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DETERMINING BASELINE ENERGY CONSUMPTION AND PEAK COOLING LOADS OF A 107-YEAR-OLD SCIENCE MUSEUM USING DOE 2.1E

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ABSTRACT

The Energy Resources Center (ERC) at the University of Illinois at Chicago conducted an energy assessment to determine the peak cooling loads of the Museum of Science and Industry (MSI) as part of MSI's Long Term Development Plan. MSI is located in Chicago, Illinois next to Lake Michigan, and experiences substantial seasonal weather changes. The DOE-2.1E program was used to accomplish this goal. The MSI intended to use the DOE-2.1E model to analyze the lifecycle costs of several mechanical equipment configurations. The modeling effort was successful using industry standard validation protocols. Future refinement of the model may require the use of updated local weather data to use in place of the typical meteorological year weather data (TMY2).

INTRODUCTION

The Energy Resources Center, a non-teaching department of the College of Engineering at the University of Illinois at Chicago, was asked to conduct an extensive energy audit of the Museum of Science and Industry in Chicago, Illinois (MSI) to determine the breakdown of its present energy usage and to assist MSI staff in making sound fiscal decisions about proposed capital expenditures with respect to their physical plant. These proposed capital outlays had been described in a long-term development plan called *The MSI 2000*, which outlines significant changes expected to be needed to MSI's physical structure. These proposed changes include rebuilding its infrastructure to meet current engineering standards and providing maximum comfort levels to MSI's over two million annual visitors. Included in this plan was a proposal to change from decentralized heating, ventilation and air conditioning (HVAC) systems to a more centralized system, which would include providing air conditioning to all areas of MSI.

This paper describes the database created by the ERC in its audit and the baseline energy model the ERC created using the DOE-2.1E computer simulation program. The baseline model was used to simulate the museum in its current condition, including the estimation of expected peak heating and cooling loads. Variations on the base model can be made to evaluate the performance of various physical plant configurations, determine life cycle costs and to address the effect of a decentralized HVAC system versus a centralized HVAC system.

BACKGROUND

The MSI facility has a complicated history that influences both analysis approaches and plant modification options. MSI had its beginnings as one of more than 200 buildings that were built for the World's Colombian Exposition held in Chicago in 1893. The buildings were meant only to be temporary structures for the fair. The Palace of Fine Arts, designed by Charles Atwood, is the only remaining structure, and now houses the Museum of Science and Industry.

The Palace of Fine Arts was originally a 140-room structure, occupying 55,742 square meters (600,000 square feet), which housed many of the world's artistic masterpieces in the over 8,000 exhibits. After the World Exposition, the Palace of Fine Arts was left standing, and housed the Field Museum until 1920. It was then left vacant until the late 1920s, when it was reduced to its steel skeleton, brick substructure and interior walls, then rebuilt in more permanent limestone. The building was re-opened as the MSI in 1933, at the same time as the Century of Progress Exposition. This original structure today comprises the main pavilions (Central, East and West) of the MSI. In 1984, the Henry Crown Space Center was added, and in 1997 a new underground garage and entry lobby was completed, bringing the total size of the Museum to 107,024 square meters (1.15 million square feet).

When the MSI was re-opened in 1933, there was no air conditioning present in the building. Instead, 12 house fans were used to circulate air within the museum. Most of these fans are still in use today, however, they are in serious disrepair. Air-conditioning (typically packaged units) was introduced circa 1940 on an as needed basis determined by the requirements of the exhibit itself.

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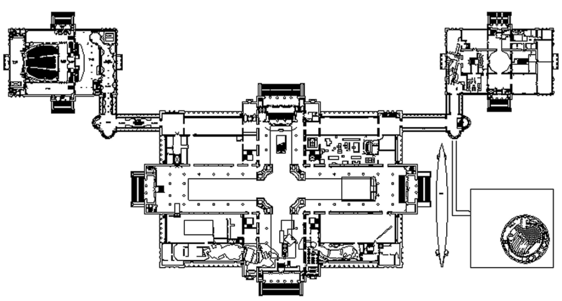
Comfort cooling for occupants was an ancillary benefit. In most cases, the exhibit sponsors were required to pay for and install the HVAC equipment. Since 1940, individual HVAC units have been installed throughout the museum, which currently amount to 55 units that provide approximately 70 percent air conditioning coverage. Currently, the only centralized chillers within the MSI are:

- 615 kW (175-ton) air-cooled unit for the Henry Crown Space Center,
- 422 kW (120-ton) chiller/cooling tower in the north portion of the Central Pavilion for the some of the office area,
- 1,407 kW (400-ton) interim air-cooled chiller serving various portions of the Central Pavilion.

The ground floor of the museum is depicted below in Figure 1. The single largest area within the MSI that is not directly air-conditioned is the public court of the Central Pavilion, which consists of the north, east, south, and west areas, in a cruciform shape. This area is part of the original structure, which was the vast exhibit space, and today is still served by the original 1938 system. These public courts make up 5,345 m^2 (57,538 ft^2) on the ground floor, but are open to exhibits on the first balcony. The height of this open space is approximately 18.9 meters (62 feet). This voluminous open unconditioned area has a load impact on many adjacent air-conditioned spaces due to the museum's "open" floor plan, with floor to ceiling openings, and no doors between exhibit spaces. Those exhibit spaces that are conditioned do not have sufficient capacity for air mixing from such a large unconditioned space and subsequently, comfort is often lacking in those areas. In fact, because of the large summer latent load within the museum due to ventilation, infiltration and the high number of visitors, comfort within the museum is suspect during most of the summer months.

Figure 1: MSI Ground Floor



Of the 107,024 square meters (1.15 million square feet), approximately 44,129 m^2 (475,000 ft^2) is the underground garage area. Of the remaining approximately 62,895 m^2 (677,000 ft^2), 69 percent is conditioned, 16 percent is indirectly conditioned (due to the "open" floor plan), and 15 percent is unconditioned. This break down of the museum by conditioned area type is shown below in Table 1.

Table 1: MSI Conditioned Area Breakdown

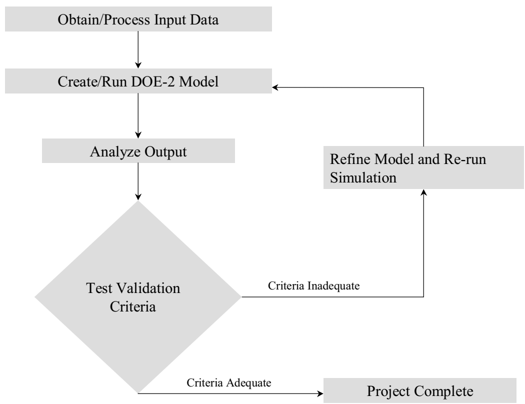
	Total	Conditioned	Indirectly Conditioned	Not Conditioned
Area (m^2)	62,895	43,712	9,874	9,309
Area (ft^2)	677,000	470,515	106,289	100,196
Area (%)	100	69.5	15.7	14.8

METHODOLOGY

Model development and calibration

The whole building analysis protocol was used when gathering data and creating the model of the MSI. This included gathering the important information regarding building operation, building envelope, HVAC systems, central plant equipment and weather data. Figure 2 shows the modeling procedure followed during this project.

Figure 2: DOE-2 Modeling Protocol



Calibration

It is necessary to calibrate a building simulation model so that the model can accurately predict building performance. For this project, monthly whole-building energy use data was calibrated against utility billing data.

Whole-Building Calibration

To evaluate the accuracy of the model calibration, the first metric measured is the monthly error (ERR_{month}) between actual and predicted utility use. The following equation determines this error.

$$ERR_{month}(\%) = \left[\frac{(M - S)_{month}}{M_{month}} \right] x100$$

Where:

M indicates measured kWh or MMBtu
S indicates simulated kWh or MMBtu
After the monthly error is calculated, the yearly error (ERR_{year}) is calculated using the following equation:

$$ERR_{year}(\%) = \sum_{year} \left[\frac{ERR_{month}}{N_{month}} \right]$$

Where:

N is the number of utility bills in the year

Since the monthly differences in measured and simulated energy consumption may cancel each other leading to artificially small levels of annual ERR data, the coefficient of variation of the root-mean-squared monthly errors ($CVRSME_{month}$) must also be checked per the following equations:

$$CV(RSME_{month}) = \left[\frac{RSME_{month}}{A_{month}} \right] x100$$

$$RSME_{month} = \left\{ \frac{\left[\sum_{month} (M - S)_{month}{}^{2} \right]}{N_{month}} \right\}^{1/2}$$

$$A_{month} = \left[\frac{\sum (M_{month})}{N_{month}} \right]$$

Once all the errors are calculated, they are compared to the acceptable simulation modeling calibration tolerances as determined by the Federal Energy Management Program (FEMP) and the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) provided in Table 2:

Table 2: Acceptable Tolerances for Monthly Data Calibration

Index	FEMP	ASHRAE 14P
ERR_{month}	± 15%	± 5%
ERR_{year}	± 10%	---
$CV(RSME_{month})$	± 10%	± 30%

<u>The DOE2.1E Model</u>

The DOE-2 simulation model of the MSI was created from January through June 2000. Much of that time was spent collecting pertinent data with help from the Museum maintenance staff. Many original drawings were missing; so most of the input data had to be field verified, including data for building envelope, primary and secondary HVAC systems, and lighting installations. The most recent utility bill data were gathered from the local utility representatives.

A variety of assumptions were made regarding the envelope of the building, the space types included and the HVAC systems and the chiller and boiler plants serving the facility to compensate for the incomplete nature of some of the data collected:

<u>Envelope</u>

The older sections of the building are primarily made up of 40.6 to 50.8 centimeters (16 to 20 inch) brick walls with 6.4 centimeters (2.5 inches) of stone facing. There is little to no insulation in any part of these old building spaces-the Central, East and West Pavilions. However, the Henry Crown Space Center was constructed in 1984 and has more efficient wall construction.

The layers method was used in creation of the wall construction for the DOE-2 model in order to accurately account for the thickness of the wall construction for the oldest sections of the Museum, (thermal mass modeling), as well as to account for the newer construction in the more recent additions. Several separate wall constructions were delineated in the input deck, to account for the various types of wall construction in the Museum as described above.

<u>Space Types</u>

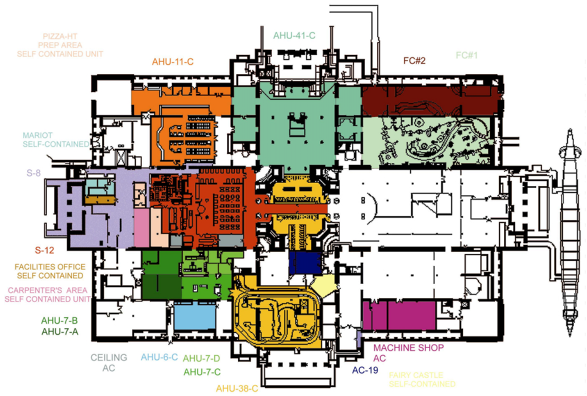
There are several space types within the Museum, as well as different system types that serve specific areas. The Museum is a multi-function facility, with a variety of exhibit types, eating areas, theaters, office areas, and open public areas. The museum areas modeled in the simulation include: the Central Pavilion, the East Pavilion, the West Pavilion, the Henry Crown Space Center, and the Lobby/Garage.

For the simulation model, these different space types were simplified. The conditioned spaces in the museum were characterized by lighting power density, plug-load power density, occupant density, lighting schedule, plug-load schedule, and occupancy schedule. These conditioned spaces in the model were characterized in turn as one of several lower tier space types. The lower tier space types include: exhibit-1 (high gains), exhibit-2 (low to medium gains), theater, restaurant, office, bathrooms, circulation, loading, and mechanical, storage. A further subcategory was established in the model to represent unconditioned spaces.

<u>HVAC Systems & Zoning</u>

In creating the DOE-2 model, the areas were categorized by not only space type, but also by the type of system that served the area. The breakdown of floor area for the museum by the actual HVAC system is shown in Figure 3.

Figure 3: MSI Zoning by Actual System



The existing HVAC systems at the Museum date from anywhere from 1938 when the first house fans were installed to serve the central, east, and west pavilions, to the new packaged unit most recently installed for an upcoming exhibit. The mechanical systems at the MSI are dominated by manual controls systems. Historically, all conditioned spaces modeled have had the same heating and cooling temperature set points. The same is true for the operating schedules of the HVAC equipment. During regular museum operating hours, the HVAC systems operate and space temperatures are maintained at 21.1ºC (70ºF) during the heating season and 23.9ºC (75 ºF) during the summer. During off-hours the HVAC systems do not operate and the building temperature floats.

For HVAC modeling, the areas were categorized by system type, and type of space served; being directly conditioned, indirectly conditioned, or unconditioned.

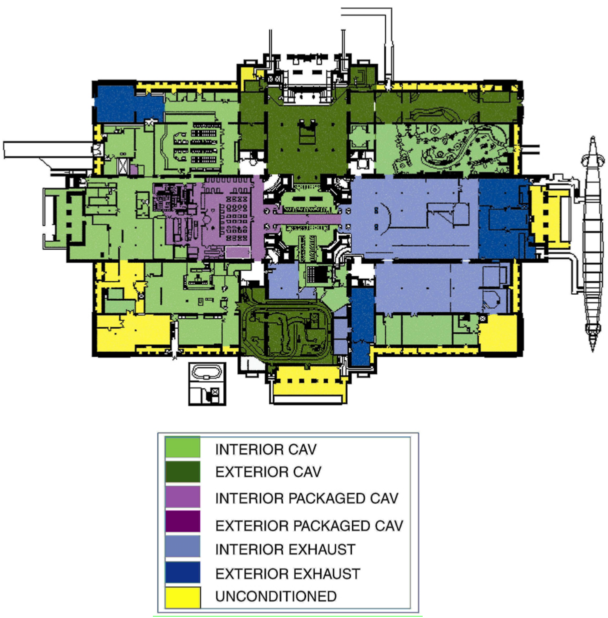
The directly conditioned museum spaces are served by either a central or packaged HVAC systems. The central systems provide space conditioning by using chilled water and hot water supplied by the central plant. The packaged systems provide cooling through a direct expansion refrigeration coil and heating from gas combustion. In the model, the spaces were assigned to a system type equivalent to what is actually installed. In the model, both system types were constant-air-volume (CAV) systems with fixed outdoor-air flow rates equal to ten percent of the supply airflow rates. This is an engineering estimate of the outdoor air volume based on the walk-through assessments conducted. Nearly all of the outdoor air dampers were inoperative and had to be manually opened and closed.

Each central CAV system was modeled as a reheat fan system (RHFS) with a fixed supply air temperature, equal to 12.8˚C (55 ºF). Each packaged CAV system was modeled as a single-zone reheat system (SZRH). A single zone controls this system type although it may serve several zones. The space load of the control zone establishes the supply air temperature for the system. Adding reheat at the zone box varies the cooling or heating capacity of any additional zones served by the system.

The indirectly conditioned museum spaces are served by either central or packaged HVAC systems. These systems differ from the directly conditioned systems since they operate with 100% outside air. This simulates the operation of the exhaust fans in the building. The exhaust fans draw outside air into the building through infiltration (outside air), which increases the space loads of the directly conditioned spaces. By including systems in the model to serve the indirectly conditioned spaces, the model assumes that enough conditioned air is "borrowed" from the museum-conditioned spaces to maintain comfortable space temperatures in the indirectly conditioned zones. That is, they are negatively pressurized with respect to adjacent directly conditioned spaces thereby stealing conditioned air from the adjoining directly conditioned spaces.

Unconditioned spaces include mechanical rooms, storage rooms, and the parking garage. The breakdown of floor area by the HVAC categories described above is shown below, in Figure 4.

Figure 4: MSI As Zoned for DOE-2 Model



Chiller and Boiler Plants

The central plant museum model includes various chillers and a boiler. The actual building has two plants, one serving the Henry Crown Space Center and the other serving the rest of the museum. For simplicity, both plants were combined in the simulation analysis. The chiller plant was modeled with three open, reciprocating, air-cooled chillers.

The boiler plant was modeled as one gas-fired, steam boiler. Again this was simplified from the actual boiler plants for the model. The model includes distribution system losses for the circulated steam/hot water.

Economics

From the given electric utility data (ComEd Rate 6L), all pertinent rate structures were input into the DOE-2 model. Monthly natural gas costs were averaged (commodity plus transportation) to arrive at the monthly cost distribution.

RESULTS

After creating and calibrating the model through numerous iterations, the following results were obtained for the MSI DOE-2 model. These findings are presented in the following sections.

Systems

Table 3 below gives a breakdown of the systems serving the directly and indirectly conditioned building spaces as simulated in the MSI DOE-2 model. The supply airflow rates are determined by the model are based on the sizing of the systems. The system supply flow rates are equal to the sum of the airflow rates supplied to the zones. The zone flow rate is determined from the space peak load and the system supply air temperature. For constant air volume systems, these flow rates do not vary over the day or year.

Table 3: MSI Modeled Systems Summary

Zones	Conditioned Area (m^2)	Conditioned Area (ft^2)	% Area Conditioned
All	62,895	677,000	100%
Central Direct	28,824	310,265	46%
Packaged Direct	14,888	160,250	24%
Central Indirect	5,777	62,183	9%
Packaged Indirect	4,098	44,106	7%
Unconditioned	9,308	100,196	15%

Overall, the flow rate per unit area for the building is low. This situation can be explained by the fact that the perimeter spaces in the building are generally unconditioned mechanical rooms or storage. These spaces provide a buffer against conduction losses/gains to ambient and solar gains. This arrangement results in lower design air flow rates for the building.

Plant

The chiller plant, consisting of three open, reciprocating, air-cooled chillers, was determined by the model to have a total capacity of 3,515 kW (1,000 tons). The design chiller efficiency is 0.88 kW/ton.

The boiler plant, consisting of one gas-fired, steam boiler, was found to have a capacity is 4,015 kW (13.7 MMBtu/hour). The distribution losses are equal to a supply –hot-water drop in temperature of 7.8 ˚C (18 F) under design flow conditions.

The actual capacity of the Museum's physical plant equipment is lower than that determined by the DOE-2 model. In the simulation, the plant equipment seldom operates at full capacity. Thus, the equipment is oversized when compared to the actual museum equipment in order to meet peak loads occurring infrequently over the year. In addition, the model maintains comfortable space temperatures in the indirectly conditioned areas of the building during the summer. This level of comfort is not usually achieved with the actual exhaust fan system. This situation contributes to the higher chiller capacity in the model than the actual physical plant.

Calibration

After dozens of iterations, the results were satisfactory when compared to the suggested values published in the FEMP Measurement and Verification Protocols, Method GVL-01-D, Computer Simulation Analysis and ASHRAE Proposed M&V Guidelines, ASHRAE 14-P (Table 4). Fine-tuning the model included adjusting the controls for the mechanical systems, both in the set-point temperatures and the hours, as well as accounting for the losses due to pipes (DOE-2.1E Enhancements, S.D. Gates, J.J. Hirsch 1996).

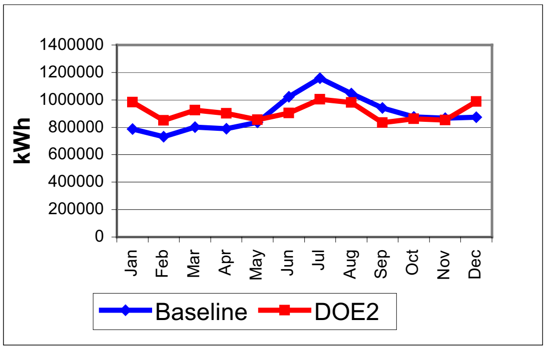
Table 4: Calibration Guidelines and Results

Index	FEMP	ASHRAE 14P	MSI Model Electric	MSI Model Nat. Gas
ERR_{month}	± 15%	± 5%	± 20%	± 19%
ERR_{year}	± 10%	---	± 5.7%	± 2.0%
$CV(RSME_{month})$	± 10%	± 30%	± 14.6%	± 15%

Electricity Usage

Figure 5 shows the predicted electric usage plotted with the baseline electricity usage for the Museum.

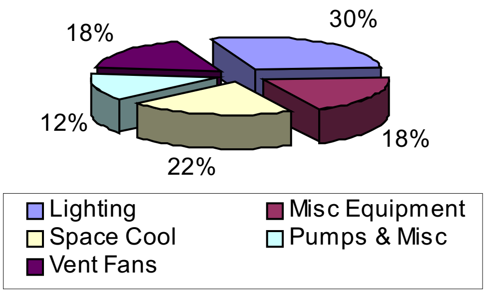
Figure 5: Electric Predicted vs. Actual



Based on the figure, the predicted load shape is very similar to the actual load shape, and the irregularities can be explained by the difference in the TMY2 vs actual weather data, as well as the fact that the Museum is not entirely conditioned during the summer.

From the DOE-2 output, the electrical energy end uses of the Museum were determined. Those data are presented in Figure 6.

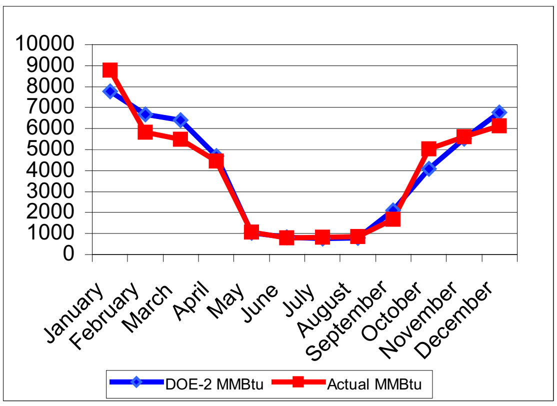
Figure 6: Electric Usage



Natural Gas Usage

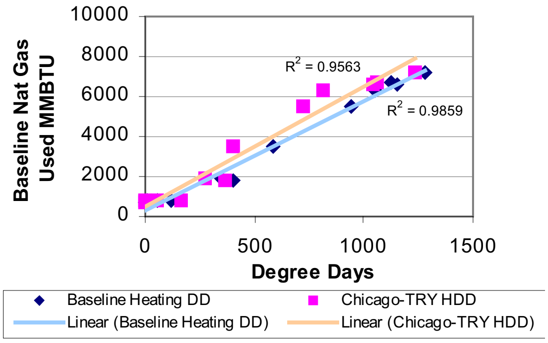
Figure 7 shows the predicted natural gas usage plotted with the baseline gas usage for the MSI.

Figure 7: Natural Gas Predicted vs. Actual



Again the predicted load shape is similar to the actual curve. The weather data can also explain for the irregularities in the natural gas curve. The weather data can also explain for the irregularities in the natural gas curve.

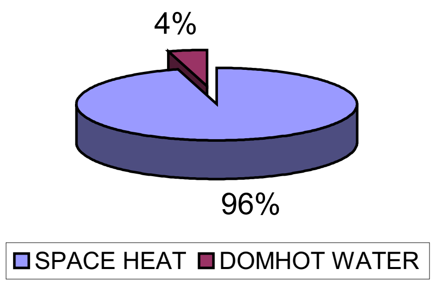
Figure 8 Heating Degree Day Correlation



The correlation between the actual heating degree days and the heating degree days determined by the TRY weather data file, and the actual natural gas usage and predicted natural gas usage is presented in Figure 8. The corresponding trend lines and correlation values (R^2) are presented here as well. As can be seen by the R^2 values, there is a much higher correlation between the actual heating degree-day data and the actual natural gas used by the Museum, than the predicted usage and packaged weather data set.

From the DOE-2 output, the natural gas end uses of the Museum were determined, and are presented below in Figure 9.

Figure 9: Natural Gas Usage



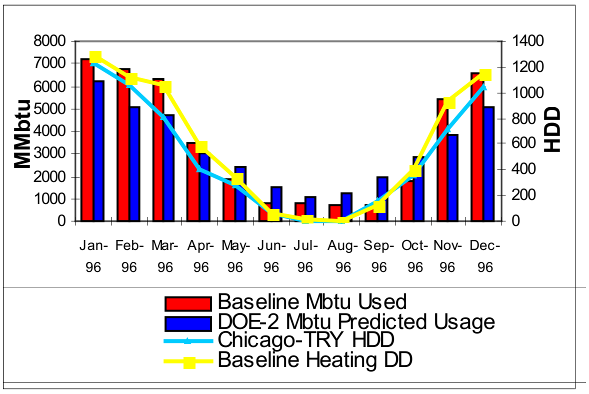
SUMMARY

We were able to accomplish the original goals of the project, including obtaining an estimated peak-cooling load for the Central Pavilion, after having created and calibrated the DOE-2 model for the entire Museum. The model predicted a peak-cooling load of 3,866 kW (1,100 tons) of cooling. This result was similar to the results of an independent study conducted by a local engineering firm, which provides further validation of the model.

In comparing the model results to the guidelines for calibration, it was thought that the weather file used might have had an impact on the CVRSME variable.

A cursory analysis was done of the actual degree-day data and actual natural gas usage versus the package weather file (TMY2 used by the DOE2 program) and the predicted natural gas usage for the museum. This analysis showed that the degree-days were related to the usage as presented in Figure 9 below and the creation of a customized weather file using a site-specific data would possibly improve the margin of error for calibration.

Figure 9: Comparison of MMbtu vs. Heating Degree Day



CONCLUSIONS

The Energy Resources Center successfully created and calibrated a complex MSI DOE-2 model. It was used immediately to determine the peak cooling load for the entire Central Pavilion, which was also validated by an engineering company who was contracted to complete the design/build phase of the MSI 200 development plan. This model will continue to serve as a useful tool to the Museum when further configurations and alterations are being considered for the Museum's physical plant.

The ERC would have liked to investigate creating a weather tape, using data from the same time period as the utility data used to calibrate the model. This would probably improve the accuracy in the calibration as compared to the ASHRAE and FEMP guidelines.

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