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Cooling Load Reduction and Air Conditioner Design in a 19th Century Florida House Museum

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Introduction

The H. S. Williams house is a late 19th century Victorian home located on Florida's central east coast undergoing restoration as a living-history museum. The extensive restoration effort placed heavy emphasis on maintaining historic character as outlined in *The Secretary of the Interior's Standards for Rehabilitation and Guidelines for Rehabilitating Historic Buildings* (36 CFR 67 1995). These Standards and guidelines are designed with two primary goals:

1) Assure the preservation of a building's important or "character-defining" architectural materials and features
2) Make possible an efficient contemporary use.

The Williams home, like any structure built in Florida before the advent of air conditioning, was designed for passive cooling. A multitude of large operable windows strategically placed for cross-ventilation, adjustable louvered window shutters that block solar gains but still allow breezes through, porches with wide overhangs and interior ceilings high enough to keep hot air above occupants' heads represent important passive cooling features. Insulation was of little use, especially during summer when the temperature inside the home would not be much cooler than the outdoor temperature. However, exterior paint colors with lighter, more reflective hues helped to minimize solar gains as indicated in historic photos.

Passive cooling is one "character-defining" aspect of the Williams home worth preserving as much for its modern-day practicality as for its historic usefulness. The necessity of a space conditioning system for the buildings new use as a living history museum was debated by the project architects and future museum operators, as well as architects from the state preservation office. Museum visitation would likely be highest during the more temperate winter season. Two expected sources of visitors, school field trips and out-of-state tourists would be at their peaks during a time when the necessity of air conditioning is at its lowest. The eventual need for the retrofit, however was based on the building being regularly occupied by volunteer docents and that it may house artifacts sensitive to Florida's environment. The system would be needed mainly for cooling and dehumidification rather than heating since the building's primary use would be during the day when cooling loads reach their peak and heating loads are reduced. The entire design analysis therefore focused on cooling-related issues.

This obvious change to the building's character prompted consideration for minimizing its visual impact on the structure as well as allowing for a straightforward return to its original character in the future. Beyond the immediate visual impacts of installing an air conditioner, there are the effects such a system may have on the building over time. A difference in temperature and/or humidity across a building envelope puts stress on the envelope and the greater the temperature or humidity difference the greater that stress will be. The envelope design of a refrigerator, for instance, is very different from a residence because it must endure greater stress. When a building in a hot humid climate approaches the conditions seen by the typical refrigerator (something not altogether uncommon) the results can vary from a negligible impact to major moisture-related damage. The construction materials and the way they are put together will determine the impact of temperature and moisture-related stresses.

A small duct, high velocity (SDHV) system was chosen for the air conditioning retrofit. This system, currently available from two manufacturers, has two advantages over a conventional system for this application. First, SDHV supply outlets are much smaller than standard residential air conditioning supplies, making them less conspicuous to the casual observer. Second, supply air temperatures are colder (and lower in volume) than in a conventional system which enhances the ability to dehumidify. Greater potential for dehumidification is especially desirable in this application as the leaky building envelope found in older homes will allow large influxes of humid outside air.

Cooling Loads

The building envelope (floor, walls and roof/ceiling) provides a barrier between the air conditioned space and the hot and humid Florida climate. It is also the point where most cooling loads occur. There are seven basic cooling loads, five of which relate to the envelope: roof, walls, floor, windows and infiltration.

The other two loads are duct gains and Internally generated heat. Internal gains can be attributed to the heat and moisture produced directly by occupants as well as the appliances and activities associated with daily living.

Cooling loads are what drive air conditioner design just as heating loads drive the design of heating systems. One important distinction between heating and cooling loads is that heating loads (or heat losses) are based purely on thermal energy transfer driven by temperature difference. Cooling loads on the other hand are normally made up of two distinct components, one thermal and the other moisture-related. These components are described more precisely as the sensible and latent portions of the cooling load respectively. The sensible cooling load is normally dominant in residential air conditioning applications, but in Florida's hot and humid climate the latent cooling load is often a significant factor in air conditioner design.

Air conditioner design in historic Florida buildings requires a thorough understanding of the latent cooling load. This is especially the case for structures, such as the Williams house, built for passive cooling prior to the introduction of air conditioning. In humid climates, passive cooling is reliant on reflective surfaces and shading to moderate indoor temperatures during the day. To supplement this, natural ventilation is needed during times when outdoor temperatures are lower than indoor temperatures. The challenge with retrofitting such a structure with mechanical cooling is the typically high rate of outdoor air infiltration which has a very large latent component in Florida's climate.

Three basic cooling load reduction strategies were employed to optimize air conditioner design at the Williams house: air sealing, insulation and shading/reflectivity. The Table 1 shows how each strategy applies to the six envelope cooling loads. While the table lists every potential application, some strategies were abandoned due to their impact on the historic character of the building. For instance wall insulation was not pursued due its high cost, poor return and questions about its effect on long-term durability. A summary of the proposed strategies follows.

Table 1: Potential Cooling Load Reduction Strategies

	Air Sealing	Insulation	Shading and/or Reflectivity
Roof	X	X	X
Walls	X	X	X
Floor	X	X	
Windows	X	X	X
Ducts	X	X	
Infiltration	X		

Roof

Description

The roof of the Williams home was originally clad with metal shingles, but these were replaced with standing-seam metal panels in 1990. While the new cladding is not historically accurate, it is functioning well and so will remain as a future project to more fully restore the building. The second floor ceiling is constructed of painted, tongue and groove, 1x4 beadboard. The gabled roof is steeply-sloped and has a large attic space accessible through a narrow stairway. Two rooms in the attic each have a window on the gable end (Fig.1). Beyond opening these gable-end windows, the attic has very little ventilation potential since there are no soffit (Fig. 2) or ridge vents and only limited gable-end venting.

Load Reduction Options

The roof represents one of the largest potential cooling loads in a Florida residence. Roof-related cooling loads can be reduced by addressing any of the three basic strategies, but the metal roof of the Williams home provides some inherent reflectivity so only insulation and air sealing were addressed. Attic ventilation was not an important consideration prior to the mid-1900s when building codes were modified to increase air change rates in attic spaces. This explains the lack of significant venting in the Williams attic. It also offers the opportunity to completely seal the attic and insulate at the roof deck instead of the ceiling. A semi-conditioned sealed-attic would reduce attic duct losses, eliminate infiltration of hot moisture-laden attic air, and create a more useable space. Currently this approach is gaining limited acceptance in southern climates among code authorities and homebuilders alike[1]. Spray polyurethane foam products applied to the roof deck are commonly used as they have the ability to both air seal and insulate in one step. This option was considered but ultimately rejected since foam applied to the roofing members would hide part of the history of the home and would cost considerably more than insulating at the ceiling level.

Blown attic insulation will reduce the cooling load at the Williams house by an estimated two tons compared to the existing uninsulated condition according the ACCA Manual J calculations (ACCA 1988). This assumes an average level of R-16 of blown cellulose or fiberglass applied to the attic floor. An insulation level of at least R-19 is expected in most locations but some inaccessible areas will receive little or no insulation. Infiltration through the ceiling is a key concern as attic air can be significantly hotter and hold more moisture than ambient air. Air sealing at the ceiling will rely on caulking and painting of the beadboard.


Figure 1 - Attic Window on Gable End


Figure 2 - Solid soffits allow minimal attic ventilation

Walls

Description

The walls of the Williams home are of rough-cut 2x4 balloon-frame construction with horizontal wood exterior siding installed shiplap fashion (Fig.3). Interior wall coverings consist of plaster and lath installed throughout the first floor and 1x4 tongue and groove beadboard on the second floor. The exterior walls are not insulated.

Balloon frame housing, which began in Chicago in the 1830s, eliminated the tedious hewn joints and massive timbers of braced-frame and post-and-beam construction (McAlester 1984). The Williams house was constructed from 1874-1880 with balloon frame walls which have continuous open cavities (Fig.4) between the 2x4 studs from the floor of the first level to the ceiling of the second level. This differs from contemporary platform framing which has stud cavities that span no more than one story.

Load Reduction Options

The open balloon-frame wall cavities of the Williams home contribute to the loose envelope construction and complicate air sealing. Successful air sealing requires an uninterrupted air barrier. A common measure of a successful air barrier is that it can be traced on a set of drawings such that the pencil never leaves the paper over its entire length. This is most easily accomplished with an exterior house wrap as is done routinely in residential construction today. Unfortunately on an historic home without such a barrier, this would require removing the original siding, something to avoid as outlined in the Secretary's Standards (36 CFR 67 1995). Air sealing of the exterior walls at the Williams house must instead rely on

[1] Ventilation should be treated as a design option in cold, wet coastal climates and hot climates. Current technical information does not support a universal requirement for ventilation of attics or cathedral ceilings in these climates (Rose and TenWolde, 2002).

the interior wall surface as the air barrier. Replacement plaster on the first floor walls is expected to provide adequate air sealing but the second floor beadboard walls will be more difficult to seal completely. Caulking and painting especially at wall, ceiling and floor junctures on the second floor will be critical.

An additional complication exists at the interface of the exterior walls and the floor cavity between the first and second floor spaces. As a by-product of balloon framing, this cavity is open and freely communicates with the exterior wall stud cavities, effectively interrupting the exterior wall air barrier where the first floor walls end and the second floor walls begin. Correcting this condition would require sealing the floor cavity where it intersects the exterior walls to create a continuous barrier along the entire inside face of the exterior walls.

Several strategies for insulating the exterior walls were considered including the use of expanding polyurethane foam which could provide air sealing as well as insulation. The decision to do without insulation in the walls was driven by the fact that only 1.5 to 2 tons of cooling load would be saved (assuming R-11 in the walls) and that extensive deconstruction would be required. Perhaps more importantly, the walls will remain uninsulated to ensure they continue to function as they have for the last 130 years. Unlike today's well-insulated wood frame homes, which use building paper or other house wrap as a drainage plane behind the exterior cladding, the exterior siding of the Williams home acts as the primary rain barrier. Adding insulation to the wall cavity may have unintended impacts on the moisture dynamics within the wall so, as in the old medical mantra, the decision was to "first, do no harm."

The uninsulated condition of the exterior walls serves to magnify another important cooling load reduction strategy – surface reflectance. Insulation is used to reduce conductive heat gains through a given thickness but that potential is directly tied to the temperature difference across that thickness. The lower the temperature difference, the less potential for reducing heat gain. With no insulation to reduce conduction of heat through the wall, a light-colored exterior paint becomes a critical cooling load reduction strategy. The new exterior paint and trim used during the renovation were chosen after evaluating existing paint scrapings and comparing with historic photographs (Figs. 5 & 6). In this respect an important character-defining feature of the building has been preserved, one which helps reduce the surface temperature of the exterior walls by reflecting solar radiation.

Maintaining the exterior walls in their original, open and breathable state prompted extra consideration of the interior wall construction. The original 3-coat plaster-on-lath used on the first floor walls has apparently performed very well over the years but must now be largely replaced due to cracking. Replacement options include duplicating the original 3-coat plaster installation or installing ¼ inch gypsum wallboard with a veneer coat of plaster. While either system can produce a visually accurate replica, there are concerns that the standard gypsum panels, which are composed partially of paper, could support mold growth with the paper acting as a food source. This prompted efforts to replicate the original plaster system which harbors no source of food for mold growth and has performed well over the years. Another, more recent option, is the availability of paper-free gypsum products that can be veneer coated with plaster to replicate the 3-coat system both in appearance and in mold resistance.

Figure 3 - First floor exterior wall cross-section

Figure 4 - Balloon wall cavity as viewed from attic


Figure 5 - Williams House, April 1902


Figure 6 - Williams House, June 2001

Floor

Description

The floor of the Williams home consists of tongue-and-groove heart pine boards supported by cross joists mounted on piers. The original brick piers remain along the perimeter of the home but most of the inner piers were replaced during an earlier stabilization project. Wood lattice work seen in historic photos around the building perimeter will be restored to allow maximum crawlspace ventilation.

Load Reduction Options

Insulation and air sealing are the available options for reducing cooling load through the floor. Even left uninsulated, summertime heat gain through the floor is relatively small compared to other cooling loads. Air leakage through the floor could have a significant impact on the air conditioner but would be difficult to quantify as a separate load. Both of these facts lend themselves to leaving the floor and crawlspace in their original states.

Two load reduction alternatives that could still be implemented at a later date are primarily focused on reducing air leakage through the floor. The first involves adding a layer of polyurethane foam insulation directly to the bottom of the floor which could provide an excellent air seal as well as R-value. The second is more extensive requiring the crawlspace to be enclosed with an insulation and air boundary and adding a vapor barrier on the ground beneath the home. While more complex, this approach has several benefits. Coupling the home with the ground has the effect of not just eliminating the cooling load but actually providing some passive cooling. It also provides a semi-conditioned space for ductwork, reducing conduction losses through the ducts and keeping duct leakage within the air and thermal boundary. While the enclosed crawlspace approach holds many benefits there are also pitfalls, primarily the necessity of a properly installed ground cover and adequate water drainage away from the home.

Windows

Description

As expected in a Florida house of its era the Williams home has numerous windows. The 19% glass to floor area ratio is considerably larger than the 13% average found in modern Central Florida homes (FPL 1995). All but one of the original windows were lost to modern replacements but have since been restored with historically accurate double-hung, wood-framed replicas (Fig.7). The window glass is single pane and clear as were the originals as far as can be determined.

Load Reduction Options

Window loads are typically one of the largest sources of heat gain in Florida homes. Today, window cooing loads can be reduced with a combination of simple and high tech strategies including shading, air sealing, special coatings, and multiple panes of glass. The only heat reduction option in the late 1800s would have been shading and the Williams home could have made use of several window shading techniques. The front porch windows are the only ones with a significant overhang which means shading would have to be provided by surrounding trees and operable attachments to the windows. Storm shutters would have been useful shading devices, especially the type with operable louvers that could be adjusted to block direct sunlight while maximizing the free area for air and light to pass through. Historic replicas of this type of shutter are planned for the windows which should prove useful in balancing heat gain and ambient lighting as needed by the museum.

Another type of shading device has an historical precedent on homes of this era according to the project architect, Chalmers Yeilding. Although their use has not been confirmed on the Williams house, insect screens were available and most likely a desirable addition to homes of this era (Fig.8). Manual J air conditioner sizing calculations show a cooling load reduction of 1.5-tons with full, exterior insect screens compared to unscreened windows (ACCA 1988). The insect screen acts as a shading device, dissipating a portion of the solar radiation it absorbs to the outside.

Figure 7 - Replica window with weight and pulley

Figure 8 - Example of full exterior insect screening

Ducts

Description

The air conditioning retrofit planned for the Williams house is a specialized small duct, high velocity (SDHV) system. As suggested by its name, the ducts in this system are much smaller than standard (2 inch diameter) and are subject to higher system pressures. The first floor duct system will be located in the crawlspace and the second floor ducts in the attic.

Load Reduction Options

Duct leakage in Florida can have a devastating impact on indoor air quality, building durability and air conditioner performance when not held in check (Cummings et al 1991). The higher pressures inherent to SDHV duct systems gives equivalent duct holes more potential to leak air than in standard systems, emphasizing the need for a tight duct system. Upon completion, duct leakage to the outside should be within 3 to 5% of air handler flow volume at 25 Pascals of pressure as tested with a duct blaster fan.

Infiltration

Description

Infiltration (or envelope air leakage) has already been detailed at individual locations like roof, walls, floor and windows, however infiltration as a cooling load is typically measured as a single value for the entire structure by inducing a standard pressure of 50 Pascals on the building envelope with a calibrated fan. The flow through the fan represents a measure of the leakage potential of the structure. Another method involves measuring the decay rate of a tracer gas.

Load Reduction Options

Infiltration of outside air through the building envelope is projected to be the single largest air conditioning load on the building. An air leakage test performed on the home in June 1992 and again in March of 2004 provided an estimated natural infiltration rate of 1 air change per hour (nACH) which is consistent with other studies showing increased envelope leakage with home age (Sherman & Dickerhoff 1998 and Cummings et al 1991). While a natural ACH (nACH) of 1.0 is the current best guess of final envelope leakage, these studies indicate that leakage could be 50% higher or lower depending on the final condition of the building envelope.

Calculations performed with Manual J air conditioner sizing procedures (ACCA 1988) show that natural infiltration of 1 nACH would account for 27,500 kBtuh of heat gain, requiring over 2-tons of cooling to remove. This represents 25% of the projected design cooling load of 110,000 kBtuh and makes infiltration the primary target for reducing building cooling load. Increasing and decreasing infiltration by 50% (0.5 and 1.5 ACH) in Manual J varied the cooling load proportionately by 14,000 kBtuh (over 1-ton), emphasizing the importance of careful air sealing.

Envelope Leakage Testing

Field testing of the Williams house and six similar historic homes was conducted in an effort to characterize envelope leakage in balloon frame and post-and-beam structures. Each home was located in East Central Florida within 20 miles of the Williams house. Envelope leakage was determined by Blower Door testing, which employs a calibrated fan to establish a leakage rate for the house at a standard test pressure of 50 Pascals (Pa).

Two commonly used metrics for envelope airtightness are described in air changes per hour. The first is ACH50 which can be directly calculated from blower door data and the house volume. Natural air changes per hour or nACH, on the other hand, is estimated from ACH50 and is strongly related to the building's location. A simple factor that has been successfully used to estimate nACH on Florida homes is division of the measured ACH50 of the home by 40. These values are used in load calculation software to determine the impact of infiltration on heating and cooling loads.

The seven tested homes shown in Table 2 and Figure 9 fell roughly into two categories. Three of the homes were within 10% of the preliminary reading taken at the Williams home, while the other three were considerably tighter. The Young home was particularly tight for a residence of its age, almost on par with modern construction. This home however was extensively renovated with almost all of the original beadboard replaced with gypsum wallboard on the walls and ceilings. Modern double pane, vinyl framed windows were also installed throughout. Another major source of air leakage, the fireplace, was blocked off. This home likely represents the upper end of airtightness achievable when all measures are taken to air seal an historic home.

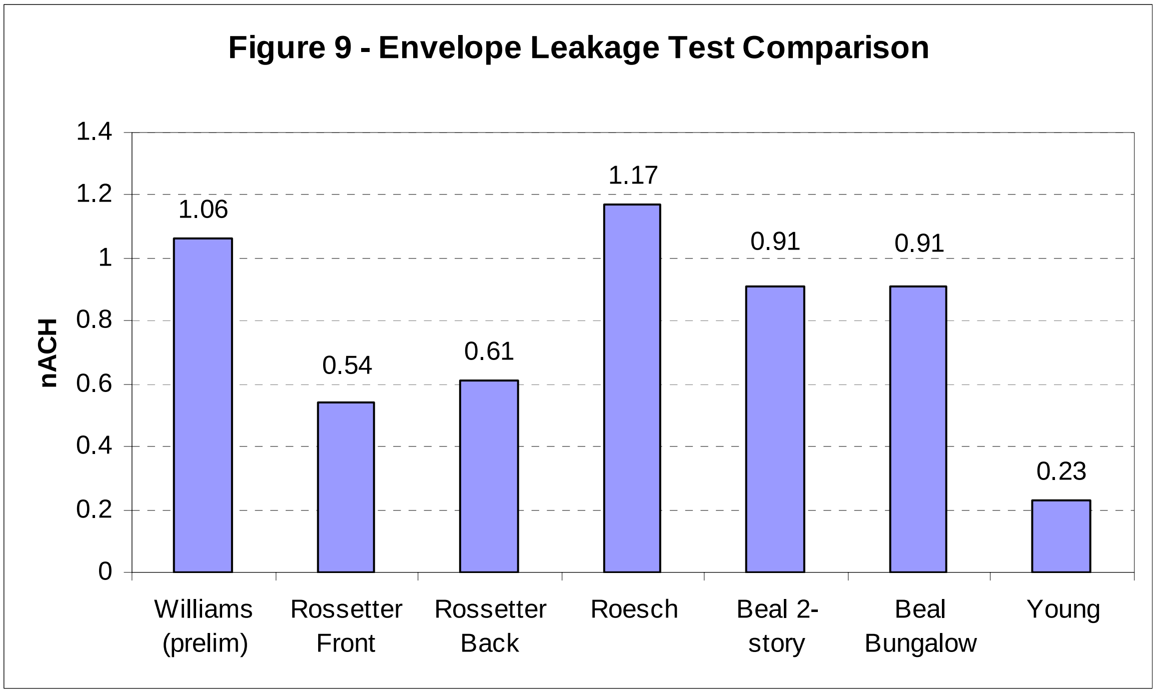


Table 2 - Envelope Leakage Test Results						
Home	**Date**	**Area (ft^2)**	**Volume (ft^3)**	**CFM50**	**ACH50**	**nACH**
Williams (prelim)	1880	3,780	34,020	24,000	42.3	1.06
Rossetter Front	1904	1,480	12,580	4,500	21.5	0.54
Rossetter Back	c1865	1,222	9,776	4,000	24.5	0.61
Roesch	1901	1,256	10,048	7,860	46.9	1.17
Beal 2-story	1915	2,150	17,610	10,700	36.5	0.91
Beal Bungalow	1920	1,240	9,300	5,670	36.6	0.91
Young	1903	1,650	12,600	1,894	9.0	0.23

Notes:
- CFM50 – Cubic Feet per Minute at 50 Pascals
- ACH50 – Air Changes per Hour at 50 Pascals
- nACH – Air Changes per Hour at natural pressures
- Williams house results are preliminary until completion of 1st floor plaster

The two Rossetter homes (Fig.10) measured relatively tight for their vintage with nearly half the leakage rate found at the Williams house. This home site consists of two separate structures connected by an open breezeway. The relative tightness on these homes may be partially due to the state of the windows, which appear seldom used and essentially rendered inoperable by several coats of paint. Older double hung windows, especially those that operate with the weight and pulley system, tend to be very leaky but in this case the paint acts as a seal against infiltration. Many of the windows in the older (back) Rossetter building were of tighter construction as they did not use a weight and pulley system.

Figure 10 - Testing at the Rossetter home site required the simultaneous use of 2 Blower Doors

This small sample of tests illustrates the variable nature of air tightness in historic homes. Air tightness is a critical factor in determining space conditioning system size and operating cost. High levels of infiltration will complicate efforts at controlling indoor humidity, especially during the temperate spring and fall months when the latent (moisture) portion of the load will greatly exceed the sensible (heat) portion. Plans are in place to incorporate dedicated dehumidifiers into both the first and second floor conditioning systems to provide humidity control throughout the year.

Air Conditioner Sizing and Design

Cooling Load Distribution Analysis

Space conditioning design begins with a basic understanding of the heating and cooling loads imposed on a structure. In Florida's cooling-dominated climate this boils down to a well-designed air conditioning system. Figure 11 illustrates the cooling load breakdown of a contemporary 1500 ft^2 Florida home, which can be described with five basic components. The three major components are: (1) internal heat gain from appliances (including lights and people), (2) attic and duct gains and (3) solar gain through the windows. Additional cooling loads from (4) conduction through walls and (5) outdoor air infiltration make up the remaining sources of heat gain.

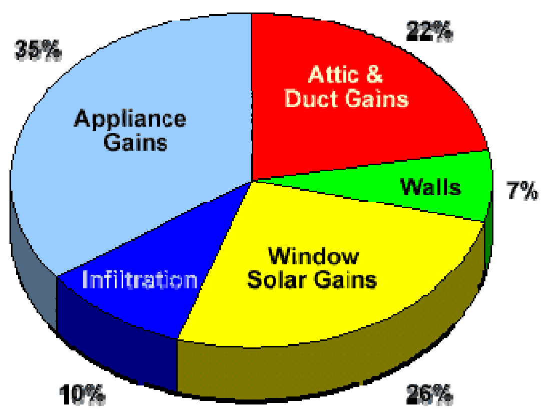
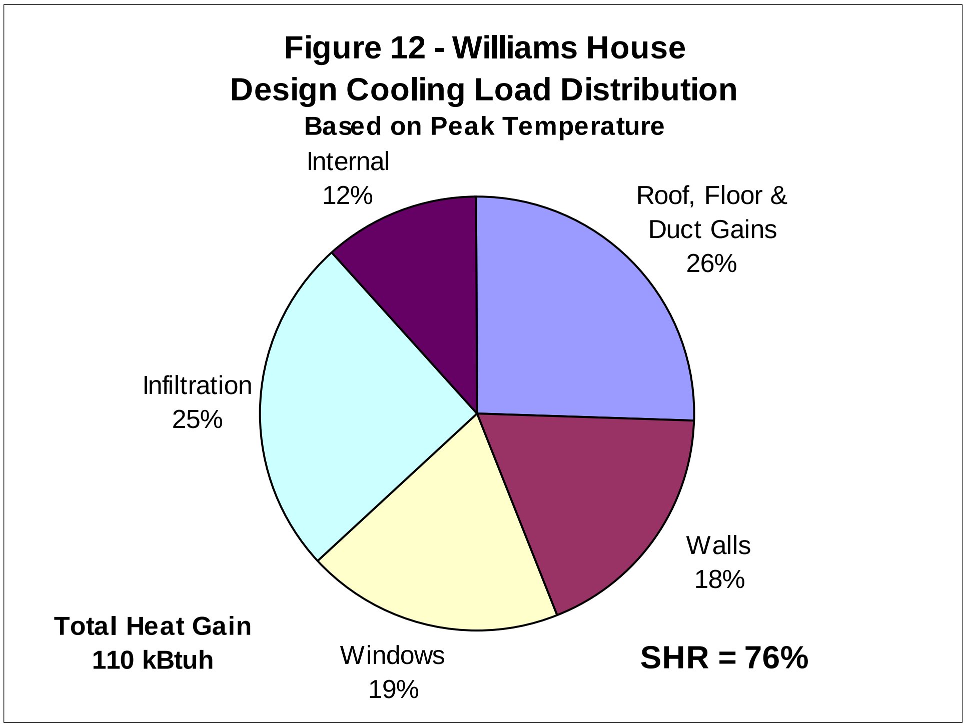


Figure 11 - Cooling Load Components
Orlando, Florida Contemporary Residence

The cooling load components (fig.12) in the restored Williams house will be largely the same as a contemporary Florida home but the distribution will differ substantially. Just as in a modern home, a considerable portion of the cooling load is attributed to solar gain from windows. Beyond that however, the picture changes considerably. Since the Williams home is not occupied like a traditional home, internal heat gain from appliances, lights and people become a smaller fraction of the total. Attic and duct gains are reduced but there is the added component of heat gain through the uninsulated floor. Wall conduction and outdoor air infiltration play a much more prominent role in the cooling load distribution. In fact, infiltration of outdoor air due to the leaky building envelope represents the largest individual cooling load component in the restored home.

Dehumidification Under Peak Temperature Conditions

With infiltration taking prominence in the cooling load distribution, a deeper look at this component is needed. As discussed earlier, cooling load analysis has two general components: sensible (or temperature-related) loads and latent (or moisture-related) loads. In figure 12 only two segments of the pie have a latent component. A small portion of the internal load is latent due to people-related activities but by far the greatest contributor of latent (or moisture load) is Infiltration. In fact, fully three quarters (75%) of the infiltration load is attributed to latent gains. This means any increase in the infiltration load will greatly increase the need for dehumidification.



In most air conditioner applications, between 75% and 80% of the cooling load is sensible with the remainder being latent, which is the specification most air conditioners are designed to handle. The Williams house design cooling load falls into this category with a sensible heat ratio (SHR) of 76% meaning 24% of the work required of the system is based on moisture removal. A standard residential air conditioner would suffice for meeting the sensible and latent cooling load, at least during peak outdoor temperatures[2] and assuming outdoor air infiltration has be accurately estimated.

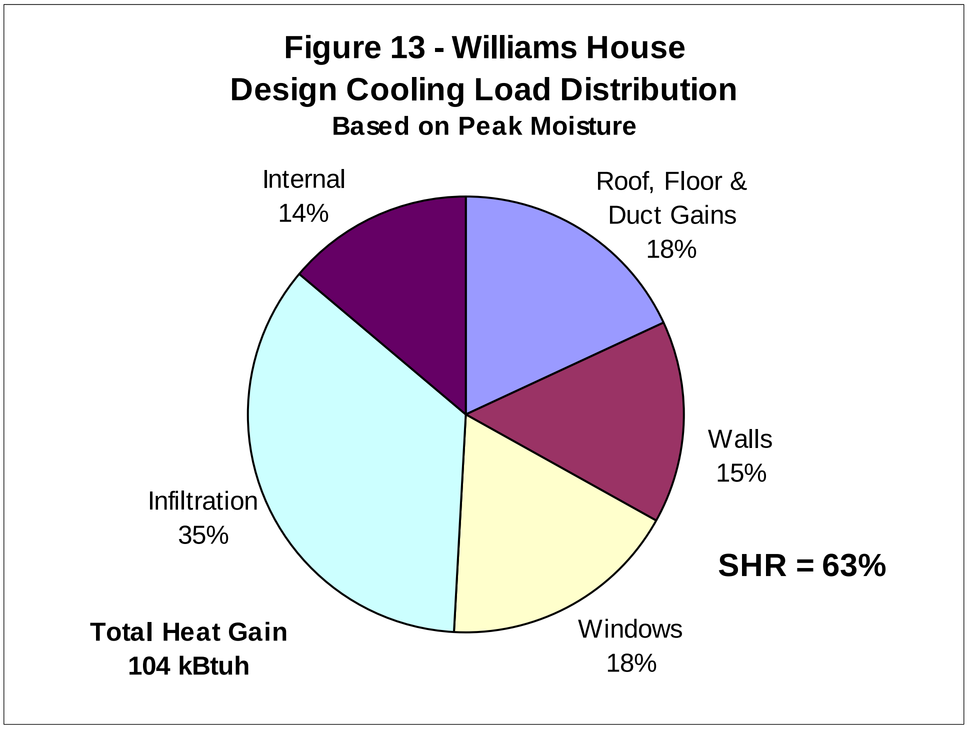
Dehumidification Under Peak Moisture Conditions

The cooling load distribution picture changes substantially however when the peak moisture condition[3] is encountered such as during cool, damp spring or autumn weather (Fig.13). While the total heat gain remains largely unchanged over the peak temperature condition (110 vs. 104 kBtuh), the infiltration segment of the cooling load grows to 35% of the total load and the SHR is lowered to 63%, meaning much more dehumidification is required. At an SHR of 63%, the dehumidification requirement is more than a standard air conditioner is designed to supply, resulting in undesirably high and possibly damaging levels of relative humidity during much of the year.

This issue is partially addressed at the Williams house by the greater moisture removal ability of the SDHV air conditioning system which has a rated SHR of 65%. In addition to this a dedicated dehumidifier will be integrated with the air conditioner and will distribute dehumidified air via the air conditioning ductwork

[2] ASHRAE Peak design cooling conditions for Melbourne, FL – 91°F dry bulb and 79°F median wet bulb, pp 27.9, Table 1B (ASHRAE 2001)

[3] ASHRAE peak design dehumidification conditions for Melbourne, FL – 79°F dew point and 85°F median dry bulb, pp 27.9, Table 1B (ASHRAE 2001)



Summary

Restoration plans at the H.S. Williams house include the installation of a space conditioning system. This report details how building envelope construction and air conditioner equipment design were optimized as a system while minimizing detrimental impacts to the building's historic character. Installing a space conditioning system is itself out of character for the home historically, however many aspects of the effort lent themselves to maintaining the building's "character-defining" features. Resurrecting some of the building's passive cooling attributes is one example of this such as the choice of light colored exterior paint and operable storm shutters which both help to reflect the sunlight and reduce heat gain in the building.

Infiltration of outdoor air proved to be the largest single load on the air conditioner, but it must first be measured to understand the full impact. Envelope leakage was measured with a Blower Door on six homes of similar construction and vintage to the Williams house to characterize the airtightness of balloon frame construction. Airtightness test values were used to estimate the natural infiltration rate which was input to ACCA Manual J (ACCA 1988) sizing software to predict the total cooling load as well as the ratio of sensible to latent cooling required. The final infiltration value upon completion of restoration work at the Williams house is expected to be about 1 air change per hour. This level of infiltration indicates the need for additional dehumidification over what a typical air conditioner can provide. To address this a small duct, high velocity air conditioner is recommended as well as an integrated, dedicated dehumidifier.

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