ASHRAE 90.1, Energy Analyses and Construction Drawings: A Brief Insight Into Energy Challenges

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This research study attempted to highlight some of the potential problems with the accuracy of energy models as they relate to ASHRAE 90.1, design analyses, construction drawings, and the physical construction of the actual facility. More specifically, the thermal resistances of materials located in the building envelope (roof, walls, and windows) were investigated throughout the entire design and construction process. A three part problem was presented when an in-depth analysis of raw data regarding thermal resistance values was performed: (1) Were the ASHRAE baseline values properly interpreted and included in the energy analysis? (2) Were the proposed values in the energy model correctly calculated and accurately reflected in the construction drawings of the building envelope? and (3) Was the building physically constructed in accordance with the details provided in the construction drawings? The data from two recently built, similar five-story barracks were analyzed to uncover potential problems that may indicate larger scale challenges that are occurring in the industry.

Keywords: ASHRAE 90.1, Energy Analysis, Construction Drawings, Thermal Resistance

Introduction

With the emergence of the USGBC and LEED over the past decade, an enormous amount of pressure has been put on designers, architects, and engineers to provide "greener" more energy efficient facilities. In order to comply with LEED, the use of energy modeling software to predict baseline and proposed values has become the standard. One would think the use of sophisticated energy modeling software would imply that actual energy savings were being realized by the end users. However, research by Newsham, Mancini, & Birt (2009) has indicated that although buildings meet the energy requirements of LEED, they do not necessarily save any energy beyond that of conventional non-LEED facility. In fact, some of the facilities that met energy performance requirements of LEED used more energy than conventional non-LEED facilities.

Sims & Meier (2012) concluded that even LEED certification of a facility cannot guarantee any energy savings, and that a recertification process is needed to ensure these proposed savings become a reality. There are many explanations and arguments as to why buildings may not be performing, however this study focuses on one factor related to consistency of the material properties for the building envelope. It should be noted that some of the challenges related to these discrepancies have not yet been officially recognized by some of the entities involved with this process. As a result, a large amount of this study is from my personal experience in the construction management field along with analysis of ASHRAE codes, energy analysis input/output data, construction documents, and as-built field conditions of actual facilities.

In a perfect world all documents related to the design and construction of a facility would be consistent throughout and would not have any discrepancies, misinterpretations, or errors. Unfortunately, this is not the case and within lays the potential for differences throughout the life of a construction project. In an attempt to highlight some of these concerns, the thermal resistivity of the exterior building envelope materials were compared throughout various stages of the design and construction process.

Purpose of the Study

The purpose of this study was to highlight some of the potential problems with the accuracy of energy models as they relate to ASHRAE 90.1, design analyses, construction drawings, and the physical construction of the actual facility. More specifically, the thermal resistances of materials located in the building envelope (roof, walls, and windows) were investigated throughout the entire design and construction process. A three part question was generated as a result of the initial analysis of raw data regarding thermal resistance values:

Were the ASHRAE baseline values properly interpreted and included in the energy analysis?
Were the proposed values in the energy model correctly calculated and accurately reflected in the construction drawings of the building envelope?
Was the building physically constructed in accordance with the details provided in the construction drawings?

Rationale for the Study

Since the beginning of the construction industry the process of translating design intent to construction documents to a real, tangible end product has always been a challenge. Among these challenges, field verification (also known as quality assurance or quality control) tends to be one of the only ways to ensure the design intent is being met in the field. This same challenge also exists with USGBC's LEED program. LEED documentation requires mass amounts of paper work, reports, product data and the like as proof the design has met the requirements for each respective credit. However, does anyone from USGBC sort through all the various LEED templates, review all the design documents, and verify this has been physically constructed in the field at the project site?

Research Design

Due to the limited amount of data available for this type of research, the sample size was limited to two projects of similar, function, location, size and type. Both facilities are multi-story, barracks (dormitory) type facilities. The data used was quantitative and was obtained from ASHRAE 90.1, energy models (TRANE Trace software), contract drawings, and via field inspections. Three different variables were selected from the energy models that could be easily compared, calculated, and validated in the field. Those variables selected were the thermal resistance values for the roof assembly, wall assembly, and window assemblies. For purposes of this research, the primary values shown are the R-value, with the U-factor in parenthesis. Two different versions of ASHRAE 90.1 were used for the energy models. Building 1 was designed under ASHRAE 90.1-2007, while Building 2 was designed under AHSRAE 90.1-2004. The ASHRAE calculated baseline value was obtained from the respective version of ASHRAE 90.1, 2004 or 2007. The energy baseline and proposed values were obtained from the respective energy analysis data, which was obtained from input values for the TRANE (Trace Energy Analysis Program). The contract drawings used were the final as-built drawings for the two facilities. To ensure these items were constructed in accordance with the drawings, either field verification was performed or the data was obtained from an interview of personnel who constructed the facility.

Data Analysis

Figure 1 is a comparison of R-values, with U-factors shown in parenthesis. Additionally, a reference has been provided for each value with the respective Appendix listed.

Building 1	Roof R-Value	Walls R-Value	Window R-Value	Reference
ASHRAE Calculated Baseline	15.38 (0.065)	11.90 (0.084)	1.54 (0.65)	Appendix A, ASHRAE 90.1-2007, Table 5.5-3
Energy Model Baseline	15.38 (0.065)	**11.76 (0.085)**	1.54 (0.65)	Appendix C, Building 1 Energy Analysis
Energy Model Proposed	52.63 (0.019)	20 (0.05)	2.38 (0.42)	Appendix C, Building 1 Energy Analysis
Contract Drawings	**56.93 (0.018)**	**21.45 (.047)**	**3.08 (0.325)**	Appendix E, Building 1 Drawings/Product Data
Constructed IAW Drawings	Yes	**No**	Yes	Verified during field visit

Building 2	Roof R-Value	Walls R-Value	Window R-Value	Reference
ASHRAE Calculated Baseline	15.87 (0.063)	8.06 (0.124)	1.75 (0.57)	Appendix B, ASHRAE 90.1-2004, Table 5.5-3

Energy Model Baseline	15.87 (0.063)	**11.90 (0.084)**	1.75 (.057)	Appendix D, Building 2 Energy Analysis
Energy Model Proposed	31.25 (0.032)	21.03 (0.048)	3.23 (0.31)	Appendix D, Building 2 Energy Analysis
Contract Drawings	31.25 (0.032)	**12.15 (.082)**	**2.17 (.46)**	Appendix F, Building 2 Drawings/Product Data
Constructed IAW Drawings	Yes	Yes	Yes	Verified during field visit

Figure 1: Comparison of R-values for various building envelope materials. Values highlighted in bold indicate differences as noted below.

ASHRAE Baseline Values vs. Energy Model Baseline Values

When comparing the ASHRAE calculated baseline value and the baseline value included in the energy analysis, the above data did not indicate any major discrepancies between the two. Building 1 had one variance in the data with a small difference of 1.18% in the wall R-value. As shown in ASHRAE 90.1-2007, Table 5.5-3 (Appendix A), the assembly maximum U-factor for above-grade, steel framed buildings is 0.084, which translates into an R-value of 11.90. However, the designer instead entered a U-factor of 0.085, R-value of 11.76, into the energy analysis input data. Although a very small difference, this energy analysis included a value that technically exceeded the maximum U-factor value of 0.084.

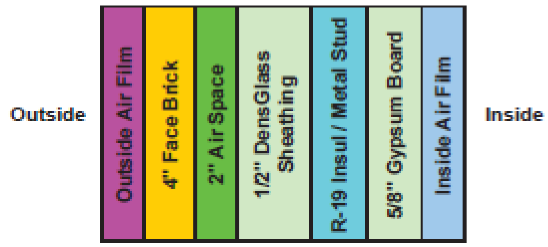
When comparing the same values above for Building 2, the only noticeable difference was also with the R-value of the walls. As shown in ASHRAE 90.1-2004, Table 5.5-3 (Appendix B), the assembly maximum U-factor for above grade, steel framed buildings is 0.124, which translates into an R-value of 8.06. However, the designer entered a U-factor of .084, R-value of 11.90, into the energy analysis input data. This discrepancy in the data results in a 38.48% difference, meaning the baseline value is too high. While this value meets ASHRAE's assembly maximum, the data is incorrect and does not accurately reflect the correct baseline for this building.

Energy Model Proposed Values vs. Contract Drawings

When comparing the energy model proposed values with the assemblies included in the contract drawings, the values for Building 1 were all better than anticipated. The roof R-value proposed was 52.63, compared to 56.93 as shown in the contract drawings. This resulted in a percent difference of 7.85%, meaning the roof performed better than originally calculated in the energy analysis. Additionally, the wall R-value proposed was 20, compared to 21.45 as shown in the contract drawings. This resulted in a percent difference of 6.99%, meaning the walls also performed better than calculated in the energy analysis. Similarly, the window R-value proposed was 2.38, compared to 3.08 as shown in the product data for the selected window type. This means the windows will perform better than shown in the energy analysis with a percent difference of 25.64%. All in all, the construction drawings and product data indicate that Building 1 will actually perform better than the inputs that were included in the energy analysis.

In the contrary, Building 2 did not reflect a similar relationship between proposed values and the contract drawings. While there was no difference in the roof values, the wall values were severely varied. The proposed R-value for the walls was shown as 21.03, while the value shown in the contract drawings when correctly calculated is 12.15. See Figure 2 for the detailed wall value analysis included as part of the energy analysis, which reflects calculation errors.

Exterior Wall U-Value Analysis:



Component Description	Heat Transfer Path	
	Wall Cavity	Framing
Outside Air Film	0.17	0.17
4" Face Brick	0.25	0.25
2" Air Space	1.33	1.33
Air Barrier	---	---
DensGlass Sheathing	0.56	0.56
R-19 Batte Insulation	19.0	---
5/8" Gyp Board	0.56	0.56
Inside Air Film	0.68	0.68
Total R-Value	**22.55**	**3.55**

Assume that the framing portion of the wall accounts for 8% of the wall area, and that the wall cavity accounts for 92% of the wall area (see attached excerpt from Chapter 25 of the ASHRAE Fundamentals Handbook).

R-wall = (0.92)(22.55) + (0.08)(3.55) = 21.03
U-wall = 1/21.03 = 0.048

From Table 5.5-3, the maximum U-value for steel-framed walls is 0.124; therefore, the designed wall construction meets the requirement of ASHRAE 90.1-2004.

Figure 2: Exterior Wall R-Value Calculation

The method being used here is allowed by the ASHRAE handbook, however it has been done incorrectly as the formula being referenced is supposed to include U-factors, not R-values as shown above. ASHRAE 90.1-2004 recommends the use of Table A9.2B to account for adjusted insulation R-values that are interrupted by steel framing. Using this table, a 6" nominal depth and cavity depth, with an R-19 insulation, and studs 24" on center yields an effective R-value of 8.6. In the above table if the R-19 batt insulation value of 19.0 is replaced with 8.6, the assembly R-value is reduced to 12.15, a percent difference of 51.2%. The walls R-values for Building 2 clearly has some significant errors resulting in a very large difference between the value included in the energy analysis and the value as shown in the construction drawings. While these values are still better than the ASHRAE baseline, this kind of error will have a significant impact on the actual thermal resistance of the walls. Lastly, the window R-value in the energy model was listed at 3.23, while the product data for the actual window specified reflected an R-value of 2.17, a percent difference of 39.26%. Similar to the walls, the windows will perform more poorly than anticipated in the energy analysis input data.

Construction Drawings vs. Actual Construction in the Field

The only difference noticed, for all variables, for both Buildings 1 and 2 was a change in exterior wall types for Building 1 as a result of an RFI. The original detail in the contract drawings did not have any exterior sheathing behind the face brick. A RFI was issued to add a layer of 5/8" sheathing behind the brick. This in fact increased to overall R-value of the assembly by 0.56 by adding a layer of exterior sheathing. This change is not significant but should be noted that a possibility exists for changes to be made during construction that could impact the data included in the energy analysis.

Conclusions & Recommendations

While the research performed in this study is not a direct indicator of any sort of trend, due to the small sample size, it does highlight three potential areas of concern regarding the R-values for assemblies being used in building energy models. The first of these concerns is in regard to the baseline values being used in the energy models. Both sets of data above have erroneous inputs that were simply misinterpreted or just blatant errors from Table 5.5.3 in ASHRAE 90.1 (See Appendix A and B). One explanation for these incorrect baseline values, especially in the cases where the baseline value is lower than it should be, is that designers are manipulating numbers to make their proposed values look better. In two different phone interviews with mechanical designers, unrelated to the provided data sets, the biggest inaccuracy identified within energy models is how easily the baseline values can be skewed as needed to get a predetermined end result. If the baseline is set low, then normal values will appear much better than they actually are in reality. The end result may be a building that is supposed to be 40% better than the baseline energy usage when in fact the building is nothing more than a standard facility. Lstiburek (2008) attempts to support this claim as well by suggesting that "green building" has gone astray by rewarding points for things that should be basic building requirements. He also suggest that buildings can get LEED ratings and not save any energy compared to traditional buildings built without the use of LEED.

The second area of concern concluded from this study is that R-values entered into the energy models and the values that end up in the drawings, specifications and/or submittals has a high potential to be different. For both sets of data, five of the six values for the R-value did not match between the energy analysis and the contract documents. Fortunately for Building 1, all values in the contract documents were better than proposed in the energy analysis. This means the assembly R-values were in fact improved in the contract documents, resulting in a better thermal resistance. In the contrary, Building 2 had a severe miscalculation for the wall assembly that did not account for the thermal bridging that is common with metal wall studs. From reviewing the design analysis data related to the wall assembly R-value for Building 2, it appears this was an honest mistake that stems from improper application of the ASHREA 90.1 code. Regardless of the reasoning behind the error, a mistake of this caliber could result in a building that has less than half the thermal resistance indicated in the energy analysis. The Cellulose Insulation Manufacturers Association has also indicated that thermal bridging can reduce the actual energy efficiency of a wall by up to 50 percent, which is in agreement with the research that has been provided as part of this study.

Finally, the third issue highlighted as part of this research is the potential for the building materials that are assumed in the energy model to be changed during the construction process. Both of these projects were of the design-build delivery type meaning there was much more freedom for the architect and engineers to change things as needed during the construction process. Requests for information, clarifications, and contract change orders all have the potential to change the exterior building materials, resulting in different thermal resistance values for wall, roof, and window assemblies. While very little evidence was provided in this research, it should be a valid concern to preserve the accuracy of the energy models. A possible solution to prevent this type of issue would be to make sure there is consistency in building materials between the energy model, construction drawings, and as-built conditions. This responsibility would rely solely on the designers, engineers, and management personnel to ensure these kinds of concerns are being considered when making changes to the exterior building envelope. Research performed by Ueno (2010) also highlights concerns with real buildings when compared to energy models and how every detail in the models may not accurately reflect what has been constructed in the field. Although probably not cost effective, to produce a more accurate energy model a post construction energy analysis could be performed and compared to the original analysis performed during the design process. This type of back-check would ensure data being provided to the USGBC for LEED is in fact representative of the actual as-built conditions.

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Appendix A: ASHRAE 90.1-2007, Table 5.5-2

TABLE 5.5-3 Building Envelope Requirements For Climate Zone 3 (A, B, C)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.173	R-5.0 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal Building	U-0.113	R-13.0	U-0.113	R-13.0	U-0.184	R-6.0
Steel-Framed	U-0.084	R-13.0 + R-3.8 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.089	R-13.0	U-0.089	R-13.0	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.107	R-6.3 c.i.	U-0.087	R-8.3 c.i.	U-0.322	NR
Steel-Joist	U-0.052	R-19.0	U-0.052	R-19.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.051	R-19.0	U-0.033	R-30.0	U-0.066	R-13.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.730	NR	F-0.730	NR
Heated	F-0.900	R-10 for 24 in.	F-0.900	R-10 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-1.450		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.65	SHGC-0.25 all	U-0.65	SHGC-0.25 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.60		U-0.60		U-1.20	
Metal framing (entrance door)[c]	U-0.90		U-0.90		U-1.20	
Metal framing (all other)[c]	U-0.65		U-0.65		U-1.20	

Appendix B: ASHRAE 90.1-2004, Table 5.5-2

TABLE 5.5-3 Building Envelope Requirements For Climate Zone 3 (A,B,C)*

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.063	R-15.0 ci	U-0.063	R-15.0 ci	U-0.218	R-3.8 ci
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.034	R-30.0	U-0.027	R-38.0	U-0.081	R-13.0
Walls, Above-Grade						
Mass	U-0.151[a,b]	R-5.7 ci[a,b]	U-0.123	R-7.6 ci	U-0.580	NR
Metal Building	U-0.113	R-13.0	U-0.113	R-13.0	U-0.184	R-6.0
Steel-Framed	U-0.124	R-13.0	U-0.084	R-13.0 + R-3.8 ci	U-0.352	NR
Wood-Framed and Other	U-0.089	R-13.0	U-0.089	R-13.0	U-0.089	R-13.0
Wall, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.107	R-6.3 ci	U-0.087	R-8.3 ci	U-0.322	NR
Steel-Joist	U-0.052	R-19.0	U-0.052	R-19.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.051	R-19.0	U-0.033	R-30.0	U-0.282	NR
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.730	NR	F-0.730	NR
Heated	F-1.020	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Non-Swinging	U-1.450		U-0.500		U-1.450	
Fenestration (for Zones 3A and 3B; see next page for Zone 3C)	**Assembly Max. U (Fixed/ Operable)**	**Assembly Max. SHGC (All Orientations/ North-Oriented)**	**Assembly Max. U (Fixed/ Operable)**	**Assembly Max. SHGC (All Orientations/ North-Oriented)**	**Assembly Max. U (Fixed/ Opera-ble)**	**Assembly Max. SHGC (All Orientations/ North-Oriented)**
Vertical Glazing,% of Wall						
0-10.0%	U_{fixed}-0.57	$SHGC_{all}$-0.39	U_{fixed}-0.57	$SHGC_{all}$-0.39	U_{fixed}-1.22	$SHGC_{all}$-NR
	U_{oper}-0.67	$SHGC_{north}$-0.49	U_{oper}-0.67	$SHGC_{north}$-0.49	U_{oper}-1.27	$SHGC_{north}$NR
10.1-20.0%	U_{fixed}-0.57	$SHGC_{all}$-0.25	U_{fixed}-0.57	$SHGC_{all}$-0.39	U_{fixed}-1.22	$SHGC_{all}$-NR
	U_{oper}-0.67	$SHGC_{north}$-0.49	U_{oper}-0.67	$SHGC_{north}$-0.49	U_{oper}-1.27	$SHGC_{north}$NR
20.1-30.0%	U_{fixed}-0.57	$SHGC_{all}$-0.25	U_{fixed}-0.57	$SHGC_{all}$-0.25	U_{fixed}-1.22	$SHGC_{all}$-NR
	U_{oper}-0.67	$SHGC_{north}$-0.39	U_{oper}-0.67	$SHGC_{north}$-0.39	U_{oper}-1.27	$SHGC_{north}$NR
30.1-40.0%	U_{fixed}-0.57	$SHGC_{all}$-0.25	U_{fixed}-0.57	$SHGC_{all}$-0.25	U_{fixed}-1.22	$SHGC_{all}$-NR
	U_{oper}-0.67	$SHGC_{north}$-0.39	U_{oper}-0.67	$SHGC_{north}$-0.39	U_{oper}-1.27	$SHGC_{north}$NR
40.1-50.0%	U_{fixed}-0.46	$SHGC_{all}$-0.19	U_{fixed}-0.46	$SHGC_{all}$-0.19	U_{fixed}-0.98	$SHGC_{all}$-NR
	U_{oper}-0.47	$SHGC_{north}$-0.26	U_{oper}-0.47	$SHGC_{north}$-0.26	U_{oper}-1.02	$SHGC_{north}$NR