat is being supplied to the building.

Fig 5.57 Comparison between simulated and measured chilled water consumption (massless model, fan schedule: 100% peak hours, 50-20% off peak, 50% weekends)

Fig 5.58 Comparison between simulated and measured chilled water consumption (fan schedule: 100% peak hours, 0% off peak hours)
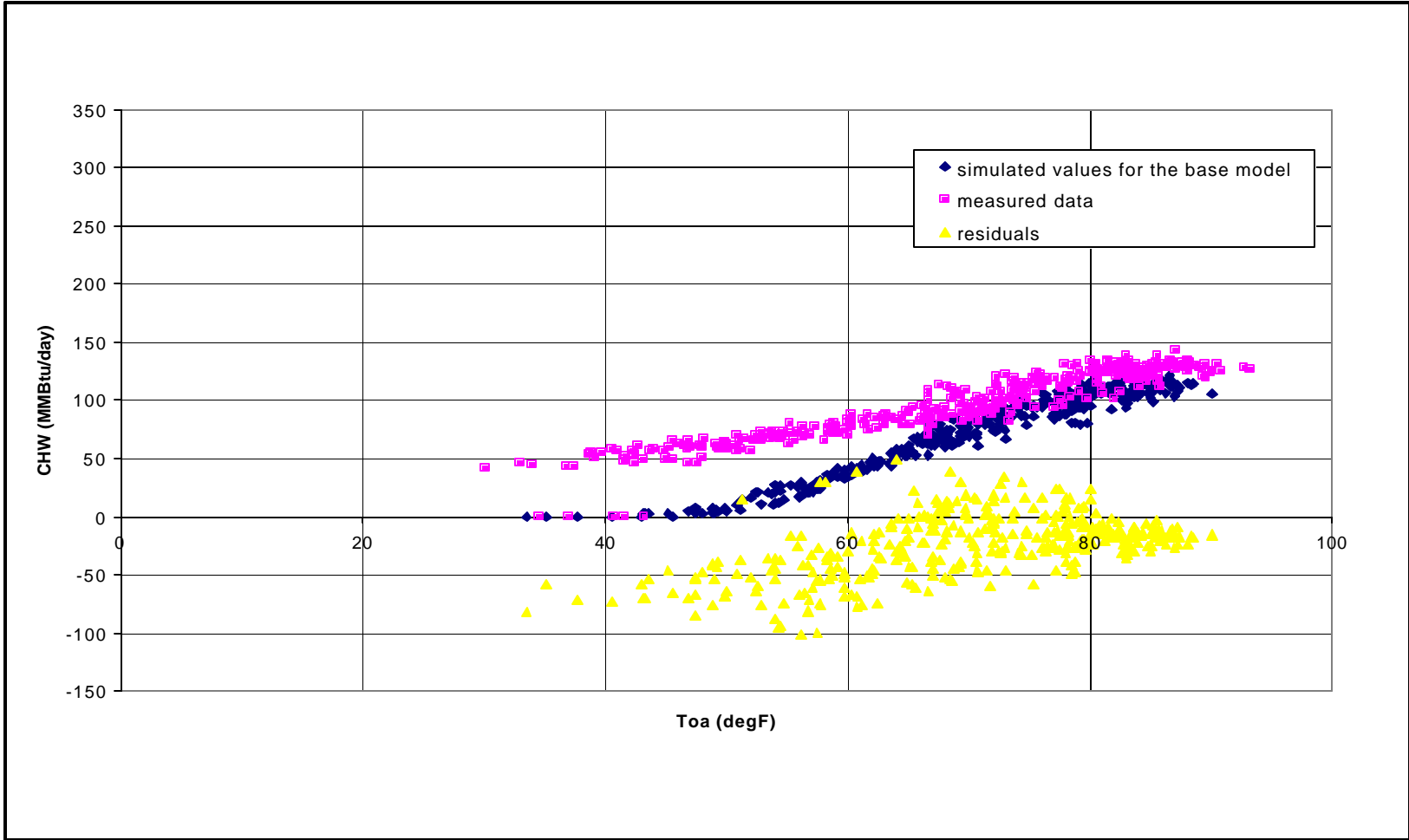
Fig 5.59 Comparison between simulated and measured hot water consumption (massless model, fan schedule: 100% peak hours, 50-20% off peak hours, 50% weekends)
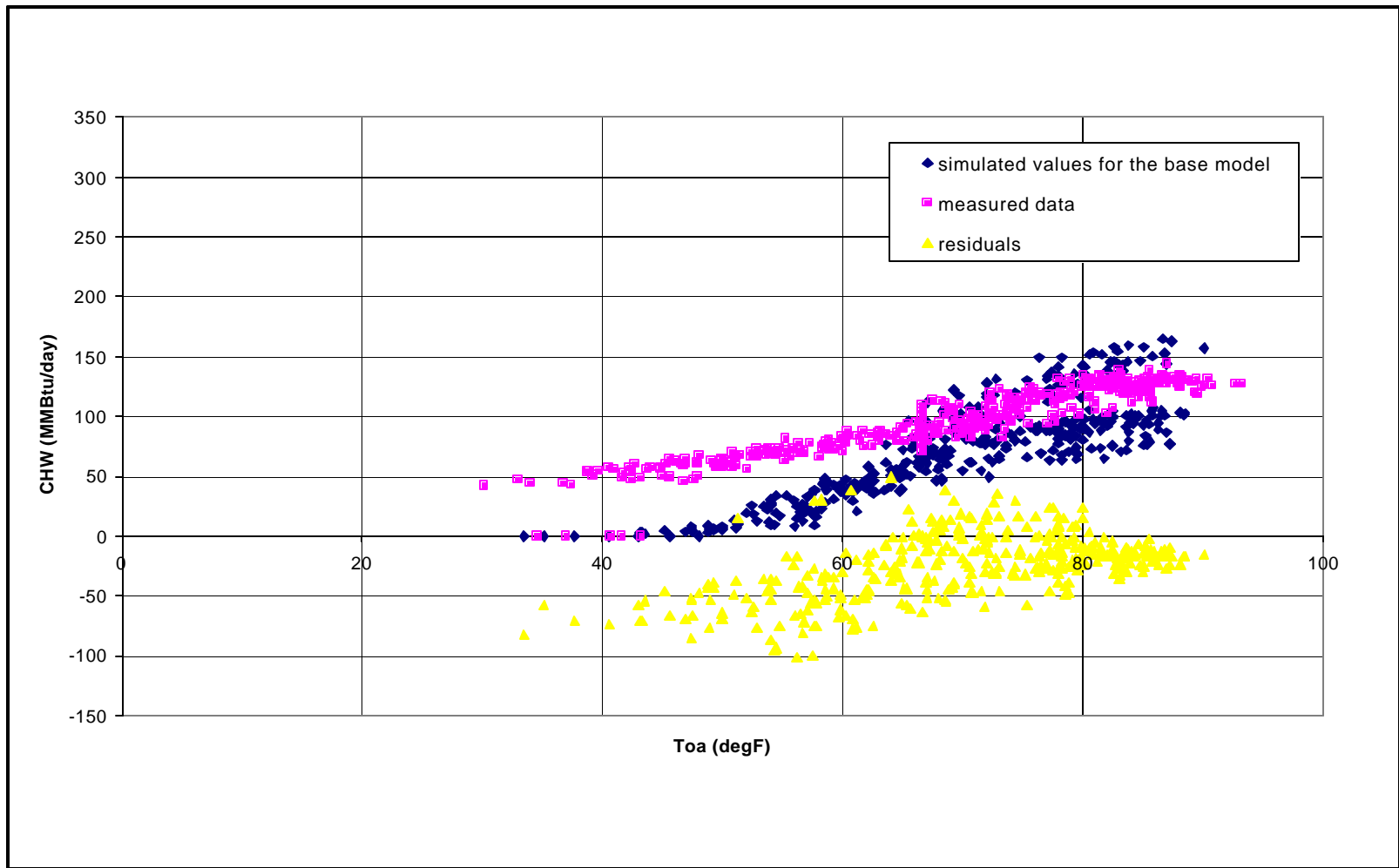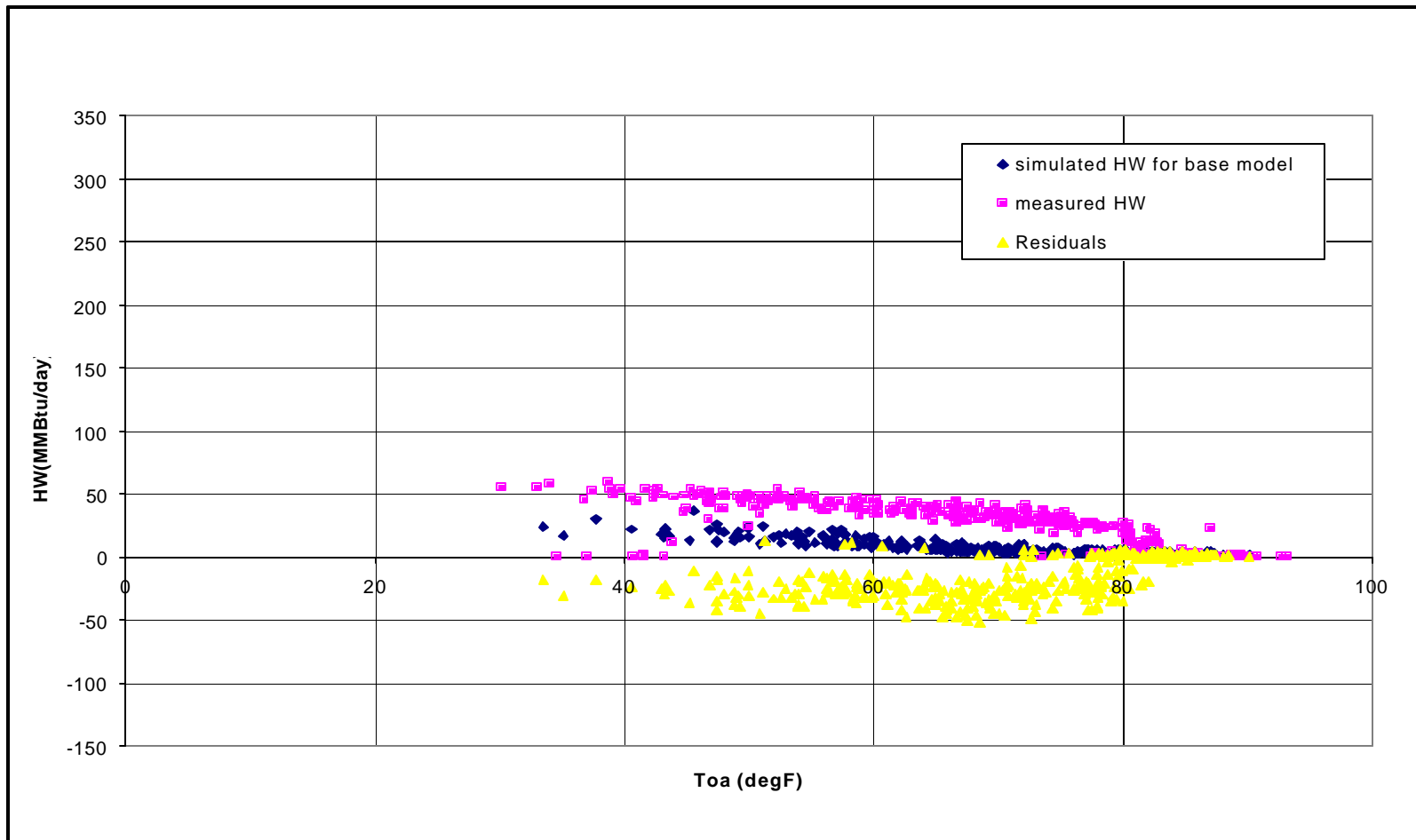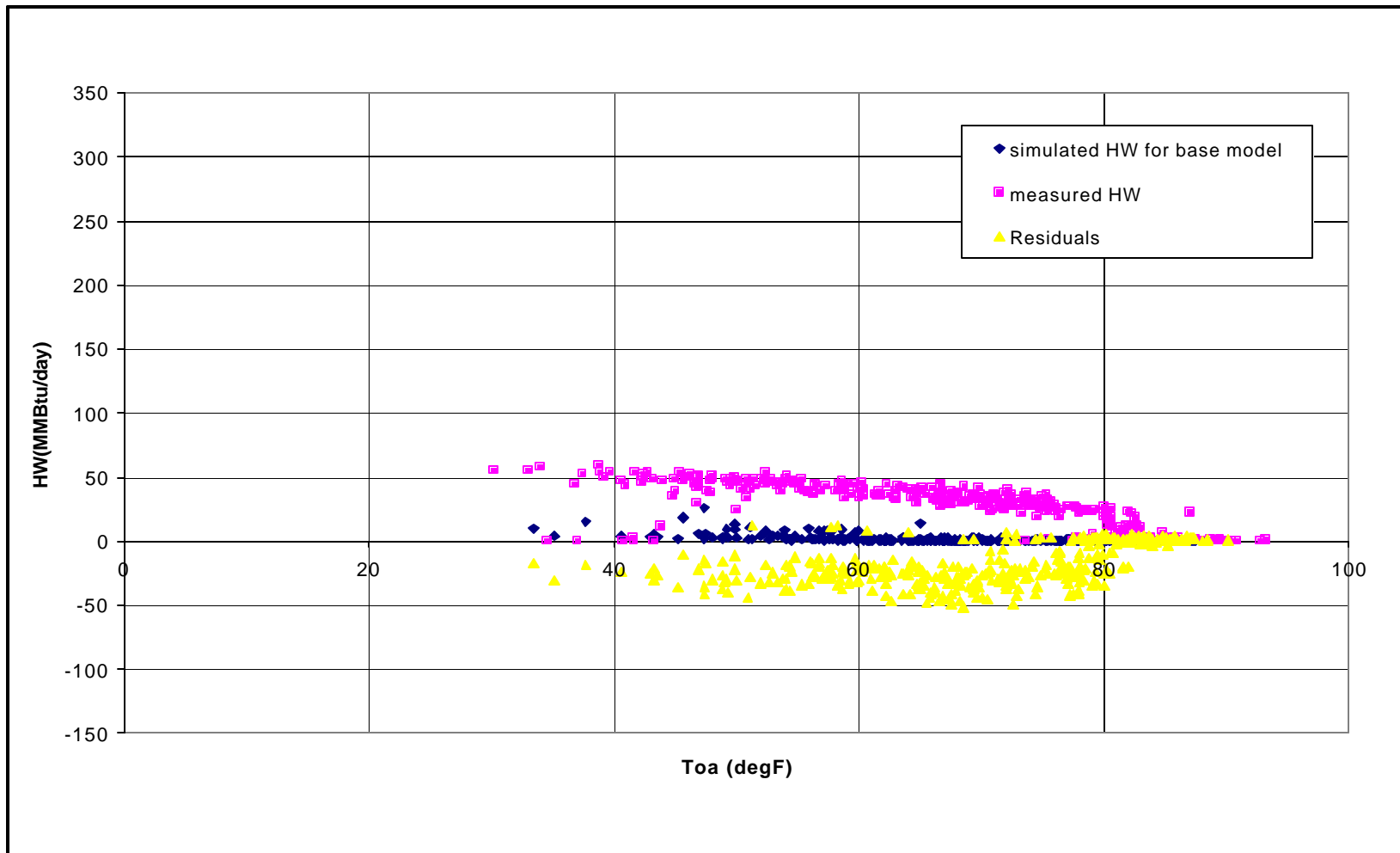
Fig 5.60 Comparison between simulated and measured hot water consumption (fan schedule: 100 peak hours, 0% off peak hours)

5.8.4 Outside Air Fraction

For this analysis three additional runs were performed. The massless model is 20 cfm/person of outside air. The first run was with zero outside air. The second was performed with 100% outside air. And the third one was done with 15% outside air. The following can be concluded from figures 5.61 to 5.68:

- Outside air also has a significant impact on the output of the simulation. Both the chilled and hot water consumption increases with the increase in the outside air fraction.

- For zero outside air the chilled water has almost a constant value for the entire temperature range. This is logical since 100% return air is being used and most of the load is due to internal gains. At lower temperatures the simulated data is matching well with the measured data. This suggests that outside air flow through the system is negligible.

- 100% outside air shows decreased consumption for lower temperatures and high consumption of higher temperatures. For low temperatures, no cooling is required for the outside air while it is the opposite at higher temperatures, which is depicted by the increased chilled water consumption values.

- The run with 15% outside air was performed to simulate the actual conditions since 0% outside air is not practical with the damper leaks. This run shows a good fit with the measured chilled water data for higher temperatures. This shows that the system understudy is deficient in outside air.

- The hot water consumption is still on the lower side of the measured values but goes up for 100% outside air. For zero percent it drops down to a constant value 4MMBtu/day. With 15% outside air the simulated hot water has the same profile but the magnitude is significantly less.

Fig 5.61 Comparison between simulated and measured chilled water consumption (massless model, 20 cfm/person)

Fig 5.62 Comparison between simulated and measured chilled water consumption (No OA)

Fig 5.63 Comparison between simulated and measured chilled water consumption (100% OA)

Fig 5.64 Comparison between simulated and measured chilled water consumption (15% OA)
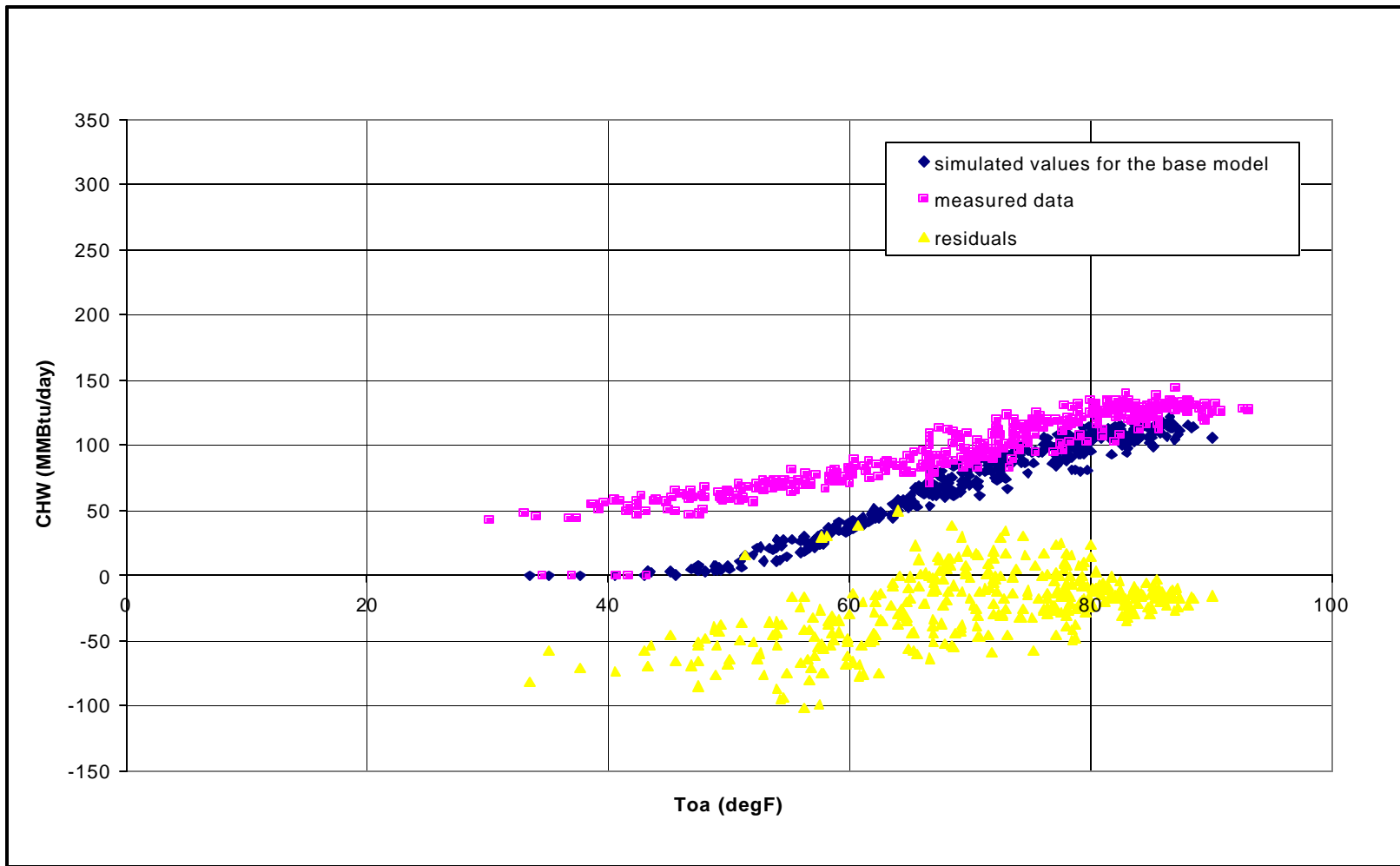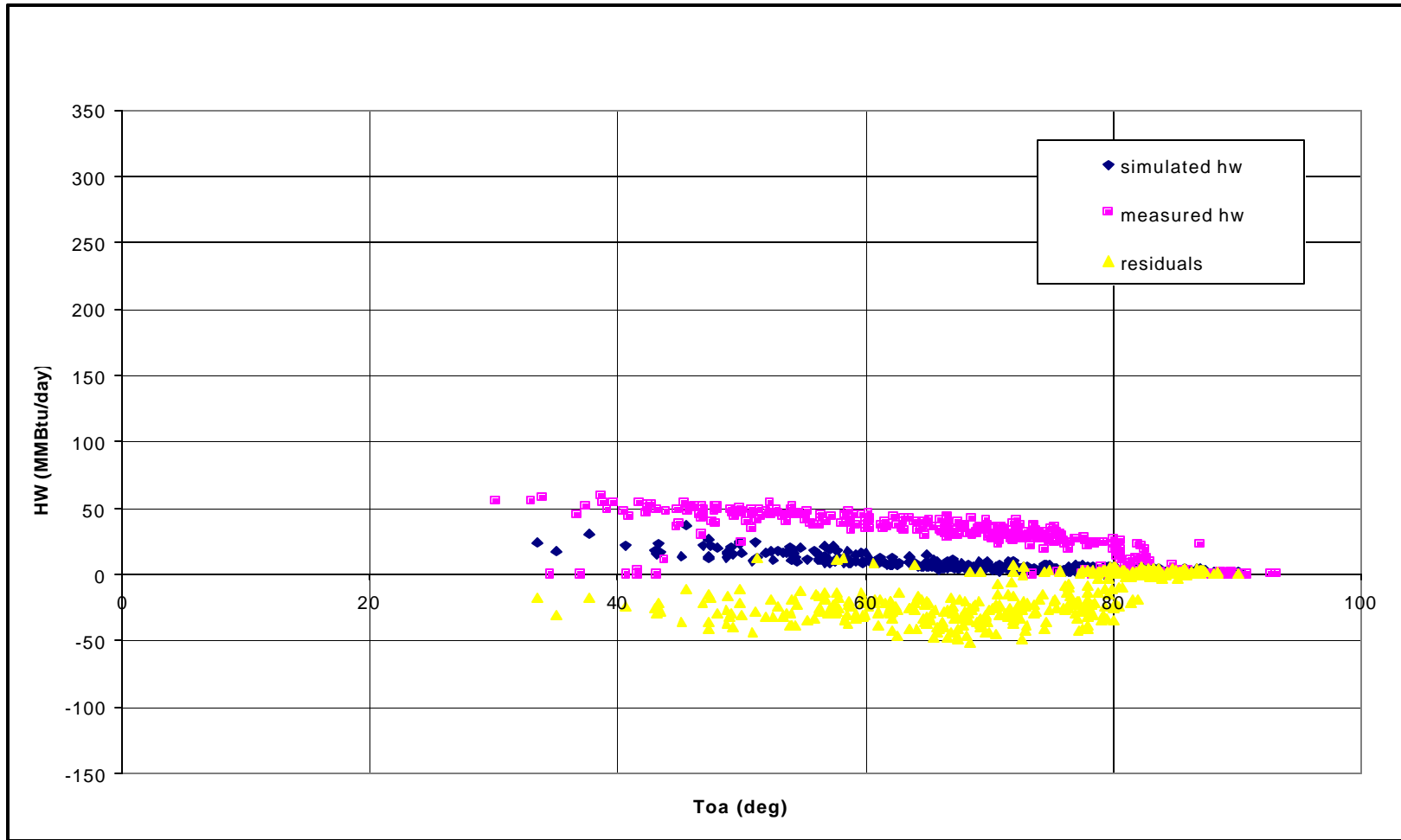
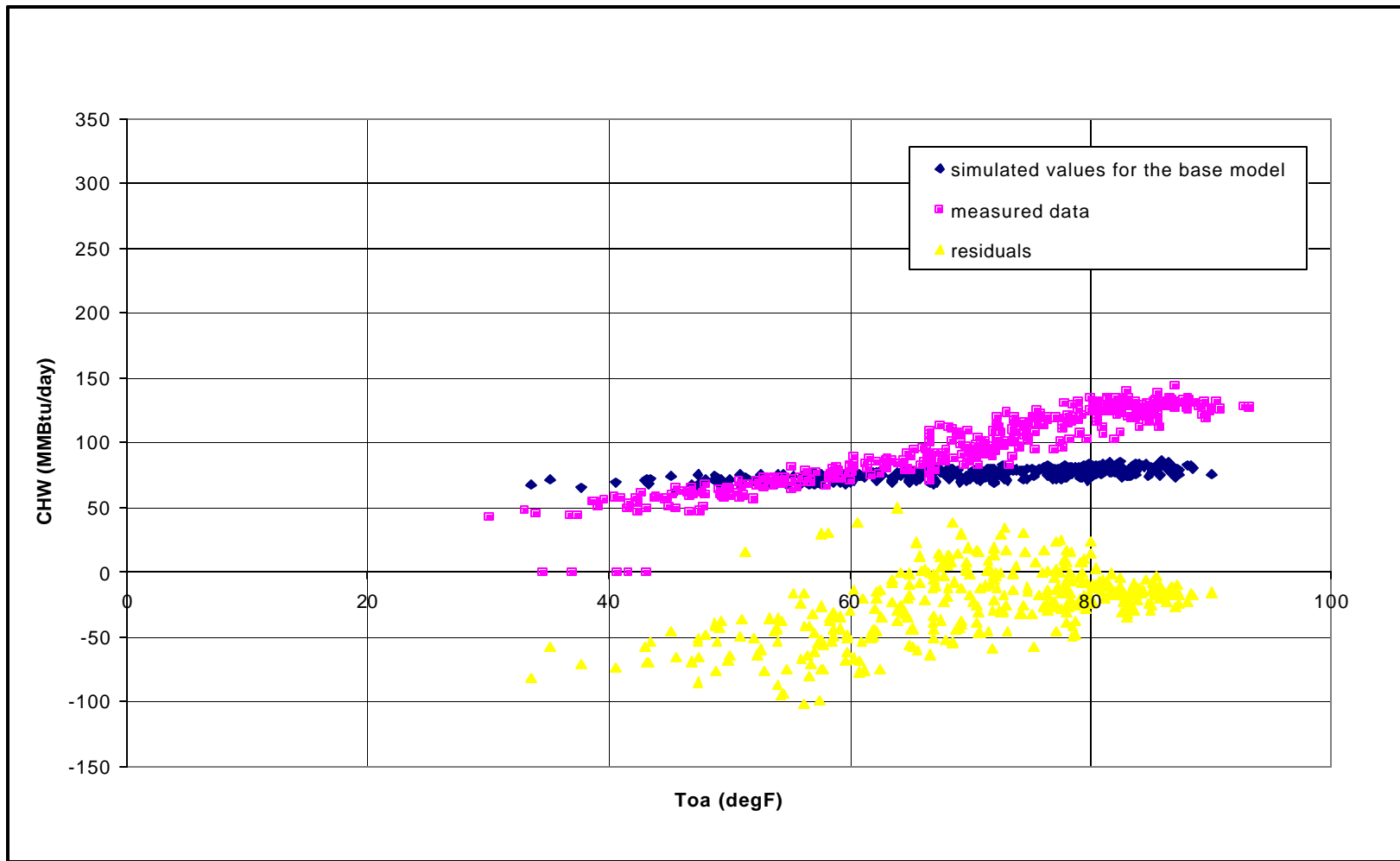**Fig 5.65 Comparison between simulated and measured hot water consumption (massless model, 20cfm/per)**

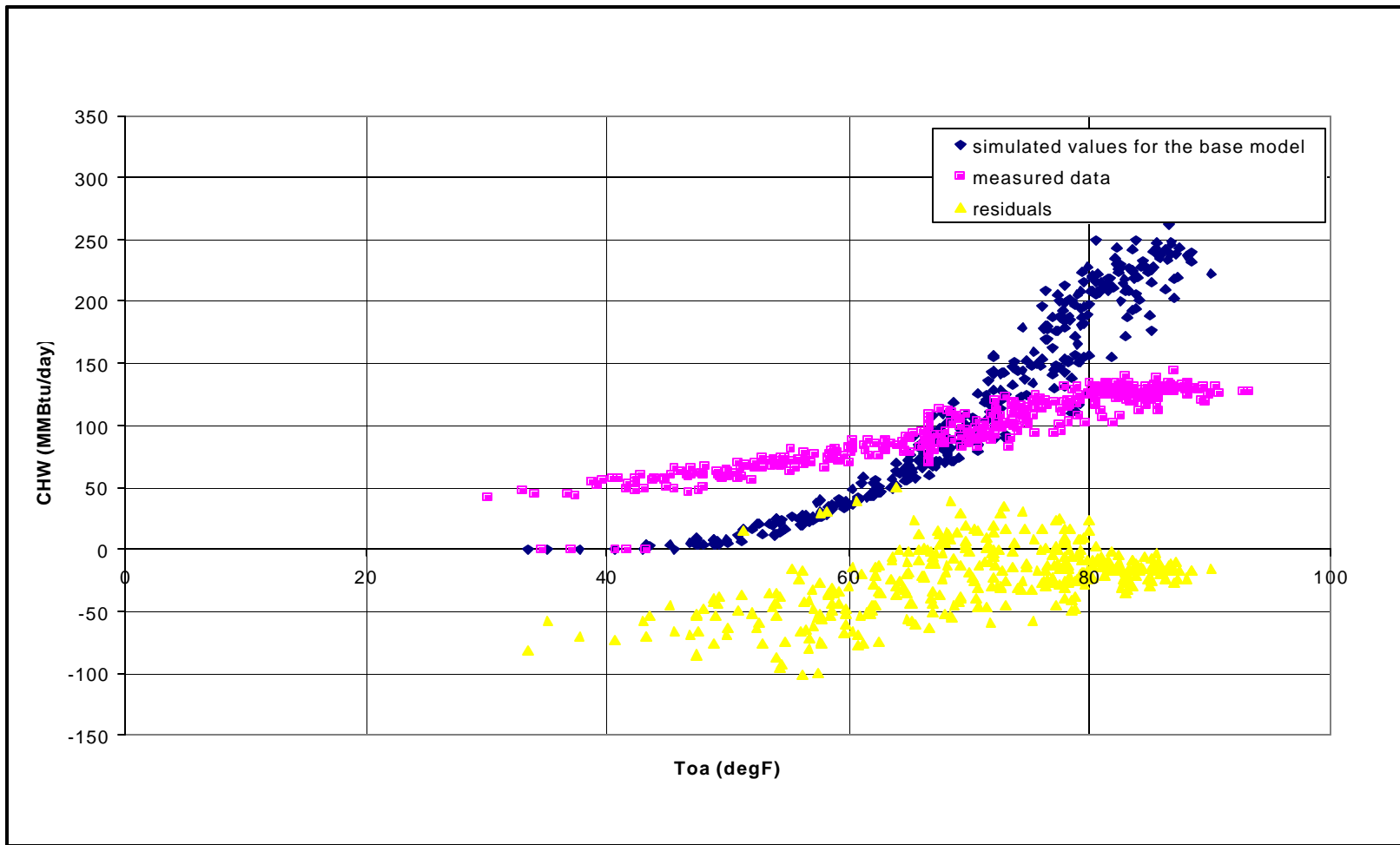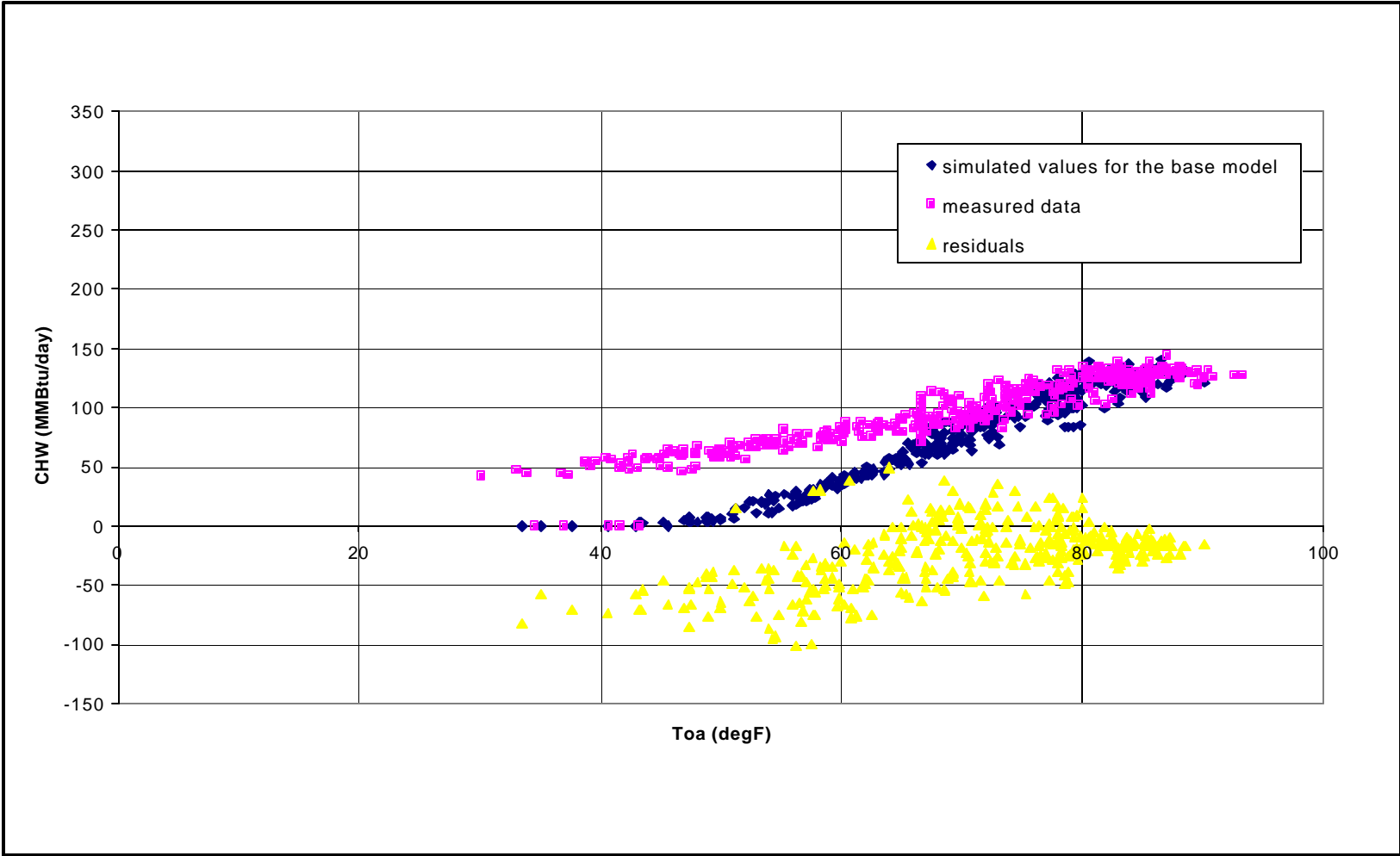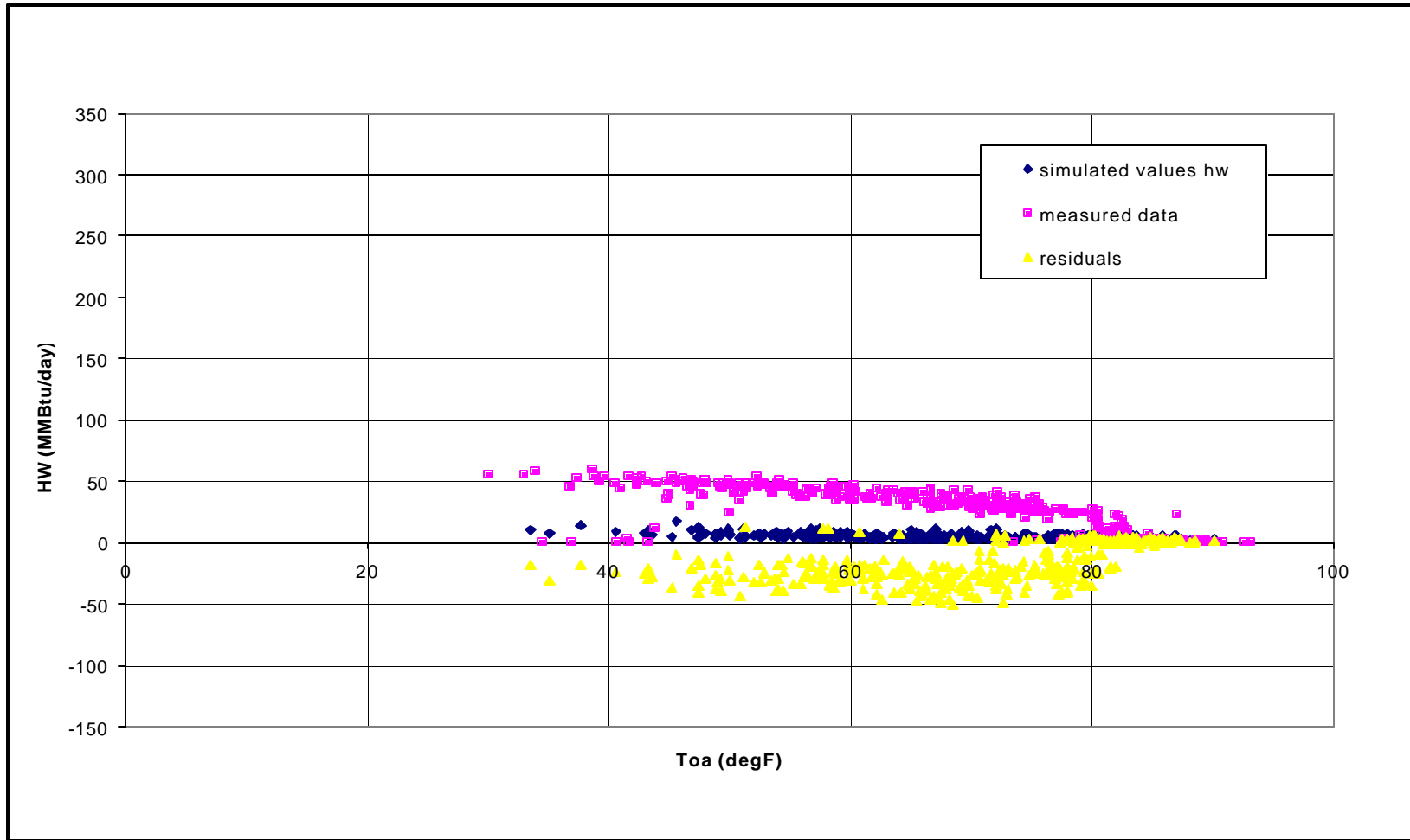**Fig 5.66 Comparison between simulated and measured hot water consumption (No OA)**
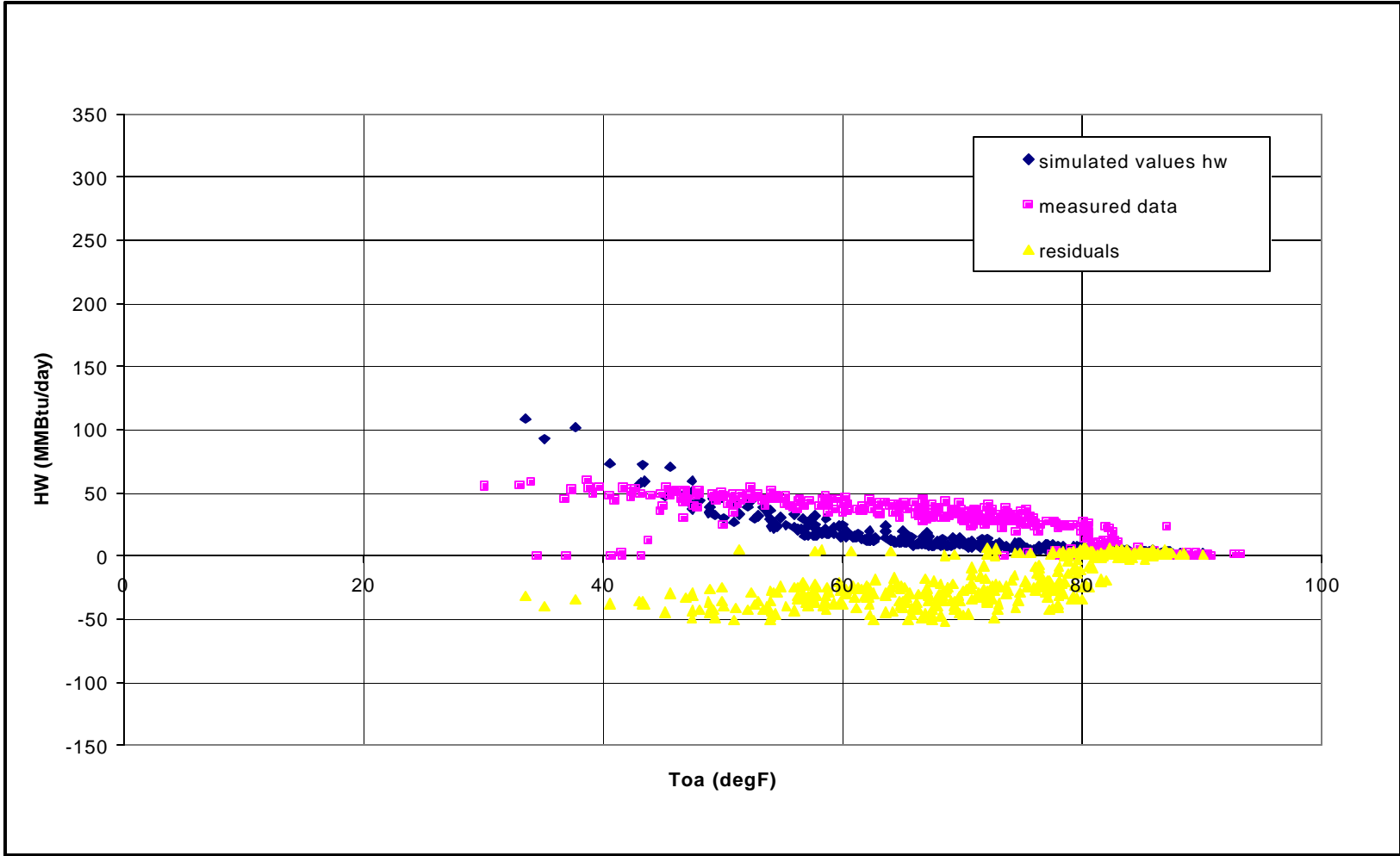
Fig 5.67 Comparison between simulated and measured hot water consumption (100% OA)
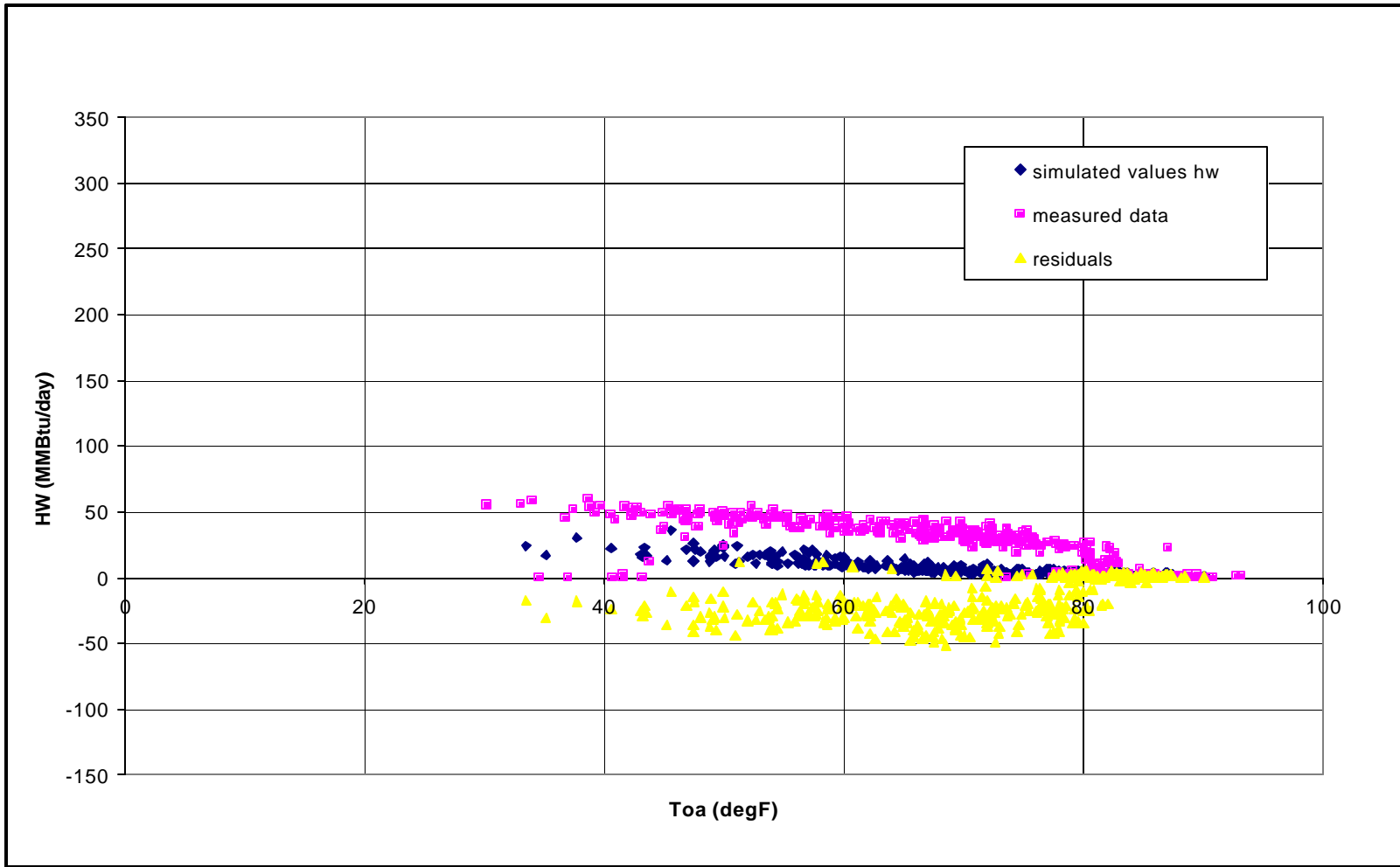
Fig 5.68 Comparison between simulated and measured hot water consumption (15% OA)

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This thesis has documented the complete procedure followed in determining the importance and accuracy of uncalibrated simulations. The DOE-2.1e simulation package was utilized in this research. A test sample of five buildings was chosen. Four of the buildings were large-scale commercial buildings with areas ranging from 100,000 to 200,000 square feet. The fifth building was a 1170 square foot house in the city of Bryan, Texas. Three simulation models were created for each of the four commercial buildings. These models are:

- Massless model, basic details and correct layout of the building.
- Advanced model, extensive as-built details and inclusion of thermal mass.
- Simplistic Model, one floor two zone equivalent area model having the same system as the massless model.

For the Habitat House only the massless and the advanced models were created. The massless and the advanced models were compared against measured data for each of the five buildings. This comparison was performed to analyze if extensive as-built information creates a better uncalibrated model than a model based on typical values. The simplistic model and the massless model were compared against each other to determine what is the impact of the correct envelope description and whether the number of floors and positioning of windows on the façade have an impact on the output or not. This analysis was performed using two weather tapes, Chicago and Houston. This was to check whether different weather conditions alter the envelope impact on the overall simulations.

For the four commercial buildings the massless model was also utilized in performing a sensitivity analysis. The emphasis of the sensitivity analysis was on system parameters. The results and conclusions are summarized below according to the three different analyses performed:

6.1 Comparison of the Massless and Advanced Simulation Model with Measured Data

6.1.1 Wisenbaker Engineering Research Center (WERC)

<div align="center">

TABLE 6.1
Summary of results (WERC)

</div>

	Annual Energy use			CV (RMSE) %			MBE %		
	CHW (MMBtU)	HW (MMBtu)	WBE (MWh)	CHW	HW	WBE	CHW	HW	WBE
Measured	35126	9390	4.46						
Massless	26341	2580	6.20	37.20	94.50	43.30	-25.10	-72.90	40.76
Advanced	19666	735	5.84	50.30	113.50	35.60	-44.26	-92.68	32.69

The results from the simulations of WERC show that the simulated data is significantly less than the measured values. Table 6.1 summarizes the simulation results. For the case of hot water consumption, the annual percentage difference is 72 and 92% respectively for the massless and advanced models. The simulated whole building electric for both the models is comparable with the measured. In DOE-2, this particular parameter can be tweaked easily as it just depicts the watt per square footage of lighting and equipment defined in the loads portion. The advanced model in this case is the least consumptive. The reason can be that this model is built on extensive design information and from looking at the measured data, the current building operation is consuming more energy than required, which is already discussed in the earlier chapter.

6.1.2 Harrington Tower

TABLE 6.2
Summary of results (Harrington Tower)

	Annual Energy use			CV (RMSE) %			MBE %		
	CHW (MMBtU)	HW (MMBtu)	WBE (MWh)	CHW	HW	WBE	CHW	HW	WBE
Measured	8870	1621	1.31						
Massless	13086	1098	2.39	71.48	129.73	101.85	47.79	-32.40	82.47
Advanced	15627	2378	2.81	100.88	149.77	133.64	76.59	47.01	115.15

From table 6.2 it can be seen that the results from the simulation of Harrington Tower are dissimilar to the ones obtained from WERC. In this case the advanced model is the most consumptive and the measured data is coming out be significantly less than the simulated data sets. The annual percentage difference of chilled water consumption for the massless and the advanced model is –47.5% and –76.1% respectively. This result also shows that simulation model built on extensive design data shows more dissimilarity to the measured data than the model based on typical values.

6.1.3 Wehner Business Building

TABLE 6.3
Summary of results (Wehner Building)

	Annual Energy use			CV (RMSE) %			MBE %		
	CHW (MMBtU)	HW (MMBtu)	WBE (MWh)	CHW	HW	WBE	CHW	HW	WBE
Measured	11592	6372	2.58						
Massless	25865	2768	6.09	152.39	76.98	137.35	123.81	-56.87	136.37
Advanced	21733	1718	3.48	128.03	90.38	36.37	87.97	-73.44	34.89

The results from the simulations of Wehner Building are summarized in table 6.3. For this case both the simulated models are showing significantly larger chilled water use for the building. It is more than double of the measured values. At the same time the hot water consumption for both the models is less than the measured. The annual percentage difference of chilled water consumption for massless and advance is –123% and –88%. The thing to note is that the WBE is cut drastically in the advanced model and compares well with the measured data. This is because to simulated occupancy sensors, the lighting schedule was made the same as the occupancy schedule.

6.1.4 John B. Connally Building

TABLE 6.4

Summary of results (John B. Connally Building)

	Annual Energy use		CV (RMSE) %		MBE %	
	Chiller electric (MWh)	WBE (MWh)	Chiller electric (kW)	WBE	Chiller electric (kW)	WBE
Measured	0.69	2.19				
Massless	0.76	3.24	41.82	74.02	10.46	48.22
Advanced	0.80	3.33	44.22	76.72	16.11	52.30

For this case the advanced model is the most consumptive. Table 6.4 provides the summary of the results. There is no measured data available for hot water. From the values in the table, the simulation models and the measured data is comparable. The annual percentage difference for the chiller electric is –10% and –15% for the massless and advanced models respectively. For the simulation models, the differences between the two are minor mainly because the only difference in the inputs is the thermal mass.

6.1.5 Habitat House

TABLE 6.5
Summary of results (Habitat House)

	Annual Energy use	CV (RMSE) %	MBE %
	Total electric (MWh)	Total electric	Total electric
Measured	0.533		
Massless	0.430	57.40	-19.33
Advanced	0.528	48.41	-0.81

From the values in table 6.5, the simulation models and the measured data matches quite well. The heating data available was not sufficient to provide analysis for a complete year and the values available are ten times larger than the simulated. The total electric shows good fit especially for the advanced case. This means that thermal mass and accurate measured schedules were important in making the simulation model realistic. The annual percentage difference of the total electric consumption is 19% and 0.94% for the massless and the advanced model respectively.

From the analysis of the above-mentioned summaries for each building, the following conclusions can be drawn:

- Uncalibrated simulation model does not reflect the real operations of a building.
- To create simulation model incorporating all the envelope details and the basic system information, time varies between 17 to 34 hours.
- From the data available for the Habitat house, it may be suggested that for buildings, which are not internally load dominated, like residential houses, incorporation of thermal mass and correctly measured lighting, occupancy and equipment schedules make a significant impact.

- For three of the four commercial buildings simulated, the measured data is less than the simulated. This can imply that the current building operations are working efficiently. The other thing, which can be inferred, is that current building operations are not maintaining the building on the minimum comfort standards.

- From observing the results of the simulation, the model created extensively from as-built information is more different from the measured data as compared to the massless model created from typical building values. It can be concluded that either there are major problems with current building operations or major changes have been incorporated in the systems, which have not been documented.

- A simulation model created with information obtained from extensive walk-throughs and as-built information may be used as a diagnostic tool to identify the operational problems in a building. But this requires further extensive research in order to be sure that as-built simulation models can be used as diagnostic tools.

6.2 Comparison of the Massless Model with the Simplistic Model for two Weather Stations

This analysis was performed to check the impact of the outer envelope and correct layout of the building for different weather conditions on the overall simulation output. Chicago (6549 HDD) and Houston (1548 HDD) were chosen as the two weather conditions. The conclusions drawn from this exercise are:

- If a building is internally load dominated, then an area equivalent simple one-floor simulation model gives the same result for cooling loads as the complete model with all the details. This result is valid for a cold climate while for a hot and humid climates the difference is larger ranging from 5 to 10%.

- The heating loads do not match for the two models irrespective of the weather conditions. The increased roof and floor area, which is not making a difference for the cooling load, is contributing to increase the heating requirements of the building.

- The deviation between the simplistic and massless model also depends on the individual building. If a building layout has different components, which have different constructions or end-uses and these components cannot be added to the simple model, then the results will be significantly different.

- The conclusion is that to create a good accurate base, all the envelope details and the exact layout of the building should be defined in order to minimize the inbuilt errors of the simulation program.

6.3 Sensitivity Analysis

This analysis was performed to identify which parameters create the most impact on the overall output of the simulation model. The sensitivity was performed on the four commercial buildings. The following parameters were chosen as sensitivity variables:

- Thermal mass
- Outside air fraction
- Thermostat schedule
- Fan schedule

In addition to these the effect of exterior wall insulation, glazing types and economizers was also analyzed. These variables were not included in the result analysis since there impact on the overall outcome of the simulation was negligible. From the above mentioned the thermal mass is incorporated in the loads portion, the rest of the variables are from the systems section. This indicates that more emphasis should be on the system portion of the input file. Since sensitivity analysis is a thoroughly researched

topic in energy simulations, the results obtained from this study are similar to a number of other studies already performed (Corson 1992, Lam and Hui 1996). From the analysis of these variables the following conclusions can be drawn:

The effect of thermal mass is negligible in internally load dominated buildings since the gains through the envelope are a small percentage of the total gains of the buildings. However for small residential houses the envelope gains make up about 50% of the total load so the addition of thermal mass can deviate the annual energy use by 15 to 20%. So for large commercial buildings creating a massless model is sufficient for the purpose of determining the energy usage.

Outside air fraction has a significant impact on the energy consumption of the building. Several runs were performed and it was found that for low outside air fraction the measured data for some buildings fit quite well with the simulated model. So in order to create a more accurate simulation model, a better practice would be to actually check the design values for the air handlers and then also to check the dampers physically. Because from experience many times these dampers are stuck at completely open or completely closed position.

The thermostat schedule, which controls the setback and setup in a building, does not have a significant effect on the output of the simulation model. This is true for the massless model. If a model is created with thermal mass than the setup/setback effects will play a more significant role. For these cases the heating energy goes up to account for the morning ramp-ups. Same is the case with cooling setups. So for the better depiction of the operation of the building, the setpoints and the schedule should be known. For extensive calibration purposes a thermal mass model with the correct thermostat settings can provide an accurate base.

The fan schedule, which regulates the airhandler fans has a small impact on the overall output whether the fans are at 100% all the time or are running at 20 to 30% during the off peak hours. However shutting the fans down completely during the night results in more scatter. This shows that more energy is being used for startups and energy is being conserved during nights and weekends. For the buildings simulated, the

fan schedule is 100% through out; the airflow is being controlled through the MIN-CFM-RATIO command. For a model with thermal mass the fan schedule can have more impact since thermal storage of the envelope will require additional energy to get the space to the prescribed comfort level.

6.4 Recommendations for Further Study

This research is an initiating study in the documentation of the usefulness of uncalibrated simulation. The following analyses can be done to further investigate how best uncalibrated simulation models can be used in depicting the operations of a facility:

- The simulation models created can be used to generate calibrated models. It will be interesting to analyze whether the massless model can achieve better calibration or the advanced model. If time required to calibrate the advanced model is the same as the massless model, then is it worth it to spend extra time in putting in additional details.
- The sensitivity completed for this research was based on the massless model. The same sensitivity parameters can be checked with the thermal mass advanced model. This can provide information about the difference in behavior of the variables with thermal mass.
- If a building with its own HVAC plant is simulated then the sensitivity of the chillers parameters can be analyzed.
- Further investigation of using as-built information simulation models as diagnostic tools should be performed. For this research the post maintenance data for only WERC was available. It will be a good exercise to look into Wehner Building because there is a long list of maintenance problems associated with that building. However till now there is no report that the problems have been resolved.

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APPENDIX A

EXECUTABLE SIMULATION INPUTS AND SPREADSHEETS

A.1 Simulation Inputs
A.2 Weather Files
A.3 Simulation Spreadsheets

The appendix is added as a separate zip file containing all the three sub sections containing all the information necessary to perform the simulations.

VITA

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