Introduction

This memo outlines Cadmus' proposed method to update UA values and total heat-loss estimates for the RBSA II. These updated methods add several elements for consistency with RBSA I and incorporate Regional Technical Forum standard practices, NREL Efficiency Measure Database and Super Good Cents load calculations, including heat loss through building assembly layers and components.

Proposed Revised Approach

Total Heat Loss (UA Values)

Consistent with the RBSA II methodology to date, total heat loss per home will be calculated from the sum of the component heat losses for each feature of the sampled homes. These heat loss values do not include infiltration losses (blower door testing). Components include, walls, ceilings, floors and foundations, windows, and doors. Total heat loss equals:

$$Total\ Heat\ Loss\ (UA) = UA_{wall} + UA_{ceiling} + UA_{floor\ \&\ foundation} + UA_{windows} + UA_{doors}$$

Unknown Constructions

For many components specific information was unable to be collected in the field. In these cases, an average U-value for records of the same category (i.e., Wall, Ceiling, Floor), type (i.e., 2x2, 2x4, Attic, Sloped / Vaulted Ceiling (no attic), etc.), state, and home type will be applied to the record.

Insulation properties

The RBSA II documented the type and thickness of the insulation in homes. The resistance to heat transfer was calculated using the properties outlined in Table 1.

Table 1. Insulation Type and R-Values

Type of Insulation	Avg. R-Value Per Inch (h*ft²*deg F/Btu*in)	Conductivity k (Btu*in/h*ft²*deg F)
Blown cellulose	3.4	0.293
Cellulose (Dense Packed)	3.2	0.313
Cellulose batts	2.5	0.400
Blown fiberglass	2.8	0.354
Fiberglass batts	3.4	0.293
Perlite	2.7	0.375
Polyisocyanurate foam board	6.2	0.161
Foil-faced polyisocyanurate foam board	6.3	0.159
Extruded polystyrene foam board	5.4	0.187
Expanded polystyrene foam board	4.2	0.241
Polyurethane foam board	6.2	0.163
Foil-faced polyurethane foam board	6.2	0.163
Closed-cell spray foam	5.8	0.174
Open-cell spray foam	3.5	0.288
Blown mineral wool	2.9	0.347
Mineral wool batts	3.6	0.278

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Type of Insulation	Avg. R-Value Per Inch (h*ft^2*deg F/Btu*in)	Conductivity k (Btu*in/h*ft^2*deg F)
Saw Dust Insulation	2.0	0.500
Urea formaldehyde	4.7	0.215
Vermiculite	2.5	0.400
Wood shavings	2.0	0.500
Unknown	3.0	0.333
Mixed	3.0	0.333
Foam board	5.7	0.175
Mineral infused rubber	3.0	0.333
Rock Wool	2.9	0.347
White Styrofoam	4.2	0.241
Brick Masonry (unknown thickness assumes 4" masonry)	0.1	9.0
Concrete Block Masonry (CMU) (unknown thickness assumes 8" masonry)	0.26	3.8
Poured Concrete (unknown thickness assumes 8" masonry)	0.06	15.00
Stone Masonry (unknown thickness assumes 8" masonry)	0.01	72.0

Cadmus will conduct parallel-path heat transfer calculations for each building element, making reasonable assumptions about construction materials used in the home where these data are unknown. Cadmus will also include interior buffer space coefficients and exterior air films.

Above-Grade Wall UA Values

UA_{Wall} will be calculated for each home using six parallel paths in the analysis to calculate the U-value for each wall type. Paths include framing, cavity insulation and cavity gaps; each path will also include continuous insulation or continuous insulation gaps resulting in six paths. Each path will be weighted using the assumed path weightings in Table 2 and field collected data on the completeness of the insulation.

Table 2. Above-Grade Wall Values

Wall Type	Wall Framing R-Value	Uninsulated Cavity	Framing Path Weighting	Cavity Path Weighting
Framed 2x2	1.53	0.90	0.23	0.77
Framed 2x3	2.55	0.90	0.23	0.77
Framed 2x4	3.57	0.91	0.23	0.77
Framed 2x6	5.61	0.93	0.23	0.77
Framed 2x8	7.40	0.93	0.23	0.77
Knee Wall	3.57	N/A	0.23	0.77
ICF	N/A	N/A	1.00	0.00
Log	N/A	N/A	1.00	0.00
Masonry	N/A	N/A	0.23	0.77
Masonry w/Furred wall	3.57	0.91	0.23	0.77
SIP	N/A	N/A	1.00	0.00

Based on industry standard assumptions for wall-construction characteristics, the U-value for the construction will be calculated using Equation 1 and the data in Table 2 and Table 3.

Equation 1. U Wall Calculation

$$U_{Wall} = \left(\frac{n * m}{a+b+c+f+g+h+j+k}\right)_{framing + \, continuous\ insulation} + \left(\frac{n * (1-m)}{a+b+c+f+g+k}\right)_{framing + \, continuous\ insulation\ gaps} + \left(\frac{n * l * m}{a+b+d+f+g+h+j+k}\right)_{cavity\ insulation\ +\ continuous\ insulation} + \left(\frac{n * l * (1-m)}{a+b+d+f+g+k}\right)_{cavity\ insulation\ +\ continuous\ insulation\ gaps} + \left(\frac{n * (1-l) * m}{a+b+e+f+g+h+j+k}\right)_{cavity\ insulation\ gaps\ +\ continuous\ insulation} + \left(\frac{n * (1-l) * (1-m)}{a+b+e+f+g+k}\right)_{cavity\ insulation\ gaps\ +\ continuous\ insulation\ gaps}$$

The UA_{Wall} for each construction will be calculated by multiplying the U_{Wall} times the area of the wall.

Table 3. Wall Assembly Assumed Layers

Variable	Term	Units	Framing Path	Cavity Path	Source
Inside Air Film	a	R-Value	0.68	0.68	Assumption
1/2" wallboard	b	R-Value	0.45 If un-furred solid construction: 0.00 Above-grade crawlspace: 0.00	0.45 If un-furred solid construction: 0.00	Assumption
Wall Framing	c	R-Value	Table 2 If un-furred solid construction: 0.00 Above-grade crawlspace: 0.00	0.00	Field Data

Variable	Term	Units	Framing Path	Cavity Path	Source
Wall Cavity Insulation	d	R-Value	0.00	R-value of cavity insulation	Field Data
Wall Cavity Insulation Gaps	e	R-Value	0.00	0.90 Above-grade crawlspace: 0.00	Assumption
1/2" plywood sheathing	f	R-Value	0.79 If un-furred solid construction, or log: 0.00 Above-grade crawlspace: 0.00	0.79 If un-furred solid construction or log: 0.00 Above-grade crawlspace: 0.00	Assumption
Solid Construction [a]	g	R-Value	Table 1	Table 1	Field Data
Continuous Insulation	h	R-Value	R-value of continuous insulation	R-value of continuous insulation	Field Data
Continuous Insulation Gaps	i	R-Value	0.0	0.0	Assumption
1/2" lapped wood siding	j	R-Value	0.81 Masonry and Log construction: 0.00 Above-grade crawlspace: 0.00	0.81 Masonry and Log construction: 0.00 Above-grade crawlspace: 0.00	Assumption
Outside Air Film	k	R-Value	0.25	0.25	Assumption
Cavity Insulation Condition	l	%	% Insulated	% Insulated	Field Data
Continuous Insulation Condition	m	%	% Insulated	% Insulated	Field Data
Weighting Factor	n	%	Table 2	Table 2	Assumption

[a] Solid construction (such as masonry, log, ICF, and SIP construction) is an additional layer in the wall assembly for all paths detailed above.

Additional assumptions

- Furred wall insulation is treated as cavity insulation.
- For ‘Unknown’ masonry wall types, assumed solid masonry.

- Knee walls are treated the same way as standard framed walls, but exclude the exterior wallboard and sheathing variables
- ICF walls are assumed to have five inches of insulation.

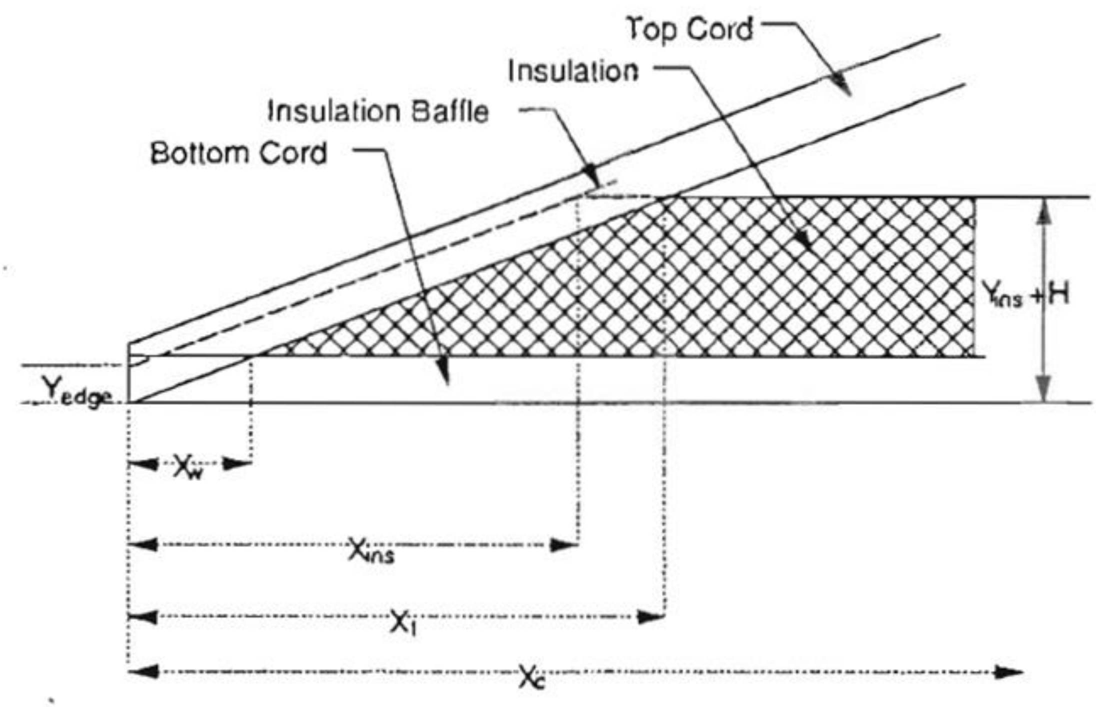
Ceiling UA Values

Cadmus proposes calculating ceiling insulation depending on the ceiling construction type.

Flat Attics

For ceilings with flat attics, Cadmus will assume that the eve of the attic edge is sloped to the end and cannot be fully insulated depending on the installed depth of insulation (Figure 1). The average ceiling assembly U-value will be calculated accounting for the diminishing insulation level near the eve of the roof and through the framing assemblies assumed in Table 4.

Figure 1. Standard Blown-in Insulation Ceiling Detail



Source: Super Good Cents Heat Loss Calculations

Because data such as roof pitch and perimeter of the wall with pitched roof are unknown, Cadmus will use standard industry assumptions detailed in the SEEM Template version 1.9 to calculate these factors. Cadmus will assume that all attic spaces with flat ceilings and a pitched roof are adequately vented and the roof deck will be ignored for the purposes of U value and UA calculations. Details on the $U_{ceiling}$ calculation for flat ceilings is shown in Table 4.

Table 4. Flat Attic Assumptions and Equations

Term	Value	Variable	Data
Xc	180	Horizontal distance from peak of roof to edge (inches)	Assumption
P	0.33	Pitch of roof (rise/run)	Assumption
kins	Insulation k value	Thermal conductivity of insulation	Field Data
Yins	Insulation Depth	Depth of insulation required for nominal R-value (inches)	Field Data
Yedge	MAX(MIN(3.5, Yins) – 2.25), 1.25)	Minimum depth of insulation, at edge of ceiling(inches)	Assumption
R1	Yedge*kins+1.22+0.6875	R-value of insulation at edge of ceiling (Yedge*Kins) plus the R-value of the top and bottom air film and ceiling board	Calculation
H	Xc*P-(Yins-Yedge)-SQRT(Xc^2*P^2-2*Xc*P*(Yins-Yedge))	Extra depth of insulation due to piling effect (inches)	Calculation
Xw	MIN(Yins, 3.5)/p	Horizontal distance from the edge to point where insulation is on top of framing member(inches)	Assumption
X1	(H+Yins)/P	Horizontal distance from edge of ceiling to full depth insulation on top of framing member(inches)	Calculation
Kw	0.98	Thermal conductivity of wood framing member (k)	Assumption
R2	3.5/Kw+1.22+0.568	Sum of R-values of framing member, air films, and ceiling board	Calculation
Rtruss	R2+(Yins+H-MIN(3.5, Yins+H))*kins	Total R-value of heat flow path through framing member at maximum insulation depth	Calculation
Xins	MAX(((Yins+H)-Yedge)/P,0)	Horizontal distance from edge of ceiling to full depth of insulation on top of ceiling board(inches)	Calculation
Uins	(1/(Xc*P*kins))*LN(1+kins*(Yins+H)/R1)+((1-(Yins+H)/(Xc*P))/(R1+kins*(Yins-Yedge+H)))	overall U-value of the ceiling assembly between truss framing members	Calculation
Utruss	(LN(Yedge*Kw+Xw*P*Kw)-LN(Yedge*Kw))/(Xc*P*Kw)+(LN(R2+Yedge*Kw-Xw*P*kins+Xins*P*kins)-LN(R2+Yedge*Kw))/(Xc*P*Kw)+(LN(Rtruss)-LN(Rtruss-Yedge*(kins-Kw)))/(Xc*Yedge*(kins-Kw)/(X1-Xins))+(1-X1/Xc)/Rtruss	Overall u-value of the ceiling assembly at the framing members where the insulation value is reduced due to the higher thermal conductivity of the wood.	Calculation
Uvoid	0.52	Overall u-value of ceiling assembly where no insulation	Calculation
FFtruss	0.07	Truss Framing Fraction (Assumes 24" OC spacing, 40' structure length)	Assumption
FFins	Insulation Condition (fraction)	% insulated	Field Data

Term	Value	Variable	Data
Uceiling	Uins*(1-FFtruss-(1-FFins))+(Utruss*FFtruss+Uvoid*(1-FFins)	Average overall u-value of ceiling assembly	Calculation

Sources: RTF SEEM Template Version 1.9 and Super Good Cents Load Calculations

Additional assumptions

- Insulation thickness is equal to the cord rafter thickness if the insulation does not completely cover the cord rafter.
    - See update to the following variables: Yedge, Xw, Rtruss, Xins
- For homes with multiple layers of insulation, the R-value for each layer is calculated and an overall attic R-value is calculated. The insulation is then treated as a homogenous material with the same thermal resistance throughout the insulation depth.

Enclosed ceilings

Where the ceiling is a closed assembly, such as vaulted ceilings or flat deck ceilings,[1] Cadmus proposes a similar calculation to wall assemblies. Enclosed ceilings will be assumed to have no venting. A parallel path approach accounts for heat transfer through both the framing members of the enclosed ceiling and insulated cavity and missing insulation in the cavity shown in Table 5.

Table 5. Enclosed Ceiling Assumed Layers

Parallel Path Analysis	Term	Framing Path (R-values)	Cavity Path (R-values)	Data
Inside Air Film	a	0.62	0.62	Assumption
5/8" wallboard	b	0.57	0.57	Assumption
Truss	c	Insulation thickness / 0.98	0.00	Field Data/ Assuming roof thickness equals insulation thickness
Insulation	d	0.00	R value of cavity insulation	Field Data
Open Cavities (R-value)	e	0.00	0.90	Assumption
1/2" plywood sheathing	f	0.79	0.79	Assumption
Asphalt shingles	g	0.44	0.44	Assumption
Outside Air Film(winter)	h	0.17	0.17	Assumption
Insulation Condition	i	0.00	% Insulated	Field Data
Weighting Factor	j	0.07	0.93	Assumption

Sources: ASHRAE Fundamentals 2013, RTF SEEM Template Version 1.9 and Super Good Cents Load Calculations

Using standard assumptions for vaulted ceiling construction characteristics, the U-value for the construction will be calculated using Equation 2 and the data in Table 5.

[1] Enclosed ceilings include the 'Other' and 'Ceiling (Unknown)' categories from the RBSA database.

Equation 2. U Vaulted Ceiling Calculation

$$U_{Vaulted\ Ceiling} = \left(\frac{j}{a+b+c+f+g+h}\right)_{framing} + \left(\frac{j*i}{a+b+d+f+g+h}\right)_{cavity\ insulation} + \left(\frac{j*(1-i)}{a+b+e+f+g+h}\right)_{cavity\ insulation\ gaps}$$

The $UA_{ceiling}$ for each construction will be calculated by multiplying the $U_{ceiling}$ times the area of the ceiling.

Foundation & Floor UA Values

Heat loss through floors and foundations can depend on the configuration and type of foundations and floors found in a home. Cadmus proposes to calculate UA values depending on those configurations by defining the thermal boundary of the home either at the foundation wall of a crawlspace or basement, the floor of a home where the space beneath is exposed to ambient conditions, or at the slab. In some circumstances where the thermal boundary of the home is difficult to quantify, the calculations will treat an area as a buffer space. For example, in homes with unconditioned, unvented crawlspaces, the crawlspace will be considered as a buffered space, with heat flow calculated across the floor above the crawlspace and through the crawlspace foundation walls.

The heat loss equations and inputs for each of these four scenarios is outlined below.

Thermal Boundary Framed Floor

For homes with a framed floor over a ventilated crawlspace or a cantilever floor over ambient condition, Cadmus proposes using a two-path analysis accounting for framing and cavity insulation.

Table 6. Framed Floor Assumed Layers

Parallel Path Analysis	Term	Framing Path (R values)	Cavity Path (R values)	Data
Inside Air Film	a	0.92	0.92	Assumption
Hardwood Flooring	b	0.63	0.63	Assumption
3/4" plywood subfloor	c	1.08	1.08	Assumption
Floor Joists	d	Floor thickness / 0.98	0.00	Field Data
Insulation	e	0.00	R value of cavity insulation	Field Data
Open Cavities (R-value)	f	0.00	0.90	Assumption
Bottom Air Film	g	0.92	0.92	Assumption
Insulation Condition	h	0.00	% Insulated	Assumption
Weighting Factor	i	0.09	0.91	Assumption

Sources: ASHRAE Fundamentals 2013, RTF SEEM Template Version 1.9 & Super Good Cents Load Calculations

Using industry standard assumptions for floor construction characteristics, the U-value for the construction will be calculated using Equation 3 and the data in Table 6.

Equation 3. U Framed Floor Calculation

$$U_{Framed\ Floor} = \left(\frac{i}{a+b+c+d+g}\right)_{framing} + \left(\frac{i*h}{a+b+c+e+g}\right)_{cavity\ insulation} + \left(\frac{i*(1-h)}{a+b+c+f+g}\right)_{cavity\ insulation\ gaps}$$

The $UA_{Foundation/Floor}$ for each construction will be calculated by multiplying the $U_{Foundation/Floor}$ times the area of the floor.

Additional assumptions

- Floor joists are assumed to be 2x8

Thermal Boundary Slab

For homes with slab on grade foundations Cadmus proposes using slab F factors from the Super Good Cents Volume II (Table 7). Where the insulation under slab on grade is unknown the analysis will assume an uninsulated-slab.

Table 7. Slab F Factors

Insulation Strategy	Overall F-Value
Uninsulated Slab	0.73
R-5 Horizontal Insulation (2Ft) no tb	0.70
R-10 Horizontal Insulation (2Ft) no tb	0.70
R-15 Horizontal Insulation (2Ft) no tb	0.69
R-5 Horizontal Insulation (4Ft) no tb	0.67
R-10 Horizontal Insulation (4Ft) no tb	0 64
R-15 Horizontal Insulation (4Ft) no tb	0.63
R-5 Vertical Insulation (2Ft)	0.58
R-10 Vertical Insulation (2Ft)	0.54
R-15 Vertical Insulation (2Ft)	0.52
R-5 Vertical Insulation (4Ft)	0.54
R-10 Vertical Insulation (4Ft)	0.48
R-15 Vertical Insulation (4Ft)	0.45
R-10 Fully Insulated Slab	0.36

The $UA_{Foundation/Floor}$ for each construction will be calculated by multiplying the F_{slab} times the perimeter of the slab.

Thermal Boundary Foundation Wall

For conditioned basements and non-ventilated crawlspaces Cadmus proposes using floor F factors and wall U-values from the Super Good Cents Volume II tables.

Table 8. Foundation Walls F Factors and U values

INSULATION STRATEGY	U-VALUE (WALL)	F-VALUE (FLOOR)
2 FT. BELOW GRADE		
Uninsulated Basement	0.35	0.59
Interior R-11 Furred Walls	0.07	0.68
Interior R-11 Furred Walls w/R-5 T.B.	0.07	0.60
Interior R-19 Furred Walls	0.04	0.69
Interior R-19 Furred Walls w/R-5 T.B.	0.05	0.61
R- 10 Exterior Insulation	0.07	0.60
3.5 FT. BELOW GRADE		
Uninsulated Basement	0.28	0.53
Interior R-11 Furred Walls	0.06	0.63
Interior R-11 Furred Walls w/ R-5 T.B.	0.06	0.57
Interior R-19 Furred Walls	0.04	0.64
Interior R-19 Furred Walls w/ R-5 T.B.	0.04	0.57
R- 10 Exterior Insulation	0.06	0.57
7 FT. BELOW GRADE		
Uninsulated Basement	0.19	0.46
Interior R-11 Furred Walls	0.05	0.56
Interior R-11 Furred Walls w/R-.5 T.B.	0.06	0.42
Interior R-19 Furred walls	0.04	0.57
Interior R-19 Furred Walls w/R-5 T.B.	0.04	0.43
R- 10 Exterior Insulation	0.06	0.42

The $UA_{Foundation/Floor}$ for each construction will be calculated by multiplying the F_{floor} times the perimeter of the floor plus the U_{wall} times the area of the foundation wall.

Additional assumptions

- Crawlspaces walls are assumed to be 4 ft tall (2 ft above grade, 2 ft below grade)
- If basement wall percent below grade is unknown, assumed wall is 70% below grade.

Thermal Boundary Buffer Space

Where an unconditioned buffer space exists between the conditioned space of the home and the exterior, such as with floors over garages, unvented crawlspaces, and unconditioned basements. Cadmus proposes a buffer space calculation similar to that used in RBSA I (Equation 4).

Equation 4. UA Foundation and Floor Calculation

$$UA_{Buffer\ Space} = \frac{UA_{framed\ floor}}{1 + (UA_{framed\ floor}/UA_{Foundation/Floor/Wall})}$$

This calculation assumes the "buffer space" is perfectly sealed with no infiltration. The $UA_{framed\ floor}$ is calculated the same as a floor above ambient conditions, and the $UA_{Foundation/Floor/Wall}$ is calculated the same as an above-grade wall (for garages) or foundation wall (for unvented crawlspaces and basements), depending on the circumstance of the space. For buffer spaces in unconditioned basements or enclosed crawlspaces both the foundation wall and foundation floor will be included.

Additional assumptions

- For floors over garages, the following are assumed:
  - Have uninsulated 2x6 walls (U-value = 0.2780)
  - Garage wall area is equal to SQRT(Framed Floor Area) * 2.5 * 8
  - Garage slab-on-grade perimeter is equal to SQRT(Framed Floor Area) * 4
- Crawlspaces heat transfer into the sub-grade ground is assumed to be equivalent to a below-grade slab (2 ft below grade)

Window UA Values

For windows heat loss Cadmus will use lookup tables from the NREL Efficiency Measures Database. U-values based on the number of panes and frame type; below in Table 9.

The UA_{window} for each home will be calculated by multiplying the U_{window} times the area of the window.

Table 9. Window U-Values

Frame Type	Glazing Type	Avg. U Factor
Aluminum	Single	1.16
Aluminum	Double	0.7
Aluminum	Triple	0.24
Metal	Single	1.16
Metal	Double	0.7
Metal	Triple	0.24
Fiberglass	Single	0.84
Fiberglass	Double	0.38
Fiberglass	Triple	0.24
Fiberglass, interior wood clad	Single	0.84
Fiberglass, interior wood clad	Double	0.38
Fiberglass, interior wood clad	Triple	0.24
Vinyl	Single	0.81
Vinyl	Double	0.38
Vinyl	Triple	0.24

Frame Type	Glazing Type	Avg. U Factor
Wood	Single	0.84
Wood	Double	0.38
Wood	Triple	0.24
Wood fiberglass clad	Single	0.84
Wood fiberglass clad	Double	0.38
Wood fiberglass clad	Triple	0.24
Wood aluminum clad	Single	0.84
Wood aluminum clad	Double	0.38
Wood aluminum clad	Triple	0.24

Door UA Values

Cadmus does not plan to make updates to door heat loss rates. Door UA values will remain as they appear in the RBSA II database.