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Craig Christensen
National Renewable Energy Laboratory

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Definitions

a	Wind boundary layer exponent
d	Wind boundary layer thickness
e	Thermal infrared emissivity
λ	Thermal conductivity of air
μ	Dynamic viscosity
Φ	Window tilt
ρ	Density of air
σ	Stephan-Boltzmann constant
A	Area
a	MoWiTT convection regression coefficient (multiplier)
b	MoWiTT convection regression coefficient (exponent)
BEopt	Building Energy Optimization Software
c_p	Specific heat of air
EES	Engineering Equation Solver
F^*	Exterior radiation view factor correction factor
$F_{a \rightarrow b}$	View factor from "a" to "b"
g	Gravitational constant
H	Window height
$h_{c,ext,f}$	Forced exterior convective coefficient
$h_{c,ext;n}$	Natural exterior convective coefficient
$h_{c,in}$	Interior convective coefficient
$h_{c,total}$	Total (forced + natural) exterior convective coefficient
h_{in}	Interior combined (radiative and convective) heat transfer coefficient
h_{out}	Exterior combined (radiative and convective) heat transfer coefficient

$h_{r,in}$	Interior radiative coefficient
Nu	Nusselt number
Q	Heat transfer rate
q	Heat flux transfer rate
QIRWI	DOE-2 correction factor for exterior radiation
R_o	Exterior combined (radiative and convective) film resistance
Ra_H	Rayleigh number (height based)
Ra_{cv}	Critical value of Rayleigh number
T_{in}	Indoor air temperature
$T_{m, f}$	Interior mean air film temperature
TMY3	Typical Meteorological Year 3
T_{out}	Outdoor air dry bulb temperature
T_{room}	Temperature of the other room surfaces (e.g., walls, ceiling, and floor)
T_{win}	Window surface temperature
TP1	DOE-2 terrain parameter 1
TP2	DOE-2 terrain parameter 2
U_{win}	Conductance of the glazing system (not including interior and exterior coefficients)
UW	Overall window conductance (between indoor and outdoor air temperatures)
V	Wind speed
z	Height of wind speed measurement

1 Introduction

Issues with building energy software accuracy are often identified by comparative, analytical, and empirical testing as delineated in the BESTEST methodology (Judkoff and Newmark 2006). As described in this report, window-related discrepancies in heating energy predictions were identified through comparative testing of EnergyPlus (DOE 2010) and DOE-2 (James J. Hirsch & Associates 2010). Multiple causes for discrepancies were identified, and software fixes are recommended to better align the models with the intended algorithms and underlying test data.[1]

The annual energy values (shown in various bar charts in this report) are specific to the case analyzed (typically single-pane windows, in a simple room geometry, with Chicago weather) and the analysis methods used (simulation engines or Engineering Equation Solver [EES]). However, the proposed software changes described in Section 1 are generally applicable as they address specific source code problems described in Appendices C and D.

1.1 Motivation

Window heat transfer can represent a significant portion of the overall heating load in buildings. This is especially true for the tens of millions of older homes with single-pane windows. When assessing these buildings for energy savings potential through retrofits, it is important to be able to accurately predict the heat transfer through the windows. For single-pane windows, the predicted heat transfer is more sensitive to the convective and radiative boundary conditions than it is for multiple-pane, less-conductive window types.

Two commonly used building energy simulation engines, EnergyPlus and DOE-2, offer a number of ways to model window heat transfer. A comparison of each window model is presented in Table 1.

The inputs for many of the more detailed models are not often available in most energy modeling applications. Therefore, it is desirable to have a model—such as the EnergyPlus detailed model with simple inputs—that can provide a detailed level of analysis given a limited, but readily available set of inputs (e.g., the information provided on a National Fenestration Rating Council energy performance label).

Although the EnergyPlus detailed model with simple inputs is not explicitly available in DOE-2, it is possible to use the same methodology to create a near-equivalent model using the WINDOW software WIN input method for the DOE-2 detailed model. This simple input methodology is thoroughly described in Arasteh et al. (2009).

[1] This study specifically investigated the DOE-2.2 software, but the same problems and recommended fixes seem to apply to the DOE-2.1E software.

Table 1. Comparison of Window Models Available in EnergyPlus and DOE-2

(Rows that are bold are the models that are used for the analysis in this report)

Simulation Engine	Model Complexity	Input Complexity	Inputs	Deficiencies
EnergyPlus	Detailed	Detailed	• Layer-by-layer construction with average spectral properties [2] • WINDOW software output (LBNL 2012)	• Input requires in-depth knowledge of glazing system
DOE-2	Detailed	Detailed		
EnergyPlus	**Detailed**	**Simple**	NFRC rating metrics: • Solar heat gain coefficient • U-factor • Visible transmittance	• Less control over spectral properties • Radiation/convection effects between panes are not explicitly calculated each time step
DOE-2	**Detailed**	**Simple [3]**		
DOE-2	Simple	Simple [4]	• Shading coefficient • Window conductance • Visible transmittance	• Less control over spectral properties • Radiation/convection effects between panes are not explicitly calculated each time step • Input does not correspond directly with NFRC rating metrics • Model does not account for variations in optical properties at off-normal solar incidence • Interior convection and radiation heat transfer coefficients are constant

EnergyPlus (version 6.0.0.023) and DOE-2 (version 2.2-47h2), each using the detailed model with the simple input methodology described by Arasteh et al. 2009, show significant differences in their calculation of window heating load. These differences were revealed through an automated test suite developed for NREL's BEopt (Building Energy Optimization) software

[2] EnergyPlus also has the capability to use full spectral properties

[3] This model is not explicitly available in DOE-2; however, it is possible to use the methodology described in Arasteh et al. (2009) to create a model nearly equivalent to the EnergyPlus detailed model with simple inputs. This methodology is implemented in BEopt

[4] The calculation methodology in this model is significantly different than the other more detailed models. As discussed in Appendix D.2, not all of the issues discussed in this paper apply to this model

(NREL 2011).[5] One test compares the heating energy associated with a fictional building where the windows[6] are the only component contributing to the load. As shown in Figure 1, the results from this test revealed 26%–41%differences in window heating load between the two simulation engines, with consistently higher predictions from DOE-2.[7]

Running the BEopt test suite simulations without solar radiation in the weather file revealed that the absolute[8] differences in window heat loss (in MMBtu) between EnergyPlus and DOE-2 are nearly identical (see Figure 1 and Figure 2). Inspection of hourly output shows that differences in window heat loss appear during the day and night, correlating strongly with indoor/outdoor temperature differences and not with incident solar radiation. The causes of the differences appear to be primarily in the calculation of heat transfer through the window (and not in the calculation of transmitted/absorbed solar radiation). Thus, the remainder of this document will focus on the differences in the algorithms for window heat transfer.

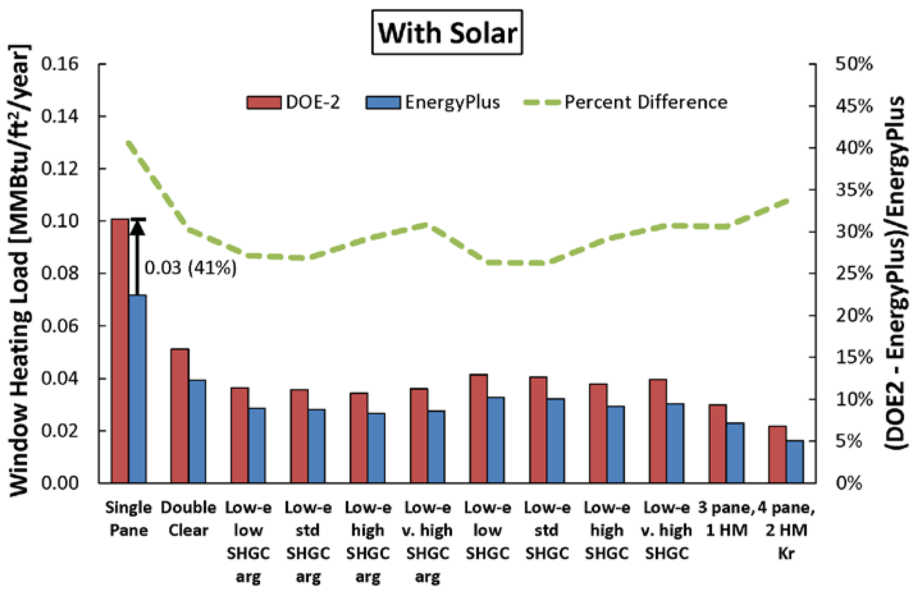

Figure 1. Comparison of annual window heat losses with solar radiation in EnergyPlus and DOE-2 from the BEopt automated test suite with Chicago TMY3 weather file

[5]This is consistent with the results of a similar suite of comparisons between EnergyPlus (version 1.4) and DOE-2 (version 2.1E) for commercial buildings (Huang et al. 2006), and may explain some of the over-predictions in heating energy perceived in the literature (see Polly et al. 2011, Appendix A).

[6]The thermal properties of the windows in the BEopt automated test suite are provided in Appendix A.

[7]When EnergyPlus was tested against DOE-2 (version 2.1E) using the ANSI/ASHRAE Standard 140-2007 procedures (see Henninger and Witte 2010) the results from the comparison tests showed higher predicted annual heating in DOE-2 than in EnergyPlus. This is consistent with the results presented in this document.

[8]Note that the percent differences between EnergyPlus and DOE-2 are lower in the case without solar than in the case with solar (24% versus 41% for single pane windows), because the window heat losses without solar are greater than the net window heat losses with solar.

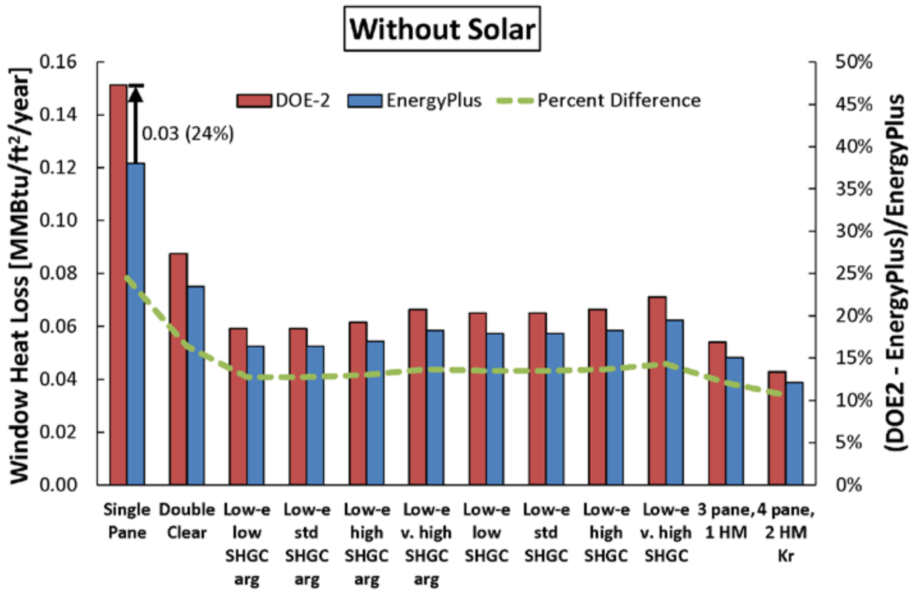

Figure 2. Comparison of annual window heat losses without solar radiation in EnergyPlus and DOE-2 from the BEopt automated test suite with Chicago TMY3 weather file

The objectives of this document are to:

- Identify issues in the window heat transfer algorithms.
- Propose changes to improve agreement and accuracy in heat transfer calculations.
- Estimate the impact of implementing the proposed changes.

1.2 Organization

The main body of this document describes the methodology employed to meet the objectives stated above. This is followed by a brief Results section listing the proposed changes to the EnergyPlus and DOE-2 algorithms and illustrating the estimated changes in annual window heat transfer. The appendices provide detailed descriptions of the window heat transfer methods and justifications for the proposed changes.

2 Methodology

Comparing the source codes of EnergyPlus and DOE-2 to each other and to the original algorithm references revealed several problems in the window heat transfer calculations in the simulation engines including typos, unit conversion issues, misinterpretations of the original references, and outdated references. To simplify the analysis and to isolate the phenomena of window heat loss, a simplified test case (a small room with a single window) was defined to compare the calculations of window heat transfer in the two simulation engines. The simplified test case includes single-pane windows, as they exhibited the greatest difference in the BEopt test suite. Details of the simplified test case are available in Appendix B.

2.1 Engineering Equation Solver Diagnostic Methodology

The algorithms, as they were found in the EnergyPlus and DOE-2 source code, were re-programmed into EES (F-Chart Software 2010) to verify that each calculation in the source code was correctly understood. This representation of the simulation engine algorithms[9] allowed for controlled diagnostics, in which each mechanism of heat transfer could be investigated independently of the other mechanisms. The impact of possible changes to the simulation engine algorithms were then evaluated in EES rather than modifying and recompiling the executable programs for EnergyPlus and DOE-2.

The simplified test case (Appendix B) was modeled in the simulation engines and in EES to validate the EES models (see Figure 3). The EnergyPlus and DOE-2 simulation results differ by 21.1%, while EES shows a 18.3% difference. This deviation may be explained, at least in part, by the following differences between calculations in the simulation engines and EES:

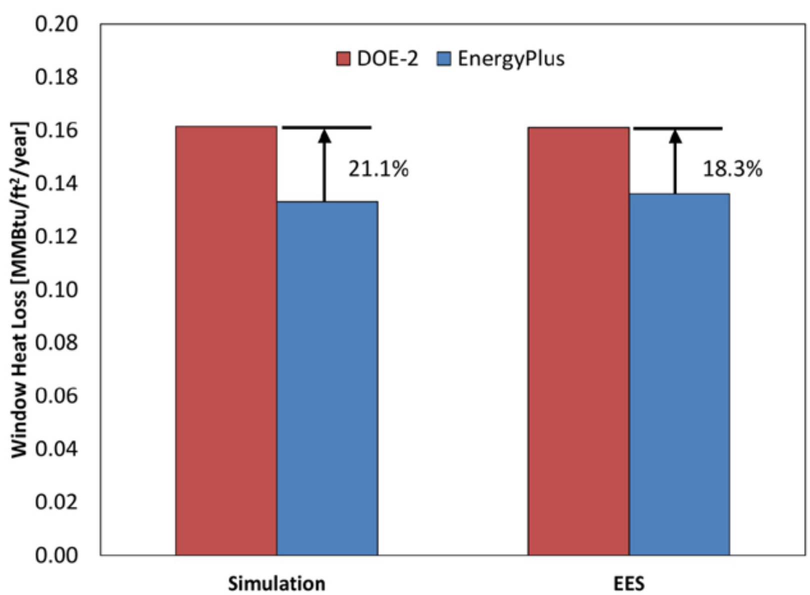

Figure 3. Comparison of annual single-pane window heat losses in EnergyPlus and DOE-2 for the simplified test case modeled in simulation engines and EES (before applying proposed changes) with TMY3 weather file (without solar)

[9]Does not include algorithms for transmitted/absorbed solar. All EES results use a Chicago Typical Meteorological Year 3 (TMY3) weather file without solar.

- In EnergyPlus, the interior and exterior boundary conditions depend on the surface temperature. These boundary conditions are calculated using surface temperatures from the previous time step (instead of performing an iterative calculation in the current time step) to reduce simulation time. The EES model iteratively solves for each temperature to ensure an energy balance within the time step.
- EnergyPlus uses a complete radiative network model to represent radiative exchange between surfaces. For the test case, this would mean that each wall, the floor, and the ceiling would be represented by their own temperatures and would exchange heat with each other and with the air node. In the EES model, the opaque surfaces of the room are all treated as a single temperature, such that radiative exchange occurs only between the window surface and the "room" surface. This allows for a simpler radiative exchange model in EES.
- In DOE-2, by default,[10] the interior and exterior heat transfer coefficients of the window assembly are calculated by guessing the temperatures of each pane of glass such that there are equal increments of temperature difference between the indoor temperature, the panes, and the outdoor temperature. For example, the temperature of a single-pane window would be halfway between indoor and outdoor temperatures. The EES model iteratively calculates the surface temperatures that satisfy the energy balances. Because the surface temperatures are used only to calculate the heat transfer coefficients, and are not used directly in the calculation of the total window heat transfer, we estimate that this has a relatively small impact on the difference (about 0.1% according to the EES model).

[10] Alternatively, a user may specify a convergence tolerance for an iterative solution of the surface temperatures that satisfy the energy balance. However, some user-defined tolerance values did not always find a stable solution, causing the program to fail. The DOE-2 simulation results in this document were generated using the default guess temperatures.

3 Results

For interior and exterior convection algorithms, discrepancies are described in detail in Appendices C and D, and proposed changes are listed in Section 3.1. For interior radiation, the two simulation engines use fundamentally different algorithms that correspond to differences in the underlying heat balance methodologies (see Appendix E). For exterior radiation, the algorithms in EnergyPlus and DOE-2 are identical (see Appendix F). For these reasons, this document does not propose any changes in interior or exterior radiation algorithms.

3.1 Proposed Changes

3.1.1 DOE-2 Interior Convection

Update the algorithm for the interior convection coefficient to vary as a function of window height (see Appendix C.2.1):

Original Coefficients: $h_{c,in} = 1.77 \Delta T^{1/4}$

Proposed Coefficients: $$h_{c,in} = 1.46 \left(\frac{\Delta T}{H} \right)^{1/4}$$

3.1.2 EnergyPlus Exterior Convection

Update the exterior forced convection regression coefficients to apply appropriately when generalizing the original empirical correlation for near-window wind speeds (see Appendix D.1.1):

Table 2. EnergyPlus Original Coefficients

SI Units:	a $\left[\frac{W}{m^2 \cdot K \cdot (m/s)^b} \right]$	b $[--]$
Windward	2.38	0.89
Leeward	2.86	0.617

Table 3. EnergyPlus Proposed Coefficients

SI Units:	a^*	b $[--]$
Windward	3.26	0.89
Leeward	3.55	0.617

3.1.3 DOE-2 Exterior Convection

Use the window-space wind speed when calculating the exterior forced convection coefficient instead of the weather station wind speed. Though DOE-2 calculates the window-space wind speed and uses it in the calculation of exterior forced convection for other surfaces, it is not used for windows (see Appendix D.2.1):

Original Coefficients: $$h_{c,forced} = aV_{ws}^{b}$$

Proposed Coefficients: $$h_{c,forced} = \left(a^{*}\right)V_{local}^{b}$$

Update the exterior forced convection regression coefficients to apply appropriately when generalizing the original empirical correlation for near-window wind speeds (see Appendix D.2.1):

Table 4. DOE-2 Original Coefficients

	a	b
IP Units:	$\left[\dfrac{Btu}{hr\cdot ft^{2}\cdot R\cdot(knots)^{b}}\right]$	$[--]$
Windward	0.289	0.89
Leeward	0.391	0.614

Table 5. DOE-2 Proposed Coefficients

	a^{*}	b
IP Units:		$[--]$
Windward	0.299	0.89
Leeward	0.399	0.617

3.2 Annual Results

Figure 4 shows the estimated impact of all the proposed changes listed in Section 3.1 (on single-pane window heat loss modeled in EES for the simplified test case with Chicago TMY3 weather file without solar). The original 18.3% difference between EnergyPlus and DOE-2 is reduced to 3.3%. Figure 5 shows the estimated cumulative impacts of the proposed changes in Section 3.1.

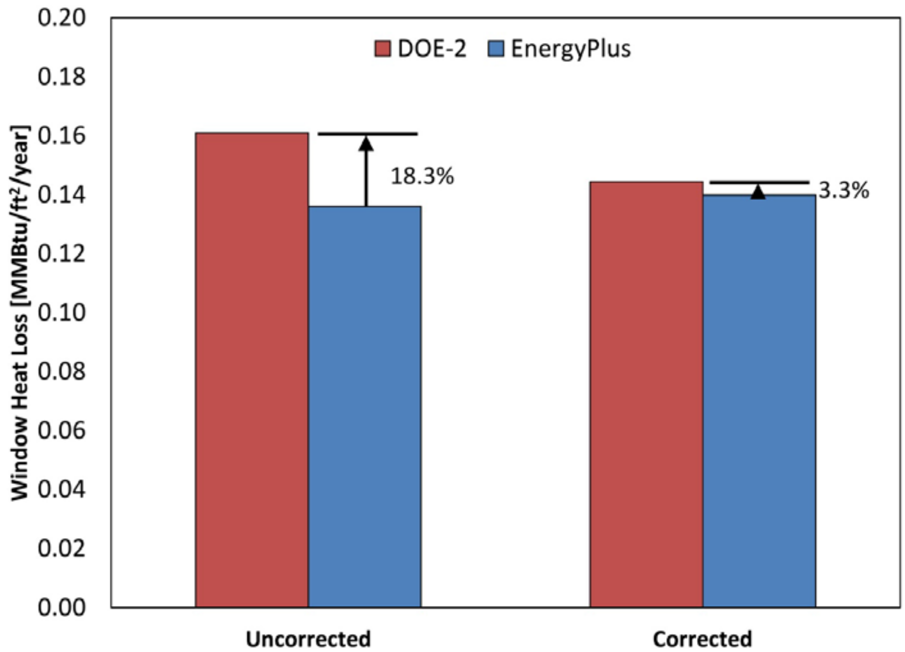

Figure 4. Estimated total impact of all the proposed changes listed in Section 3.1 (on single-pane window heat losses modeled in EES for the simplified test case with Chicago TMY3 weather file without solar)

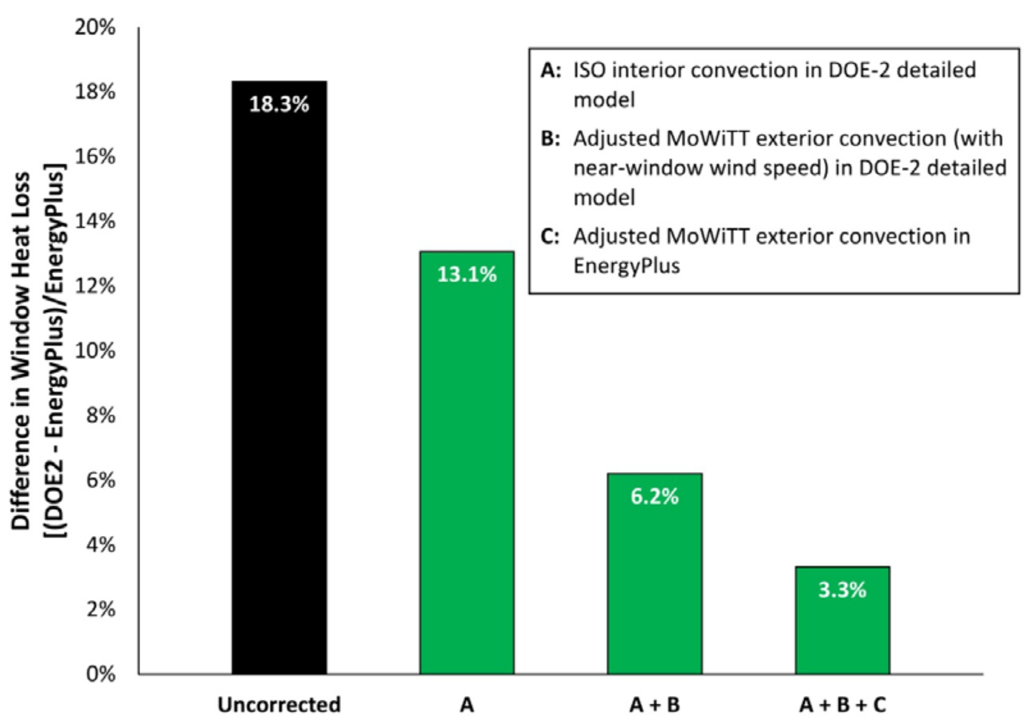

Figure 5. Estimated cumulative impacts of the proposed changes listed in Section 3.1 (on single-pane window heat losses modeled in EES for the simplified test case with Chicago TMY3 weather file without solar)

As shown in Appendix E, the remaining difference (3.3%) appears to be mostly related to differences in interior radiation algorithms. If EnergyPlus and DOE-2 use the same interior radiation algorithm, the difference between the EES results is reduced to almost zero (–0.3%). However, the interior radiation algorithms in EnergyPlus and DOE-2 use fundamentally different heat balance methodologies, and it is not practical to change DOE-2 to calculate the surface temperatures required to perform similar radiative exchange calculations to those of EnergyPlus.

4 Conclusions

DOE-2 (version 2.2-47h2) and EnergyPlus (version 6.0.0.023) show significant differences in the calculated heating loads related to windows, up to 41% for single-pane windows in Chicago. No issues were identified related to the transmitted/absorbed solar radiation or the exterior radiation algorithms.

The following changes are proposed to address issues identified in the source code of the simulation engines. Impacts of the changes on the difference between EnergyPlus and DOE-2 window heat loss, based on EES representation of window heat transfer algorithms, are shown in parentheses.

4.1 EnergyPlus

The exterior forced convection coefficient should be calculated using regression coefficients that are appropriate for use with near-surface wind speeds. (Window heat loss is increased, resulting in a 16% reduction of the simulation engine difference.)

4.2 DOE-2

- The interior convection algorithm is out of date and should be updated to incorporate a dependence on the height of the window. (Window heat loss is reduced, resulting in a 28% reduction of the simulation engine difference.)

- The exterior forced convection coefficient should be calculated using: (1) the near-surface wind speed for detailed windows (as it is for other surfaces), not the weather station wind speed; and (2) regression coefficients that are appropriate for use with near-surface wind speeds. (Window heat loss is reduced, resulting in a 38% reduction of the simulation engine difference.)

Implementing the proposed changes will improve the accuracy and consistency of window heating load calculations in EnergyPlus and DOE-2. (The combination of all the proposed changes addresses 82% of the original simulation engine difference. The remaining 18% is likely related to fundamental differences between interior radiation algorithms.)

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Appendix A. BEopt Automated Test Suite Description

The BEopt automated test suite results shown in Figures 1 and 2 were generated for a single-story house with a total of 144 ft^2 of window area distributed to each façade of the building as follows: North: 20%, East: 20%, South: 40%, and West: 20%. Thermal properties are shown in Table A-1.

Table A-1. Thermal Properties of the Windows Simulated in the BEopt Automated Test Suite

	Single Pane	Double Clear	Low-e Low SHGC arg	Low-e Standard SHGC arg	Low-e High SHGC arg	Low-e Very High SHGC arg
$U-factor$ $\left[\frac{Btu}{hr \cdot ft^2 \cdot R}\right]$	0.869	0.447	0.285	0.285	0.298	0.325
SHGC $[--]$	0.619	0.547	0.266	0.295	0.417	0.511

	Low-e Low SHGC	Low-e Standard SHGC	Low-e High SHGC	Low-e Very High SHGC	3 Pane, 1 HM	4 Pane, 2 HM Kr
$U-factor$ $\left[\frac{Btu}{hr \cdot ft^2 \cdot R}\right]$	0.318	0.318	0.325	0.352	0.257	.197
SHGC $[--]$	0.266	0.302	0.424	0.511	0.345	0.324

Appendix B. Simplified Test Case Description

Annual window heat loss results throughout this paper were generated using a simple test case. This test case consisted of a single room (8 ft × 8 ft × 8 ft [2.4 m × 2.4 m × 2.4 m]) with a single-pane window that is 15% of a single wall and 3.4 ft (1.4 m) from the floor (see Figure B-1). Therefore:

$$\begin{aligned} A_{wall} &= 8\ ft \times 8\ ft = 64\ ft^2 \\ A_{window} &= 0.15 \times A_{wall} = 9.6\ ft^2\ \left(3.6\ ft\ high \times 2.7\ ft\ wide\right) \\ A_{room,total} &= 6 \times A_{wall} - A_{window} = 374.4\ ft^2 \end{aligned} \tag{B.1}$$

Because the wall that contains the window does not exchange radiation with the window, the effective area of the room (that radiates to the window) is:

$$A_{room} = 5A_{wall} = 320\ ft^2 \tag{B.2}$$

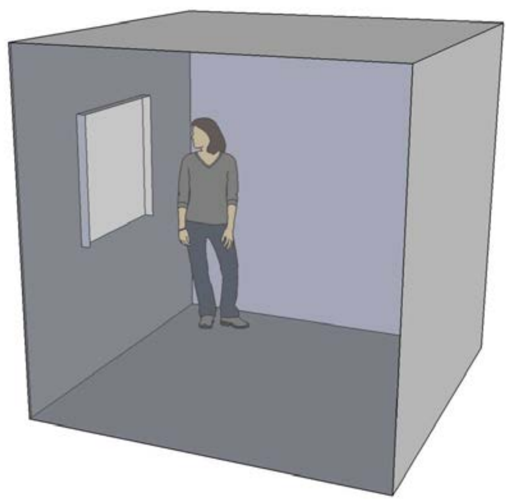

Figure B-1. Schematic of room model used for the simplified test case simulations

All the opaque surfaces (walls, floor, and ceiling) are modeled as adiabatic, massless surfaces. This simplifies the heat balance of the wall surfaces to have only radiative and convective components (i.e., there is no conductive component). The indoor temperature is controlled at 71°F (22°C).

Window heat loss was simulated using a Chicago weather file in TMY3 format (NREL 2010) and at a location with terrain that could be characterized as “urban, industrial or forest area” for the wind speed adjustment calculations. The heat loss calculated represents only the outward heat loss through the window and ignores transmitted and absorbed solar radiation. This is used to isolate the effects of convection and long-wave radiation in the model.

Appendix C. Interior Convection

Interior convection is modeled as natural convection for both DOE-2 and EnergyPlus.

C.1 EnergyPlus Algorithm

EnergyPlus uses the International Organization for Standards (ISO) 15099:2003 (ISO 2003) correlation to calculate the interior convection coefficient:

$$h_{c,int} = \frac{Nu \cdot \lambda}{H} \tag{C.1}$$

where

$$Nu = \begin{cases} 0.56 \cdot \left(Ra_H \cdot \sin\left(\frac{\phi}{2}\right)\right)^{1/4} & Ra_H \le Ra_{cv} \\ 0.13 \cdot (Ra_H^{1/3} - Ra_{cv}^{1/3}) + 0.56 \cdot \left(Ra_{cv} \cdot \sin(\frac{\phi}{2}))^{1/4} \right) & Ra_H > Ra_{cv} \end{cases} \tag{C.2}$$

where ϕ is the angle of the surface with respect to vertical (π is vertical) and

$$Ra_{cv} = 2.5 \times 10^5 \cdot \left(\frac{e^{0.72 \cdot \frac{\phi}{2}}}{\sin\left(\frac{\phi}{2}\right)} \right)^{1/5} \tag{C.3}$$

$$Ra_H = \frac{\rho^2 \cdot H^3 \cdot g \cdot c_P \cdot |T_{win} - T_{in}|}{T_{m,f} \cdot \mu \cdot \lambda} \tag{C.4}$$

$$T_{m,f} = T_{in} + \frac{T_{win} - T_{in}}{4} \tag{C.5}$$

$$\lambda = 2.873 \times 10^{-3} \left[\frac{W}{m \cdot K} \right] + 7.76 \times 10^{-5} \left[\frac{W}{m \cdot K^2} \right] \cdot T_{m,f} \tag{C.6}$$

$$\mu = 3.723 \times 10^{-6} \left[Pa \cdot s \right] + 4.94 \times 10^{-8} \left[\frac{Pa \cdot s}{K} \right] \cdot T_{m,f} \tag{C.7}$$

ρ and c_P are determined through standard psychrometric functions.

C.1.1 Proposed Changes to EnergyPlus

No changes are proposed.

C.2 DOE-2 Algorithm

The DOE-2 detailed model uses a correlation from Chapter 27 of the *1993 ASHRAE Handbook Fundamentals* (ASHRAE 1993):

$$h_{c,int} = 1.77\left[\frac{W}{m^2 \cdot K^{5/4}}\right] \cdot \Delta T^{1/4} \tag{C.8}$$

The resulting interior convection coefficient is then adjusted to account for non-vertical window tilts.

In the *1997 ASHRAE Handbook Fundamentals* (ASHRAE 1997), Eq. C.8 was replaced by a new correlation from Curcija and Goss (1995):

$$h_{c,int} = 1.46\left[\frac{W}{m^{7/4} \cdot K^{5/4}}\right] \cdot \left(\frac{\Delta T}{H}\right)^{1/4}, \tag{C.9}$$

which has a dependence on the height of the window.

C.2.1 Proposed Changes to DOE-2

The 1997 *ASHRAE Handbook* correlation shows very good agreement with the ISO correlation for most building applications (i.e., vertical windows with convection in the subcritical flow regime [$Ra_H \le Ra_{cv}$]). However, ISO provides the most complete correlation— accounting for window tilt, second-order temperature dependencies, and multiple buoyant flow regimes.

Comparisons of all three correlations are shown in Figure C-1. Given the very good agreement between the 1997 ASHRAE Handbook correlation, Eq. C.9, and the ISO correlation used by EnergyPlus, Eq. C.1–C.7, it is proposed to replace the 1993 ASHRAE Handbook correlation, Eq. C.8 with Eq. C.9. This requires updating the internal heat transfer coefficient correlation in LOADS subroutine FILMI line 19 to Eq. C.9. This will also require adding the window height, H , as an input to the subroutine FILMI and changing THERM line 67, which calls FILMI.

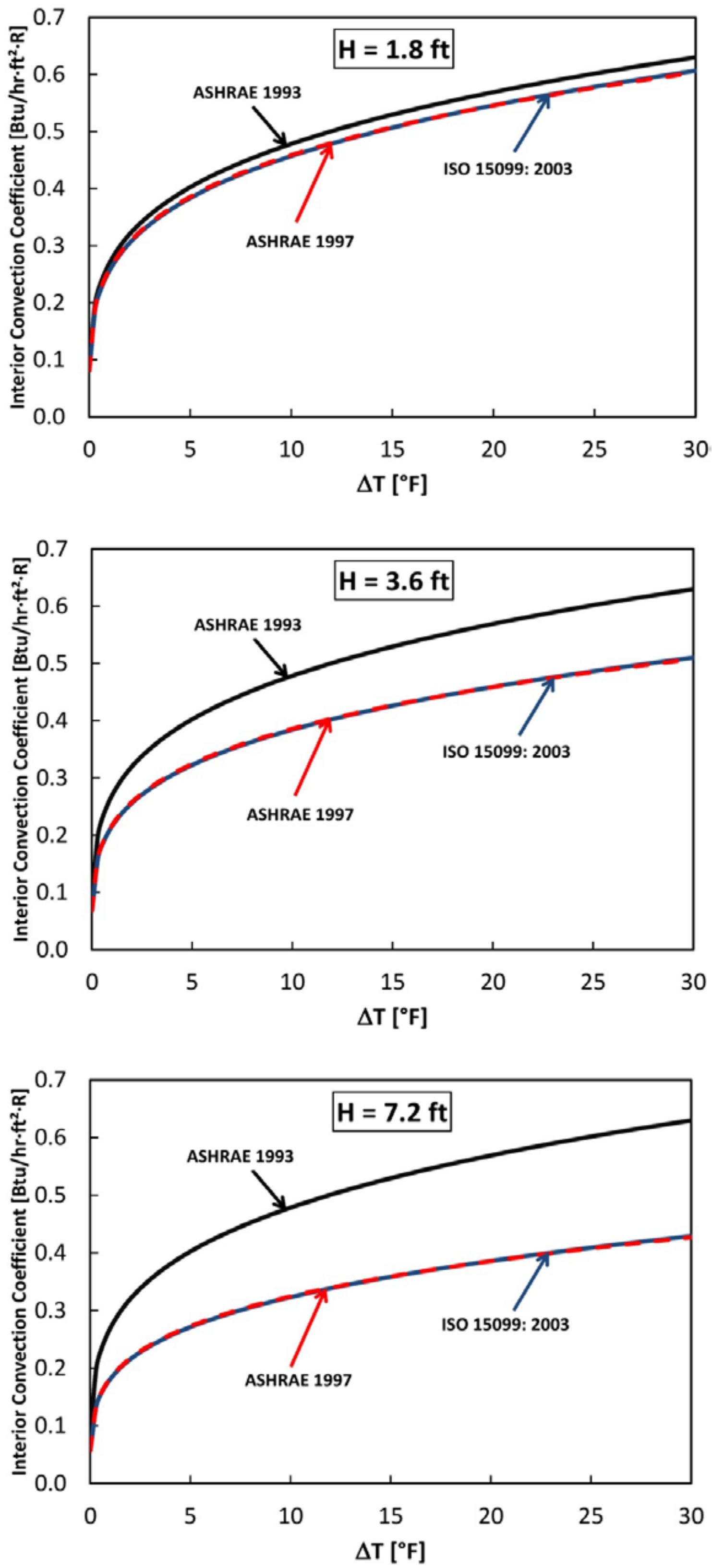

Figure C-1. Comparison of three interior convection heat transfer coefficient correlations for windows. EnergyPlus models use ISO 15099: 2003; the DOE-2 detailed model uses ASHRAE 1993.

Appendix D. Exterior Convection

Both DOE-2 and EnergyPlus describe an exterior total convection heat transfer coefficient as a quadratic summation of natural and forced convection components:

$$h_{c,ext,tot} = \sqrt{h_{c,ext,f}^2 + h_{c,ext,n}^2} \tag{D.1}$$

Both simulation engines implement the same correlation for the exterior natural convection heat transfer coefficient:

$$h_{c,ext,n} = C_t (\Delta T)^{\frac{1}{3}} \tag{D.2}$$

where C_t, for vertical surfaces, is a constant of $1.31\ W/m^2{\cdot}K^{\frac{4}{3}}$ $\left(0.19\ Btu/hr{\cdot}ft^2{\cdot}R^{\frac{4}{3}}\right)$, and ΔT is the magnitude of the temperature difference between the outside air and the outside window surface.

Because exterior natural convection coefficient is the same between the two simulation engines, this section will focus on describing the differences in the exterior forced convection heat transfer coefficients. For forced exterior convection, DOE-2 and EnergyPlus both reference the MoWiTT (Mobile Window Thermal Test facility) correlations put forth by Yazdanian and Klems (1994). Though the correlations in both simulation engines reference the same algorithm, it appears that neither interprets the original publication correctly. This section proposes a more accurate interpretation of the original publication that will make the respective algorithms more consistent.

The original MoWiTT correlation for exterior forced convection is

$$h_{c,ext,f} = aV^b \tag{D.3}$$

where a and b are constants defined in Table D-1, and V is the free-stream measured wind speed at the MoWiTT test site, 10 m above the ground.

According to Yazdanian and Klems (1994), the coefficients in Table D-1 were generated using a regression that correlates the forced convection coefficient to the wind speed measured at 10 m, $V_{M,ws}$ (not the wind speed near the window, $V_{M,win}$ in Figure D-1).

Table D-1. MoWiTT Forced Convection Regression Coefficients (Based on Wind Speed at 10 m)

(Yazdanian and Klems 1994)

SI Units:	$a\left[\frac{W}{m^2 \cdot K \cdot (m/s)^b}\right]$	b $[--]$
Windward	**2.38 ± 0.036**	**0.89 ± 0.009**
Leeward	**2.86 ± 0.098**	**0.617 ± 0.017**
IP Units:	$\left[\frac{Btu}{hr \cdot ft^2 \cdot R \cdot (mph)^b}\right]$	$[--]$
Windward	**0.203 ± 0.005**	**0.89 ± 0.01**
Leeward [11]	**0.335 ± 0.016**	**0.59 ± 0.017**

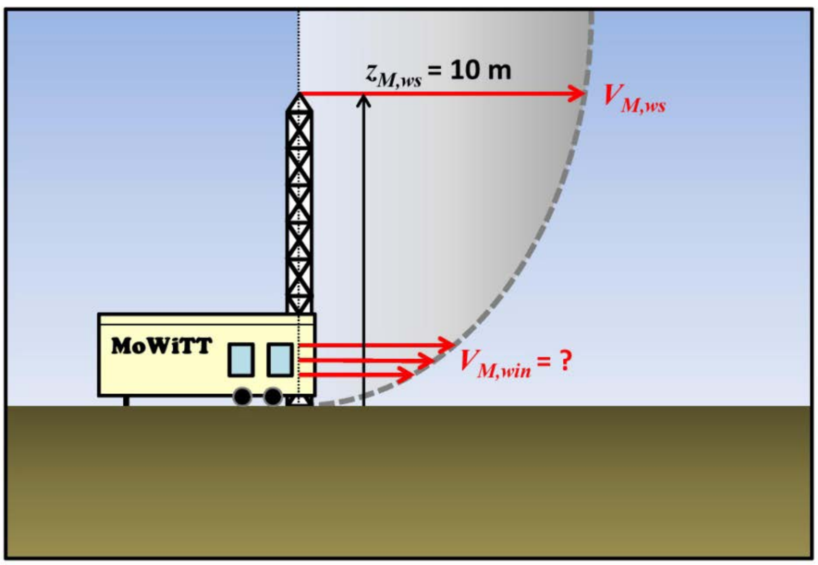

Figure D-1. Wind speed at the MoWiTT facility

In order to apply the MoWiTT correlation properly in the simulation engines, we will develop simulation engine-specific regression coefficients that (based on the physical characteristics of the MoWiTT test site and wind speeds as calculated in the simulation engines), will give the same external forced convection coefficients as in Yazdanian and Klems (1994). Then, the simulation engines (with the engine-specific coefficients) can be used with windows at different heights and in locations with different terrain correction parameters.

[11] The leeward values in IP units appear to be incorrect based on unit conversion inconsistency in the source document. The values are presented for reference only and are not used elsewhere in this report. Rather, leeward values in IP units are calculated by unit conversion from the SI values.

Based on the location of the MoWiTT facility on the University of Nevada, Reno campus, and the description and the photograph in Yazdanian and Klems (1994):

- The terrain is assumed to be classified as "urban, industrial or forest area" in Tables D-2 and D-5.
- The weather station height is 32.8 ft (10 m).
- The window centroid height (used to define the wind speed near the window in EnergyPlus) is assumed to be 6.6 ft (2 m).
- The space height (used to define the wind speed near the window in DOE-2) is assumed to be 10 ft (3.2 m).

D.1 EnergyPlus Algorithm

EnergyPlus uses the SI-unit regression coefficients from Table D-1—which were correlated to the free-stream wind speed at 32.8 ft (10 m)—with the estimated wind speed at the window centroid. Because the wind speed at the window centroid is always estimated to be lower than that measured at 32.8 ft (10 m), the calculated forced convection coefficient in EnergyPlus will always be less than that predicted in the original MoWiTT correlation.[12]

EnergyPlus, in general, estimates window-centroid wind speeds by adjusting the weather station wind speed as follows:

$$V_{win,centroid} = V_{ws}\left(\frac{\delta_{ws}}{z_{ws}}\right)^{\alpha_{ws}}\left(\frac{z_{win,centroid}}{\delta_{local}}\right)^{\alpha_{local}} \quad \text{(D.4)}$$

The terrain parameters δ_{ws}, δ_{local}, α_{ws} and α_{local} are given in Table D-2. z_{ws} and $z_{win,centroid}$ are the heights of the weather station and window centroid, respectively.

Table D-2. EnergyPlus Terrain Correction Parameters

(DOE 2010)

Terrain Description	δ [m]	α
Ocean or large body of water	210	0.1
Flat terrain with isolated obstacles	270	0.14
Flat terrain with isolated obstacles	370	0.22
Urban, industrial or forest area	370	0.22
Cities	460	0.33

D.1.1 Proposed Change to EnergyPlus

The proposed change to EnergyPlus is to derive coefficients that (when used with the EnergyPlus calculated window-centroid wind speeds) will give the same exterior forced convection coefficient as calculated by the MoWiTT correlation (when used with the wind speed at 32.8 ft

[12]This issue also applies to the exterior convection of opaque surfaces (walls, roofs, etc.).

[10 m]). The window-centroid wind speed in the MoWiTT situation, illustrated in Figure D-2,[13] can be estimated using Eq. D.4:

$$V_{M,win,centroid} = V_{M,ws}\left(\frac{\delta_{M,ws}}{z_{M,ws}}\right)^{\alpha_{M,ws}}\left(\frac{z_{M,win,centroid}}{\delta_{M,local}}\right)^{\alpha_{M,local}} \quad \text{(D.5)}$$

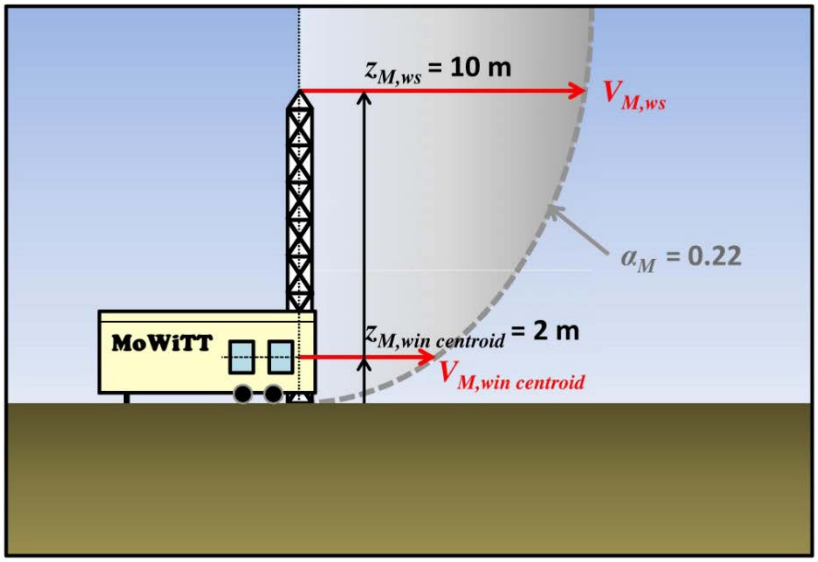

Figure D-2. EnergyPlus wind speed adjustment for the MoWiTT facility (window wind speed defined at the window-centroid height, as defined by EnergyPlus)

The MoWiTT weather station height, $z_{M,ws}$, is 32.8 ft (10 m); the window-centroid height, $z_{M,win,centroid}$, is assumed to be 6.6 ft (2 m). Since the weather station data for the MoWiTT tests were taken at the same site as the facility (assumed to be classified as "urban, industrial or forest area"), $\delta_{M,ws} = \delta_{M,local}$ and $\alpha_{M,ws} = \alpha_{M,local} = \alpha_M = 0.22$, giving us:

$$V_{M,win,centroid} = V_{M,ws}\left(\frac{z_{M,win,centroid}}{z_{M,ws}}\right)^{\alpha_{M,local}} = V_{M,ws}\left(\frac{2\ m}{10\ m}\right)^{0.22} = V_{M,ws}\cdot 0.702 \quad \text{(D.6)}$$

Next, we use Eq. (D.3) and introduce the new regression coefficient, a^*, to relate the forced convection coefficient, $h_{c,ext,f}$, to the window-centroid wind speed:

$$h_{c,ext,f} = aV^b = aV^b_{M,ws} = a^*V^b_{M,win,centroid} \quad \text{(D.7)}$$

The window-centroid wind speed correction from Eq. D.6 is substituted to give:

---

[13]Parameters evaluated at MoWiTT conditions are denoted by a subscript M (e.g., α_{ws} at MoWiTT conditions is $\alpha_{M,ws}$).

$$aV_{M,ws}^{b} = a^{*}\left(V_{M,ws} \cdot 0.702\right)^{b} \tag{D.8}$$

Equation D.8 simplifies to solve for a^{*}:

$$a^{*} = \frac{a}{0.702^{b}} \tag{D.9}$$

Equation D.9 has been evaluated for both windward and leeward window positions to give the proposed changes to the regression coefficients in Table D-3.

Table D-3. EnergyPlus Adjusted Forced Convection Regression Coefficients (for Use with Window-Height Local Wind Speeds)

SI Units:	a^{*} $\left[\frac{W}{m^{2} \cdot K \cdot (m/s)^{b}}\right]$	b $[--]$
Windward	3.26	0.89
Leeward	3.55	0.617

D.2 DOE-2 Algorithm

There are two issues related to exterior forced convection in DOE-2.

- Most significantly, DOE-2 incorrectly uses the weather station wind speed (instead of near-surface wind speed) to calculate the exterior forced convection coefficient. However, DOE-2 does correctly use near-surface wind speeds when calculating the exterior forced convection coefficient for other surfaces (e.g., walls, roofs, and even for windows using the simpler "SHADING-COEF" model).

- The regression coefficients, a and b, used in DOE-2 source code (Table D-4) are different from those listed in the original reference (Table D-1). Neither the coefficients from the source code nor the coefficients in Table D-1 are appropriate for use with the wind speed near the window.[14]

Table D-4. DOE-2 Forced Convection Regression Coefficients

IP Units:	a $\left[\frac{Btu}{hr \cdot ft^{2} \cdot R \cdot (knots)^{b}}\right]$	b $[--]$
Windward	0.289	0.89
Leeward	0.391	0.614

[14] This problem also applies to the exterior convection of opaque surfaces (e.g., walls, roofs).

In DOE-2, the wind speed near windows is calculated at the height of the space to which they belong, denoted $z_{space\ height}$. In general, the window-space wind speed is estimated by adjusting the weather station wind speed as follows:

$$V_{space\ height} = V_{ws}\left(TP1_{local}\left(\frac{z_{space\ height}}{32.8\ ft}\right)^{TP2_{local}}\right)\left(\frac{1}{TP1_{ws}}\left(\frac{32.8\ ft}{z_{ws}}\right)^{TP2_{ws}}\right) \qquad \text{(D.10)}$$

The terrain parameters $TP1_{local}$, $TP2_{local}$, $TP1_{ws}$ and $TP2_{ws}$ are given in Table D-5. z_{ws} and $z_{space\ height}$ are the heights of the weather station and window space, respectively.

Table D-5. DOE-2 Terrain Correction Parameters

(James J. Hirsch & Associates 2010)

Terrain Description	TP1	TP2
Ocean or large body of water	1.30	0.10
Flat terrain with isolated obstacles	1.00	0.15
Flat terrain with isolated obstacles	0.85	0.20
Urban, industrial or forest area	0.67	0.25
Cities	0.47	0.35

D.2.1 Proposed Change to DOE-2

The proposed change to DOE-2 to correct the issue of incorrectly using the weather station wind speed in the forced convection routine is to simply pass the window-space wind speed instead. This requires changing subroutine THERM line 74 to use WNDSPZ instead of WNDSPD when calling subroutine FILM2.

The proposed change to correct the regression coefficients for a more general application is to derive coefficients that (when used with the DOE-2 calculated window-space wind speeds) will give the same exterior forced convection coefficient as calculated by the MoWiTT correlation (when used with the wind speed at 32.8 ft [10 m]). This requires changing the windward and leeward coefficients in subroutine FILM2 line 63 and line 66, respectively.

This derivation begins by understanding the window-space wind speed in the MoWiTT situation, illustrated in Figure D-3,[15] can be estimated using Eq. D.11:

$$V_{M,space\ height} = V_{M,ws}\left(TP1_{M,local}\left(\frac{z_{M,space\ height}}{32.8\ ft}\right)^{TP2_{M,local}}\right)\left(\frac{1}{TP1_{M,ws}}\left(\frac{32.8\ ft}{z_{M,ws}}\right)^{TP2_{M,ws}}\right) \qquad \text{(D.11)}$$

[15]Parameters evaluated at MoWiTT conditions are denoted by a subscript M (e.g., α_{ws} at MoWiTT conditions is $\alpha_{M,ws}$)

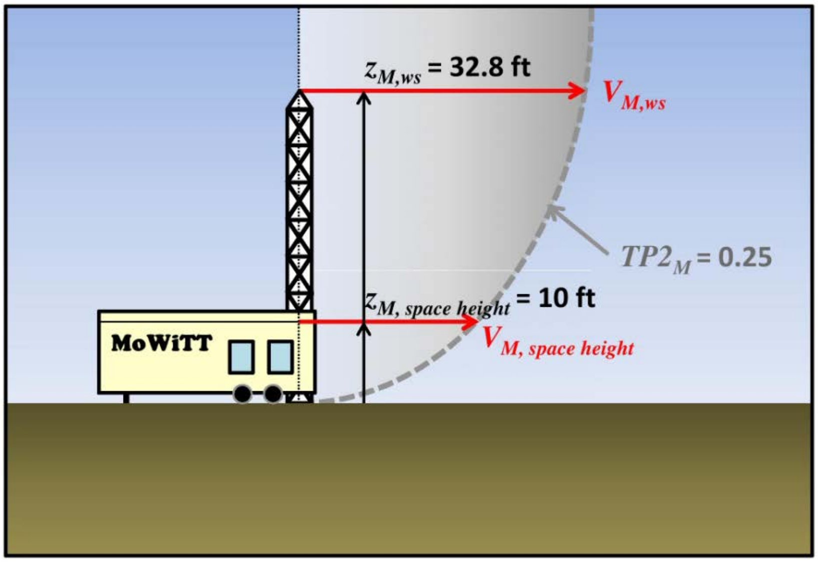

Figure D-3. DOE-2 wind speed adjustment for the MoWiTT facility (window wind speed defined at the window-space height, as defined by DOE-2)

The MoWiTT weather station height, $z_{M,ws}$, is 32.8 ft (10 m); the window-space height, $z_{M,space\ height}$, is assumed to be 10 ft (3.2 m). Because the weather station data for the MoWiTT tests were taken at the same site as the facility (assumed to be classified as "urban, industrial or forest area"), $TP1_{M,ws} = TP1_{M,space}$ and $TP2_{M,ws} = TP2_{M,space} = TP2_M = 0.25$, giving us:

$$V_{M,space\ height} = V_{M,ws}\left(\frac{z_{M,space\ height}}{z_{M,ws}}\right)^{TP2_M} = V_{M,ws}\left(\frac{3.2\ m}{10\ m}\right)^{0.25} = V_{M,ws} \cdot 0.752 \qquad \text{(D.12)}$$

Next, we use Eq. D.3 and introduce the new regression coefficient, a^*, to relate the forced convection coefficient, $h_{c,ext,f}$, to the window-space wind speed:

$$h_{c,ext,f} = aV^b = aV^b_{M,ws} = a^*V^b_{M,space\ height} \qquad \text{(D.13)}$$

The window-space wind speed correction from Eq. D.12 is substituted to give:

$$aV^b_{M,ws} = a^*\left(V_{M,ws} \cdot 0.752\right)^b \qquad \text{(D.14)}$$

Equation D.14 simplifies to solve for a^*:

$$a^* = \frac{a}{0.752^b} \qquad \text{(D.15)}$$

Equation D.15 has been evaluated for both windward and leeward window positions to give the proposed changes to the regression coefficients in Table D-6.

Table D-6. DOE-2 Adjusted Forced Convection Regression Coefficients (For Use with Window-Space Height Local Wind Speeds [in knots])

IP Units:	a^* $\left[\frac{Btu}{hr \cdot ft^2 \cdot R \cdot (knots)^b}\right]$	b $[--]$
Windward	0.299	0.89
Leeward	0.399	0.617

The adjusted forced convective heat transfer coefficients resulting from the proposed changes can be seen in Figure D-4. The two changes to DOE-2 are listed separately: (1) the adjustment to the space-height wind speed; and (2) adjustment plus the correction to the regression coefficients.

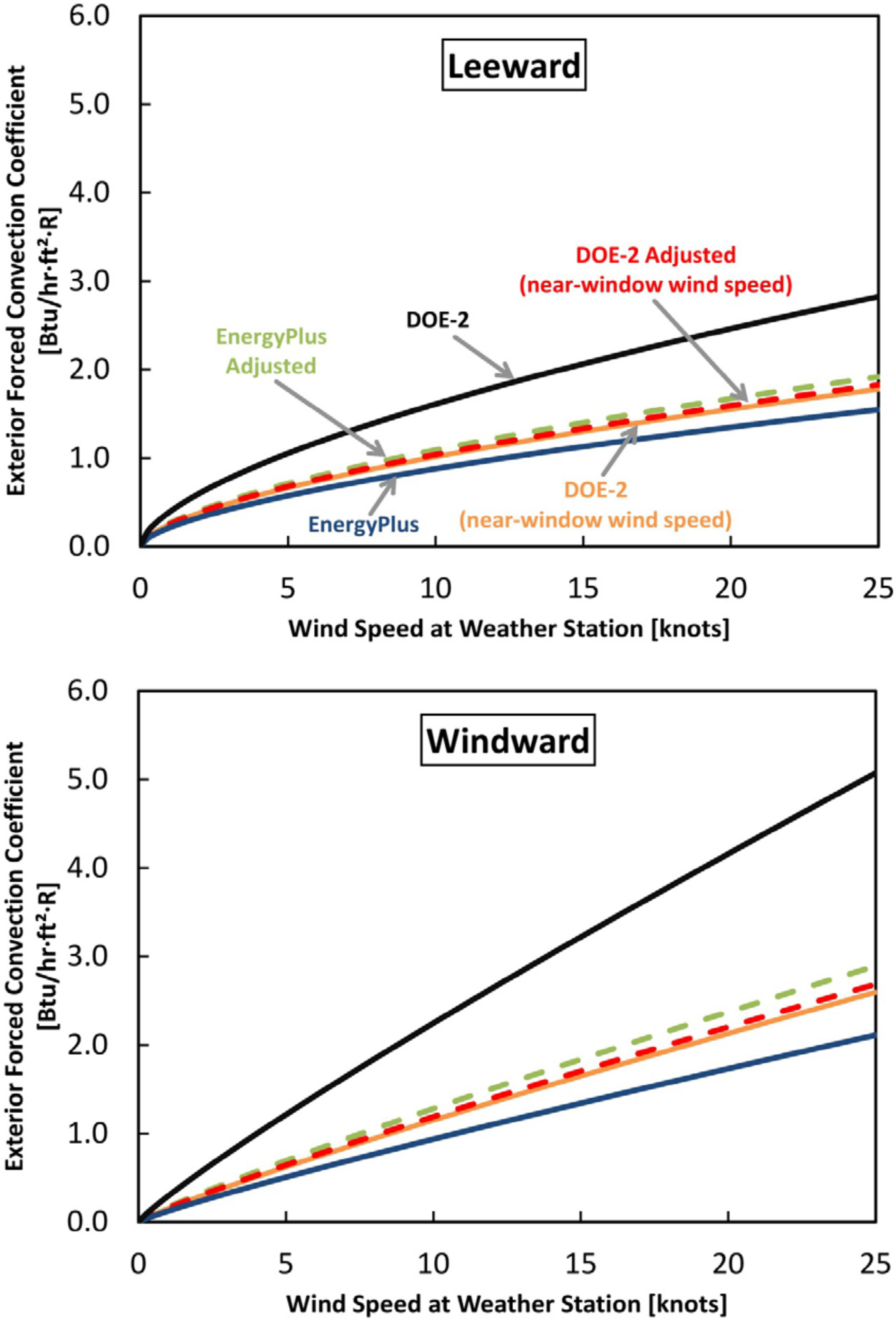

Figure D-4. Exterior forced convective heat transfer coefficient (for the window in the simplified test case [Appendix B]) with wind speed and regression coefficient corrections indicated

Appendix E. Interior Radiation

This appendix illustrates the differences between the DOE-2 and EnergyPlus models for interior radiation.

E.1 EnergyPlus Algorithm

EnergyPlus takes a physically fundamental approach to estimating heat radiated between windows and other surfaces in a zone. EnergyPlus employs a radiation matrix method called "Script F" developed by Hottel and Sarofim (1967).

E.1.1 Proposed Changes to EnergyPlus

No changes are proposed.

E.2 DOE-2 Algorithm

Interior radiation in DOE-2 is modeled as:

$$Q_{IR} = \varepsilon_{win} \sigma A_{win} \left(T_{win}^4 - T_{in}^4 \right) \tag{E.1}$$

which results in

$$h_{r,in} = \frac{Q_{IR}}{A_{win} \left(T_{win} - T_{in} \right)} = \frac{\sigma \varepsilon_{win} \left(T_{win}^4 - T_{in}^4 \right)}{\left(T_{win} - T_{in} \right)} \tag{E.2}$$

E.2.1 Proposed Changes to DOE-2

The interior radiation algorithms in DOE-2 and EnergyPlus use fundamentally different heat balance methodologies, and it would be a very involved effort to change DOE-2 to calculate the surface temperatures required to perform similar radiative exchange calculations to those of EnergyPlus. However, if an EnergyPlus-like algorithm is implemented in DOE-2 (as modeled in EES) the magnitude of the difference in window heat loss related to interior radiation can be illustrated as in the following section.

E.2.2 Impact of Using the EnergyPlus Interior Radiation Model in DOE-2

To evaluate the impact of the differences in the DOE-2 and EnergyPlus interior radiation algorithms, we investigate how the residual difference (3.3%) in Figure 3 would change if there were no differences in the interior radiation calculations, that is, if both simulation engines used an EnergyPlus-like algorithm modeled in EES. Due to complexity, the "Script F" method from EnergyPlus was not exactly reproduced in the EES representation. Instead, a simple approximation,[16] based on Duffie and Beckman (2006), is used to represent the radiative transfer between the window and the other surfaces of the room.[17] Because no surface radiates to itself, the wall that contains the window is not considered when calculating the view factor from the window to the room surfaces in either program. Hence the view factor from the window to the

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[16]This approximation was also part of the EES model used to calculate the results in Section 3.

[17]All room surfaces are assumed to be the same temperature, which is reasonable in the simplified test case where all the surfaces are assumed to be adiabatic.

other surfaces of the room, $F_{win,room}$, is unity (=1). The EES representation of the EnergyPlus model has net heat transfer from the window to the room surfaces of:

$$Q_{IR} = \frac{\sigma\left(T_{win}^4 - T_{room}^4\right)}{\frac{1-\varepsilon_{win}}{\varepsilon_{win} A_{win}} + \frac{1}{A_{win} F_{win \to room}} + \frac{1-\varepsilon_{room}}{\varepsilon_{room} A_{room}}} \tag{E.3}$$

An energy balance at the room surfaces (assuming the surfaces are adiabatic and the same temperature) is calculated based on the fact that the heat radiated from the window to the room surfaces equals the heat convected from the room surfaces to the air:

$$Q_{IR} = Q_{c,room} = h_{c,room \to air} A_{room,total} \left(T_{room} - T_{in}\right) \tag{E.4}$$

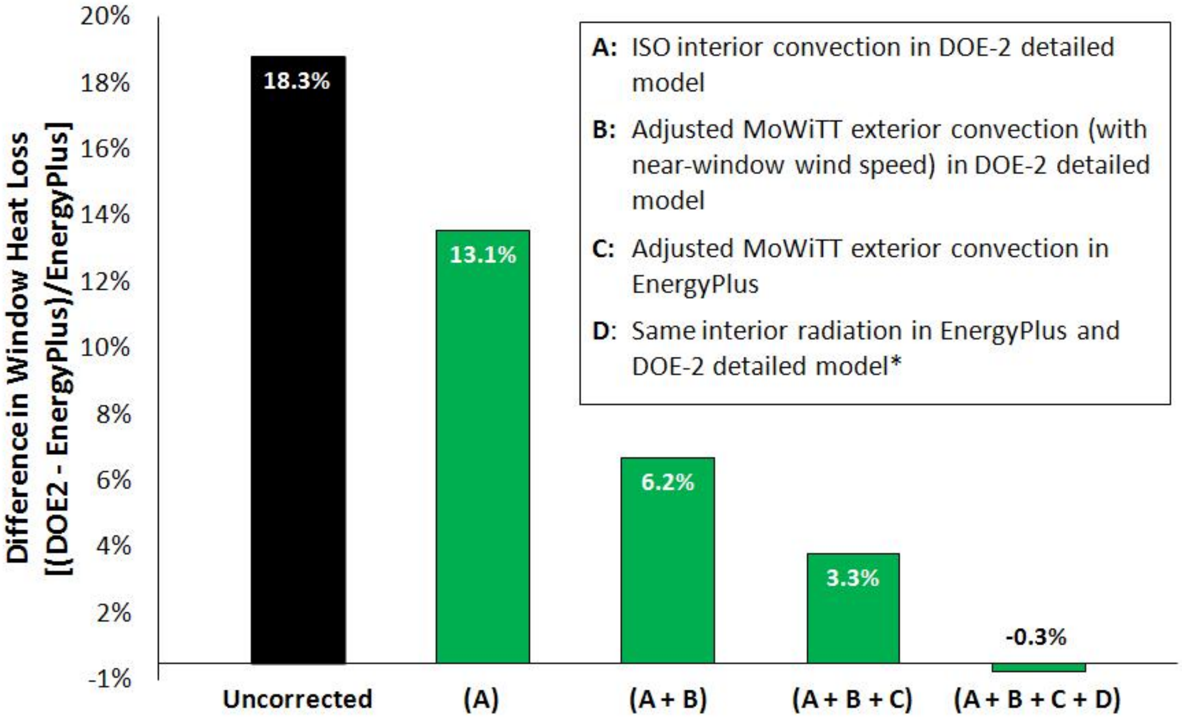
where

$$h_{c,room \to air} = 1.31 \,|\, T_{room} - T_{in} \,|^{1/3} \tag{E.5}$$

The coefficient 1.31 is a dimensional constant with units of $W/m^2 \cdot K^{\frac{4}{3}}$.

The final bar in Figure E-1 shows the estimated impact if DOE-2 and EnergyPlus were to use the same interior radiation algorithm. The final result of 0.3% indicates that the difference in the interior radiation models appears to account for nearly all of the remaining difference (after both simulation engines use corrected convection algorithms).

The EnergyPlus algorithm is clearly more detailed and likely to be more accurate across a wide range of conditions. However, using the same algorithm in DOE-2 would require a fundamental reworking of the source code to calculate the zone energy balance and surface temperatures. Therefore, interior radiation is not included with the other proposed changes in Section 3. The results are presented here simply to indicate possible closure when all window heat transfer mechanisms are evaluated.



*These results show the impact of using EnergyPlus-like zone radiation exchange in EnergyPlus and DOE-2 (modeled in EES). DOE-2 does not currently calculate the zone energy balance and interior temperatures of opaque surfaces that would be needed to implement the EnergyPlus radiative exchange algorithm.

Figure E-1. Estimated cumulative impacts of the proposed changes listed in Section 1 plus use of an EnergyPlus -like interior radiation algorithm in EnergyPlus and DOE-2 (on single-pane window heat loss modeled in EES for the simplified test case with Chicago TMY3 weather file)

Appendix F. Exterior Radiation

The calculated exterior radiation in EnergyPlus and DOE-2 are essentially identical. The only difference is in the way the calculations are performed. In both simulation engines surfaces radiate to the sky, air, and ground temperatures (though the ground is assumed to be the same temperature as the ambient air). In EnergyPlus, each portion of the radiation is calculated explicitly to the respective temperatures (see DOE 2010). DOE-2 has a two-step process of calculating the exterior radiation heat transfer coefficients first, assuming radiation to the ambient air temperature only and then applying a correction factor to account for radiation to the sky and ground based on Walton (1983). This is essentially a “patch" for correcting the radiation heat transfer (although not the reported radiation heat transfer coefficient, $h_{r,out}$ or the reported overall conductance of the window, UW) to be the same as EnergyPlus and Walton.

A simple method for implementing the correction from Walton is presented as an alternative to the current DOE-2 approach. The alternative approach in DOE-2 is to move the correction for radiation into the calculation for $h_{r,out}$. This will correctly implement the change from Walton (1983) when calculating the external radiative heat transfer and heat transfer coefficient as well as the overall heat transfer rate.

F.1 EnergyPlus Algorithm

EnergyPlus calculates radiation to the sky, air, and ground temperatures, though the ground is assumed to be the same temperature as the ambient air (DOE 2010).

The total infrared radiation from the window is defined as the total absorbed infrared radiation from the sky, air, and ground, minus the total infrared radiation emitted by the window:

$$q_{IR} = q_{IR,abs} - q_{IR,em} \tag{F.1}$$

where the incident infrared radiation is

$$q_{IR,abs} = \varepsilon_{win}\sigma\left(F_{sky,partial}T_{sky}^4 + F_{air}T_{air}^4 + F_{gnd}T_{gnd}^4\right) \tag{F.2}$$

and the emitted infrared radiation is

$$q_{IR,em} = \varepsilon_{win}\sigma T_{win}^4. \tag{F.3}$$

The view factors are

$$\begin{aligned}
F_{gnd} &= 0.5\left(1-\cos(\phi)\right) \\
F_{air} &= 0.5\left(1+\cos(\phi)\right)\left(1-\beta\right) \equiv F_{sky}\left(1-\beta\right) \\
F_{sky,partial} &= 0.5\left(1+\cos(\phi)\right)\beta \equiv F_{sky}\beta \\
1 &= F_{gnd} + F_{air} + F_{sky,partial} \equiv F_{gnd} + F_{sky}
\end{aligned} \tag{F.4}$$

where ϕ is the tilt of the window, and

$$\beta = \sqrt{\frac{1}{2}(1+\cos\phi)} = \cos\left(\frac{\phi}{2}\right) \tag{F.5}$$

The sky temperature, T_{sky}, in Eq. F.2 is given by

$$T_{sky} = \varepsilon_{sky}^{1/4} T_{out} \tag{F.6}$$

where the sky emissivity, ε_{sky}, is

$$\varepsilon_{sky} = (0.787 + 0.764 \ln \frac{T_{dewpoint}}{T_{out}} (1 + 0.0224 f_c - 0.0035 f_c^2 + 0.00028 f_c^3) \tag{F.7}$$

where f_c is the cloud cover fraction and is obtained from the input weather file.

The air and ground temperatures are assumed equal to T_{out}, and Eqs. F.6 and F.4 can be substituted into Eq. F.2:

$$\begin{aligned} q_{IR,abs} &= \varepsilon_{win}\sigma\left(F_{sky}\beta\varepsilon_{sky}T_{out}^4 + F_{sky}(\beta-1)T_{out}^4 + F_{gnd}T_{out}^4\right) \\ &= \varepsilon_{win}\sigma T_{out}^4\left(F_{sky}\beta\varepsilon_{sky} + F_{sky}(\beta-1) + F_{gnd}\right) \\ &= \varepsilon_{win}\sigma T_{out}^4\left(F_{sky}\beta\left(\varepsilon_{sky}-1\right) + F_{sky} + F_{gnd}\right) \\ &= \varepsilon_{win}\sigma T_{out}^4\left(F_{sky}\beta\left(\varepsilon_{sky}-1\right) + 1\right) \end{aligned} \tag{F.8}$$

For simplicity, we define

$$F^* = F_{sky}\beta\left(\varepsilon_{sky}-1\right) + 1 \tag{F.9}$$

such that Eq. F.8 becomes

$$q_{IR,abs} = \varepsilon_{win}\sigma T_{out}^4 \cdot F^* \tag{F.10}$$

Substituting back into Eq. F.1, we arrive at

$$q_{IR} = \varepsilon_{win}\sigma\left(T_{win}^4 - T_{out}^4 F^*\right) \tag{F.11}$$

F.1.1 Proposed Changes to EnergyPlus

No changes are proposed.

F.2 DOE-2 Algorithm

DOE-2 has a two-step process for calculating window external radiation. It calculates external radiation heat transfer coefficients first, assuming radiation to the ambient air temperature only. It then applies a correction when calculating total conduction through the window to account for radiation to the sky and ground based on Walton (1983). This is essentially a "patch" for correcting the radiation heat transfer (although not the reported radiation heat transfer coefficient, $h_{r,out}$, or the reported overall conductance of the window, UW) to be the same as EnergyPlus and Walton (1983).

DOE-2 begins the radiation heat transfer calculations similarly to EnergyPlus. In subroutine FLUXES, line 22

$$h_{r,out} = \frac{\sigma T_{out}^4 - \left(\varepsilon_{win}\sigma T_{win}^4 + (1-\varepsilon_{win})T_{out}^4\right)}{T_{out} - T_{win}} \tag{F.12}$$

where $(1-\varepsilon_{win})T_{out}^4$ represents the reflected infrared radiation.

The exterior radiative and convective heat transfer coefficients can be combined to obtain

$$R_o = \frac{1}{h_{out}} = \frac{1}{h_{r,out} + h_{c,out}}. \tag{F.13}$$

This is used along with the interior heat transfer coefficient, h_{in}, and the effective heat transfer coefficient through the window, U_{win}, to calculate the overall heat transfer coefficient, UW

$$\frac{1}{UW} = \frac{1}{h_{out}} + \frac{1}{U_{win}} + \frac{1}{h_{in}} \tag{F.14}$$

UW Overall window conductance (between indoor and outdoor air temperatures) U_{win} Conductance of the glazing system (not including interior and exterior coefficients)

In subroutine CALWIN line 83, DOE-2 calculates the correction to the infrared radiation incident on the window due to radiation to the sky, ambient air and ground temperatures, $QIRWI$, citing Walton (1983).

$$QIRWI = \varepsilon\sigma T_{out}^4\left(1 - F_{sky}\left(1-\cos\left(\frac{\phi}{2}\right)\left(1-\varepsilon_{sky}\right)\right) - F_{gnd}\right) \tag{F.15}$$

This is simplified by substituting Eq. F.5 and rearranging:

$$
\begin{aligned}
QIRWI &= \varepsilon_{win}\sigma T_{out}^4\left(1 - F_{sky}\left(1-\beta\left(1-\varepsilon_{sky}\right)\right) - F_{gnd}\right) \\
&= \varepsilon_{win}\sigma T_{out}^4\left(1 - \left(F_{sky} + F_{sky}\beta\left(\varepsilon_{sky}-1\right) + F_{gnd}\right)\right) \\
&= \varepsilon_{win}\sigma T_{out}^4\left(1 - \left(F_{sky}\beta\left(\varepsilon_{sky}-1\right) + 1\right)\right) \\
&= \varepsilon_{win}\sigma T_{out}^4\left(1 - F^*\right) \\
&= \varepsilon_{win}\sigma T_{out}^4 - q_{IR,abs}
\end{aligned}
\tag{F.16}
$$

$QIRWI$ is used in subroutine CALWIN line 626 as a "patch" to modify the heat transfer through the window, Q_{con}, calculated using UW (and therefore $h_{r,out}$):

$$
\begin{aligned}
Q_{con} &= A_{win}\left(UW\left(T_{out} - T_{in}\right) - R_o \cdot UW \cdot QIRWI\right) \\
&= A_{win}\left(UW\Delta T - R_o \cdot UW \cdot QIRWI\right)
\end{aligned}
\tag{F.17}
$$

The term $R_o \cdot UW$ represents the fraction of $QIRWI$ that flows inward from the outer surface of the window. Note that the "patch" adjusts the overall heat transfer, Q_{con}, but does not adjust components such as external thermal resistance, R_o, or overall heat transfer coefficient, UW. Proof that Eq. F.17 results in the same exterior radiative heat transfer as the algorithm in EnergyPlus is given in Section F.2.2.

Note that absorbed solar radiation is not included in the equations presented here, but is included in the DOE-2 source code. It was intentionally ignored to avoid confusion in this derivation.

F.2.1 Proposed Changes to DOE-2

Though both simulation engines effectively calculate the same external radiation, a simple method for implementing the correction from Walton is presented as an alternative to the current DOE-2 approach. The proposed change to DOE-2 is to move the correction for radiation into the calculation for $h_{r,out}$. This will correctly implement the change from Walton when calculating heat transfer coefficients as well as the overall heat transfer rates for external radiation. This correction requires $h_{r,out}$ to be defined as

$$
h_{r,out} = \frac{\varepsilon_{win}\sigma\left(T_{win}^4 - T_{out}^4 F^*\right)}{T_{win} - T_{out}}
\tag{F.18}
$$

and changing subroutine CALWIN line 83 to be

$$
Q_{con} = A_{win} UW\left(T_{in} - T_{out}\right).
\tag{F.19}
$$

F.2.2 Proof of Equivalence of DOE-2 Exterior Radiation Calculation to EnergyPlus

It is not obvious that Eq. F.17 results in the same exterior radiative heat transfer as the algorithm in EnergyPlus. To prove that they are equivalent, we begin by assuming that the heat transfer coefficients relevant to exterior radiation in DOE-2 and EnergyPlus are not equal, but the other heat transfer coefficients, $h_{r,in}$, $h_{c,in}$, $h_{c,out}$, and U_{win}, which are not directly related to exterior radiation, are equal in EnergyPlus and DOE-2.

Next, we acknowledge that the heat conducted through the window, q_{con}, is equal to the heat transferred from the window to the exterior environment, q_{out}:

$$q_{con} = q_{out} = h_{out,T}\left(T_{win} - T_{out}\right) \tag{F.20}$$

where $h_{out,T}$ is the true combined (radiative and convective) exterior heat transfer coefficient as defined in EnergyPlus (DOE 2010) and Walton (1983).

Define the true overall window conductance as:

$$UW_T = \frac{q_{con}}{\left(T_{in} - T_{out}\right)} = \frac{h_{out,T}\left(T_{win} - T_{out}\right)}{\left(T_{in} - T_{out}\right)} \tag{F.21}$$

Note that this implies

$$\begin{aligned}\left(T_{in} - T_{out}\right) &= \frac{h_{out,T}}{UW_T}\left(T_{win} - T_{out}\right)\\ \left(T_{win} - T_{out}\right) &= \frac{UW_T}{h_{out,T}}\left(T_{in} - T_{out}\right)\end{aligned} \tag{F.22}$$

Then the heat conduction through the window in Eq. F.20 becomes

$$q_{con} = UW_T\left(T_{in} - T_{out}\right) = h_{out,T}\left(T_{win} - T_{out}\right) \tag{F.23}$$

Divide Eq. F.23 by UW

$$\frac{q_{con}}{UW} = \frac{h_{out,T}\left(T_{win} - T_{out}\right)}{UW} \tag{F.24}$$

Substitute Eq F.22 and multiply by h_{out}

$$q_{con}\frac{h_{out}}{UW} = \frac{h_{out}UW_T}{UW}\left(T_{in} - T_{out}\right) \tag{F.25}$$

We note that by definition,

$$\begin{aligned}\frac{1}{UW}-\frac{1}{UW_T} &= \left(\frac{1}{h_{out}}+\frac{1}{U_{win}}+\frac{1}{h_{in}}\right)-\left(\frac{1}{h_{out,T}}+\frac{1}{U_{win}}+\frac{1}{h_{in}}\right)\\ &= \frac{1}{h_{out}}-\frac{1}{h_{out,T}}\\ &= \frac{h_{r,out,T}-h_{r,out}}{h_{out,T}h_{out}}\end{aligned} \tag{F.26}$$

which can be rearranged and multiplied by h_{out} to give

$$\frac{h_{out}}{UW}=\frac{h_{out}}{UW_{EP}}+\frac{\left(h_{r,out,T}-h_{r,out}\right)}{h_{out,T}} \tag{F.27}$$

This can be substituted into the right hand side of Eq. F.25

$$\begin{aligned}q_{con}\frac{h_{out}}{UW} &= \left(\frac{h_{out}}{UW_T}+\frac{\left(h_{r,out,T}-h_{r,out}\right)}{h_{out,T}}\right)UW_T\left(T_{in}-T_{out}\right)\\ &= \left(h_{out}+\frac{UW_T\left(h_{r,out,T}-h_{r,out}\right)}{h_{out,T}}\right)\left(T_{in}-T_{out}\right)\end{aligned} \tag{F.28}$$

Next, split h_{out} into convective and radiative components

$$q_{con}\frac{h_{out}}{UW}=\left(h_{c,out}+h_{r,out}+\frac{UW_T\left(h_{r,out,T}-h_{r,out}\right)}{h_{out,T}}\right)\left(T_{in}-T_{out}\right) \tag{F.29}$$

Factor out $\frac{UW_T}{h_{out,T}}$ from $h_{r,out}$ and the third term in parenthesis:

$$\begin{aligned}q_{con}\frac{h_{out}}{UW} &= \left(h_{c,out}+\frac{UW_T}{h_{out,T}}\left(\frac{h_{r,out}h_{out,T}}{UW_T}+h_{r,out,T}-h_{r,out}\right)\right)\left(T_{in}-T_{out}\right)\\ &= \left(h_{c,out}+\frac{UW_T}{h_{out,T}}\left(h_{r,out,T}+h_{r,out}\left(\frac{h_{out,T}}{UW_T}-1\right)\right)\right)\left(T_{in}-T_{out}\right)\end{aligned} \tag{F.30}$$

We note that

$$\begin{aligned}\frac{h_{out,T}}{UW_T}-1 &= h_{out,T}\left(\frac{1}{h_{out,T}}+\frac{1}{U_{win}}+\frac{1}{h_{in}}\right)-\frac{h_{in}U_{win}}{h_{in}U_{win}} \\ &= h_{out,T}\left(\frac{h_{out,T}h_{in}+h_{out,T}U_{win}+h_{in}U_{win}}{h_{out,T}U_{win}h_{in}}\right)-\frac{h_{in}U_{win}}{h_{in}U_{win}} \\ &= \frac{h_{out,T}h_{in}+h_{out,T}U_{win}}{h_{in}U_{win}}\end{aligned} \tag{F.31}$$

Equation F.31 can be substituted into Eq. F.30:

$$q_{con}\frac{h_{out}}{UW} = \left(h_{c,out}+\frac{UW_T}{h_{out,T}}\left(h_{r,out,T}+h_{r,out}\left(\frac{h_{out,T}h_{in}+h_{out,T}U_{win}}{h_{in}U_{win}}\right)\right)\right)(T_{in}-T_{out}) \tag{F.32}$$

Now distribute $(T_{in}-T_{out})$ and rearrange the second term in parenthesis

$$\begin{aligned}q_{con}\frac{h_{out}}{UW} = {} & h_{c,out}(T_{in}-T_{out}) \\ & +\frac{UW_T}{h_{out,T}}\left(h_{r,out,T}+h_{r,out}\left(\frac{h_{out,T}h_{in}+h_{out,T}U_{win}}{h_{in}U_{win}}\right)\right)(T_{in}-T_{out}) \\ = {} & h_{c,out}(T_{in}-T_{out})+\frac{UW_T}{h_{out,T}}\left(h_{r,out,T}+h_{r,out}h_{out,T}\left(\frac{h_{in}+U_{win}}{h_{in}U_{win}}\right)\right)(T_{in}-T_{out})\end{aligned} \tag{F.33}$$

Substitute for $(T_{in}-T_{out})$ in the second term based on Eq. F.22

$$q_{con}\frac{h_{out}}{UW} =$$

$$h_{c,out}\left(T_{in}-T_{out}\right)+\frac{UW_T}{h_{out,T}}\left(h_{r,out,T}+h_{r,out}h_{out,T}\left(\frac{h_{in}+U_{win}}{h_{in}U_{win}}\right)\right)\frac{h_{out,T}}{UW_{EP}}\left(T_{win}-T_{out}\right)$$

$$= h_{c,out}\left(T_{in}-T_{out}\right)+\left(h_{r,out,T}+h_{r,out}h_{out,T}\left(\frac{h_{in}+U_{win}}{h_{in}U_{win}}\right)\right)\left(T_{win}-T_{out}\right) \tag{F.34}$$

$$= h_{c,out}\left(T_{in}-T_{out}\right)+h_{r,out,T}\left(T_{win}-T_{out}\right)+h_{r,out}h_{out,T}\left(\frac{h_{in}+U_{win}}{h_{in}U_{win}}\right)\left(T_{win}-T_{out}\right)$$

Use the definition of $h_{r,out,T}$ (from Walton [1983]),

$$h_{r,out,T} = \frac{\varepsilon\sigma\left(T_{win}^4-T_{out}^4F^*\right)}{\left(T_{win}-T_{out}\right)}, \tag{F.35}$$

and the definition of $h_{r,out}$ (from DOE-2),

$$h_{r,out} = \frac{\varepsilon\sigma\left(T_{win}^4-T_{out}^4\right)}{\left(T_{win}-T_{out}\right)}, \tag{F.36}$$

and substitute into F.34:

$$q_{con}\frac{h_{out}}{UW} =$$

$$h_{c,out}\left(T_{in}-T_{out}\right)+\varepsilon\sigma\left(T_{win}^4-T_{out}^4F^*\right)+\left(\frac{h_{out,T}h_{in}+h_{out,T}U_{win}}{h_{in}U_{win}}\right)\varepsilon\sigma\left(T_{win}^4-T_{out}^4\right) \tag{F.37}$$

Equation F.31 can be substituted again (in reverse), followed by distributing terms:

$$q_{con}\frac{h_{out}}{UW} = \quad h_{c,out}\left(T_{in}-T_{out}\right)+\varepsilon\sigma\left(T_{win}^4-T_{out}^4F^*\right)+\left(\frac{h_{out,T}}{UW_T}-1\right)\varepsilon\sigma\left(T_{win}^4-T_{out}^4\right)$$

$$= \quad h_{c,out}\left(T_{in}-T_{out}\right)+\varepsilon\sigma\left(T_{win}^4-T_{out}^4F^*\right)+\left(\frac{h_{out,T}}{UW_T}\right)\varepsilon\sigma\left(T_{win}^4-T_{out}^4\right) - \varepsilon\sigma\left(T_{win}^4-T_{out}^4\right) \tag{F.38}$$

Terms can be rearranged to be:

$$q_{con}\frac{h_{out}}{UW}=h_{c,out}\left(T_{in}-T_{out}\right)+\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)+\left(\frac{h_{out,T}}{UW_{T}}\right)\varepsilon\sigma\left(T_{win}^{4}-T_{out}^{4}\right) \quad \text{(F.39)}$$

Isolate q_{con}:

$$q_{con}=\frac{UW}{h_{out}}\left(h_{c,out}\left(T_{in}-T_{out}\right)+\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)+\left(\frac{h_{out,T}}{UW_{T}}\right)\varepsilon\sigma\left(T_{win}^{4}-T_{out}^{4}\right)\right) \quad \text{(F.40)}$$

Then substitute $R_o=\frac{1}{h_{out}}$, change the sign on the second term and multiply the last term by $\frac{T_{win}-T_{out}}{T_{win}-T_{out}}(=1)$:

$$q_{con}= R_oUW\left(h_{c,out}\left(T_{in}-T_{out}\right)-\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)+\left(\frac{h_{out,T}}{UW_{T}}\right)\varepsilon\sigma\left(T_{win}^{4}-T_{out}^{4}\right)\left(\frac{T_{win}-T_{out}}{T_{win}-T_{out}}\right)\right) \quad \text{(F.41)}$$

Substitute $h_{r,out}$ for using the definition in Eq. F.36:

$$q_{con}=R_oUW\left(h_{c,out}\left(T_{in}-T_{out}\right)-\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)+\left(\frac{h_{out,T}}{UW_{T}}\right)h_{r,out}\left(T_{win}-T_{out}\right)\right) \quad \text{(F.42)}$$

Using Eq. F.22, substitute for the last term

$$q_{con}=R_oUW\left(h_{c,out}\left(T_{in}-T_{out}\right)-\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)+h_{r,out}\left(T_{in}-T_{out}\right)\right) \quad \text{(F.43)}$$

Combine the convective and radiative components

$$\begin{aligned} q_{con} &= R_oUW\left(h_{out}\left(T_{in}-T_{out}\right)-\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)\right) \\ &= UW\left(T_{in}-T_{out}\right)-R_oUW\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right) \end{aligned} \quad \text{(F.44)}$$

Multiply by area, A_{win},

$$\begin{aligned} Q_{con} &= A_{win}\left(UW\left(T_{in}-T_{out}\right)-R_oUW\varepsilon\sigma T_{out}^{4}\left(1-F^{*}\right)\right) \\ &= A_{win}\left(UW\Delta T-R_o\cdot UW\cdot QIRWI\right) \end{aligned} \quad \text{(F.45)}$$

Equation F.45 is identical to Eq. F.17, thus proving that the DOE-2 correction to heat conduction through windows due to radiation to the sky, ambient air and ground rather than just ambient air is the same as EnergyPlus. However, it is important to note that the calculated exterior radiative heat transfer rate, q_{IR}, and associated heat transfer coefficient, $h_{r,out}$, are not corrected.

Appendix G. Summary of Proposed Changes in DOE-2 Source Code

G.1 Interior Convection

Adding window height dependence to the interior convection coefficient, hc, requires updating the internal heat transfer coefficient correlation in LOADS subroutine FILMI line 19 from:

$$hc = 1.77 * adelt^{0.25} \tag{G.1}$$

to

$$hc = 1.46 * \left(\frac{adelt}{white} \right)^{0.25} \tag{G.2}$$

This will also require adding the window height, $white$, as an input to the subroutine FILMI line 2 and changing:

$$subroutine filmi(tout, tair, t, tilt, hf, dhf, hc, adelt) \tag{G.3}$$

to

$$subroutine filmi(tout, tair, t, tilt, hf, dhf, hc, adelt, white) \tag{G.4}$$

FILMI is called by THERM line 67 which will need to be changed from:

$$\begin{aligned} &call filmi(tout, tin, thetas(nface), tilt, \\ &hf(nface), dhf(nface, nlayer), hcin, adelt) \end{aligned} \tag{G.5}$$

to

$$\begin{aligned} &call filmi(tout, tin, thetas(nface), tilt, \\ &hf(nface), dhf(nface, nlayer), hcin, adelt, white) \end{aligned} \tag{G.6}$$

G.2 Exterior Convection

The proposed change to DOE-2 to correct the issue of incorrectly using the weather station wind speed, ($wndspd$), in the forced convection routine is to simply pass the window-space wind speed, ($wndspz$), instead. This requires changing subroutine THERM line 74 from:

$$call film2(tsr, toutr, tltrad, emis(1), 6, wndspd, mdir, hcout, dum) \tag{G.7}$$

to

$$call film2(tsr, toutr, tltrad, emis(1), 6, wndspz, mdir, hcout, dum) \tag{G.8}$$

The proposed change to correct the regression coefficients for a more general application is to derive coefficients that (when used with the DOE-2 calculated window-space wind speed) will give the same exterior forced convection coefficient as calculated by the MoWiTT correlation (when used with the wind speed at 32.8 ft [10 m]). This requires changing the windward and leeward coefficients in subroutine FILM2 line 63 and line 66, respectively from:

WINDWARD

$$hcforc = 0.289*(wspdk)**0.89$$

else

LEEWARD

$$hcforc = 0.391*(wspdk)**0.614 \tag{G.9}$$

to

WINDWARD

$$hcforc = 0.299*(wspdk)**0.89$$

else

LEEWARD

$$hcforc = 0.399*(wspdk)**0.617 \tag{G.10}$$