U-FACTORS AND R-VALUES

When it is colder on one side of an envelope element, such as a wall, roof, floor, or window, heat will conduct from the warmer side to the cooler side. Heat conduction is driven by temperature differences and is a major component of heating and cooling loads in buildings. The building envelope requirements of the 90.1 Code address heat conduction by specifying minimum R-values (thermal resistance to heat flow) for insulation or maximum U-factors (the rate of steady-state heat flow) for building envelope construction assemblies.

Basic Concepts

U-factor

The U-factor is the rate of steady-state heat flow. It is the amount of heat in Btu (British thermal units) that flows each hour through one square foot, when there is a one degree temperature difference between the inside air and outside air. The heat flow can be in either direction, as heat will flow from the warmer side to the cooler side. Steady-state heat flow assumes that temperatures on both sides of a building envelope element (while different) are held constant for a sufficient period of time so that heat flow on both sides of the assembly is steady. The steady-state heat flow method is a simplification, because in the real world, temperatures change constantly. It can, however, predict average heat flow rates over time, and is used by the 90.1 Code to limit conductive heat losses and gains. Because they are easy to understand and use, the terms for steady-state heat flow are part of the basic vocabulary of building energy performance.

Each layer of a building assembly, such as the sheathing and the insulation, has its own *conductance*, or rate of heat transfer. The conductance for an individual layer is like the U-factor, and it has the same units. The difference is that it is only for a single element or layer. The U-factor includes the conductance of every element of the building assembly, including the air films on the interior and exterior surfaces of the construction assembly. The surface conductances quantify the rate at which heat is transferred between the surface of the construction assembly and the surrounding environment.

For light frame walls, the steady-state U-factors provide an adequate description of heat transfer. For heavy concrete and masonry walls, however, this is only true under constant or average temperature conditions. The dynamic heat storage properties of the concrete and masonry alter the thermal behavior of the wall, and the U-factor becomes less accurate as a predictor of heat flow rates.

R-value

R-values are also used to describe steady-state heat flow, but in a slightly different way. The R-value is the *thermal resistance* to heat flow. A larger R-value has greater thermal resistance, or more insulating ability, than a smaller R- value. The big advantage of R-values is that they can be added together. For homogeneous assemblies, the total R-value of a construction assembly is the sum of the R-values of each of the layers. The layers should include the sheathing and finishes, the insulation and weatherproofing elements, and the surface air films. The U-factor is the inverse of the total R-value.

$$\text{U - Value} = \frac{1}{\text{Total R - Value}}$$

The R-value is widely recognized in the building industry and is used to describe insulation effectiveness. The insulation R-value is not the total R-value of the wall, however. It only describes the thermal resistance of the insulation material. The R-value of the entire wall assembly can be significantly lower when metal framing penetrates the insulation.

Framing Effects

Most construction assemblies include more than one material in the same layer. For example, a wood stud wall includes cavity areas where the insulation is located and other areas where there are solid wood framing members. The wood areas have a lower R-value, and conduct heat more readily than the insulated areas. It is incorrect to neglect framing members when calculating the U-factor for the wall, roof, or floor assembly. The correct U-factor includes the insulation portion of the wall and the U-factors through the solid (or framed) portion of the wall. The 90.1 Code requires that the U-factor of each envelope assembly be calculated taking into account framing and other thermal bridges within the construction assembly.

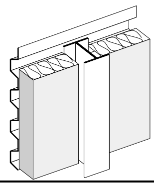
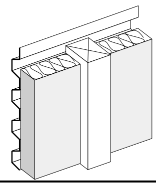
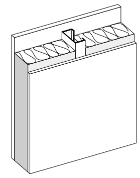
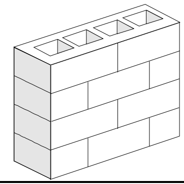
Default U-factors

Precalculated U-factors are provided in this section for typical construction assemblies, including roofs, floors, and doors. These values are calculated using acceptable methods, and may be used for compliance with the code.

Acceptable Calculation Methods

The 90.1 Code specifies acceptable calculation methods for determining U-factors, and makes a distinction between construction assemblies with metal framing members, and assemblies with non-metal framing such as wood or concrete. It also distinguishes between metal sheathing and non-metal sheathing. Heat flow through construction assemblies with metal framing and/or sheathing is more complex and requires special consideration. Table 402Q shows the calculation methods that can be used with each general type of construction.

Table 402Q Applicability of U-factor Calculation Methods

	Metal Sheathing Metal Framing	**Metal Sheathing Non-Metal Framing**	**Non-Metal Sheathing Metal Framing**	**Non-Metal Sheathing Non-Metal Framing**
				
Laboratory Tests	x	x	x	x
Series-Parallel Path (Isothermal Planes)		x		x
Parallel Path Correction Factors			x	
Two-Dimensional Models	x	x	x	x
Zone Method			x	

Laboratory Tests

Laboratory tests are the most accurate way to determine the U-factor of a construction assembly, and are acceptable for all types of construction. An 8 ft by 8 ft sample of the construction assembly is placed in a test unit. For steady-state measurements, the temperatures on either side of the wall are held constant until temperatures within the construction have stabilized; then the rate of heat flow is measured. The biggest advantage of laboratory testing is that it gives equally good data for any type of construction assembly. The major disadvantage is that it is costly and time consuming. There is a large variety of possible construction assemblies, and it is impractical to test them all. For this reason, it is usually more cost effective to use calculation methods. Laboratory measurements must use one of the following test procedures: Guarded Hot Plate (ASTM C-177-85), Heat Flow Meter (ASTM C-518-85), Guarded Hot Box (ASTM C-236-87), or Calibrated Hot Box (ASTM C-976-82).

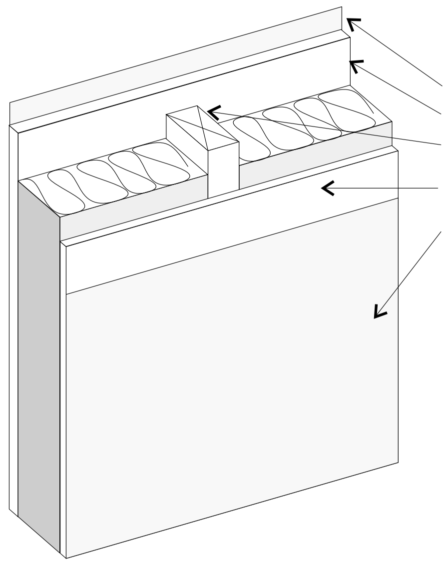
Series-Parallel Path (Isothermal Planes) Method

The *series-parallel method* is a reasonably accurate procedure for calculating the U-factor when one or more elements in a construction are relatively conductive. It may be used for wood framed walls and for concrete and masonry walls. Hollow masonry units are a good example of when this calculation method is appropriate. The solid webs connecting the faceshells are quite conductive compared to the air spaces in the hollow cores, and the faceshells conduct heat laterally. The heat, in effect, flows around the hollow cores. The series-parallel method divides the construction assembly into a series of layers. For a masonry unit, the layer containing the webs and cores is treated with a parallel path calculation to arrive at an average

R-value for the layer. This is then added to the R-values of the two faceshells, as in a series method calculation. Finally, the total R-value is inverted to the U-factor. This method is also referred to as the isothermal planes method, because it assumes uniform temperature across the planes separating the layers.

Example 402M U-factor Calculation – Series - Parallel Path

Q What is the thermal transmittance of the wood framed wall shown in the following drawing?



A The series and parallel path method may be used for this type of construction. The U-factor is calculated separately for the cavity and framing portions of the wall based on the thermal resistance of each element of the wall. These calculations are made in the following table:

	Cavity	Framing
Outside air film	0.17	0.17
7/8 in. stucco	0.18	0.18
Building paper	0.06	0.06
Cavity insulation	13.00	
Framing		4.375
1/2 in. gypsum board	0.45	0.45
Inside air film	0.68	0.68
Sum of thermal resistance	14.54	5.01

The estimated framing is 15% of the wall area and the U-factor may be calculated as shown below.

$$U = \frac{0.15}{5.01} + \frac{1 - 0.15}{14.54} = 0.088$$

Parallel Path Correction Factors

The 90.1 Code provides a simple way to calculate the thermal resistance (R-value) of certain types of roofs and walls with metal framing. Tables 402.1.2.1a and 402.1.2.1b in the code contain two sets of parallel path correction factors: one for metal trusses surrounded by insulation and one for metal wall studs. The correction factor is essentially a multiplier times the insulation R-value. It provides a very easy way of accounting for the effect of metal framing in wall and roof construction assemblies. These tables are repeated below as Tables 402R and 402S.

Two Dimensional Heat Flow

Two-dimensional heat flow analysis may be used to accurately predict the U-factor of a complex construction assembly. While the series-parallel path calculation method assumes that heat flows in a straight line from the warm side of the construction to the cooler side, with two dimensional models, heat can also flow laterally in the construction, following the path of least resistance. Calculating two-dimensional heat flow involves advanced mathematics and is best performed with a computer. A model is set up by dividing the construction into a large number of small pieces, and defining the thermal resistance between each piece. The result is analyzed with electric circuit theory. The network consists of a rectangular array of nodes connected by resistances. As in the real material, the energy flow will take the path of least resistance. The computer can perform the complicated calculations necessary to solve the network, yielding the U-factor for the unit at steady state. It can also solve the network for dynamic energy conditions. Short of performing laboratory tests, this is the most accurate method available for determining the U-factors of concrete and masonry walls.

Zone Method

For conditions for which there are no parallel path correction factors, the zone method may be used. It may be used for construction assemblies with metal framing and non-metallic sheathing, such as concrete or masonry. The use of this method is documented in the ASHRAE Fundamentals Handbook (1985) and involves dividing the construction assembly into zones. Heat flow in the zone near the metal framing is assumed to be conducted toward the framing and the thermal resistance is smaller.

Compressed Insulation

Insulation that is compressed must be derated in accordance with Table 402T. or the reduction may be calculated in accordance with the procedures in the ASHRAE Fundamentals Handbook (1985).

Table 402R Parallel Path Correction Factors for Metal Roof Trusses

Size of Members	Spacing of Framing (inches o.c.)	Insulation R-value	Correction Factor	Effective R-value
All	48	R-0	1.00	R-0
		R-5	0.96	R-4.8
		R-10	0.92	R-9.2
		R-15	0.88	R-13.2
		R-20	0.85	R-17.0
		R-25	0.81	R-20.3
		R-30	0.79	R-23.7
		R-35	0.76	R-26.6
		R-40	0.73	R-29.2
		R-45	0.71	R-32.0
		R-50	0.69	R-34.5
		R-55	0.67	R-36.0

Table 402S Effective R-values for Wall Insulation Installed Between Metal Framing

Nominal Framing Depth	Nominal Insulation R-value	Correction Factor	Effective R-value
4"@16"o.c.	R-11	0.50	R-5.5
	R-13	0.46	R-6.0
	R-15	0.43	R-6.4
4"@24"o.c.	R-11	0.60	R-6.6
	R-13	0.55	R-7.2
	R-15	0.52	R-7.8
6"@16"o.c.	R-19	0.37	R-7.1
	R-21	0.35	R-7.4
6"@24"o.c.	R-19	0.45	R-8.6
	R-21	0.43	R-9.0
8"@16"o.c.	R-25	0.31	R-7.8
8"@24"o.c.	R-25	0.38	R-9.6

The correction factors for metal framed walls may be used with metal studs of 16 ga. or lighter.

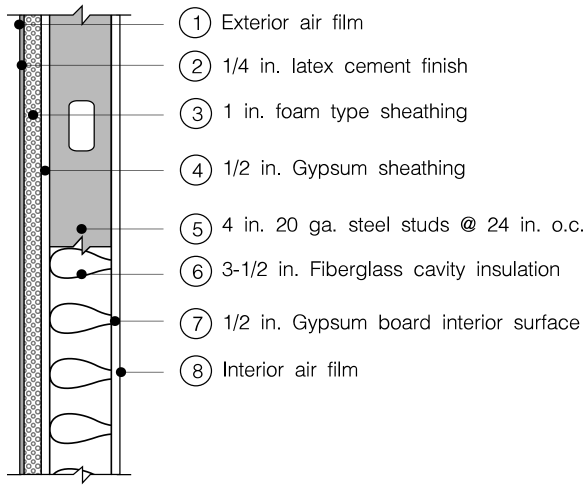
Table 402T Effective R-value of Fiberglass Batts Compressed in Various Depth Cavities (h-ft^2-°F/Btu)

Nominal Lumber Size	Actual Depth of Cavity	Insulation R-values at Standard Thickness													
		38C	38	30C	30	25	22	21	19	15	13	11	8	5	3
2" × 12"	11-1/4"	38	37												
2" × 10"	9-1/4"		32	30											
2" × 8"	7-1/4"		27		26	24									
2" × 6"	5-1/2"				21		20	21	18						
2" × 4"	3-1/2"						14		13	15	13	11			
2" × 3"	2-1/2"										10				
2" × 2"	1-1/2"										6.5	6.0	5.7		
2" × 1"	1/2"													3.2	3.0

The standard thicknesses are as follows: 10-1/4" for R-38C, 12" for R-38, 8-1/4" for R-30C, 9-1/2" for R-30, 8" for R-25, 6-3/4" for R-22, 5-1/2" for R-21, 6-1/4" for R-19, 3-1/2" for R-15, 3-1/2" for R-13, 3-1/2" for R-11, 2-1/2" for R-8, 1-1/2" for R-5 and 3/4" for R-3.

Example 402N U-factor Calculation – Parallel Path Correction Factors

Q What is the thermal transmittance of the metal framed wall shown in the following drawing?



Component	**R-value**
(1) Exterior air film	0.17
(2) Latex cement finish	0.21
(3) Foam sheathing	4.00
(4) Gypsum sheathing	0.45
(5) 2×4 steel studs 24 in. o.c.	N.A.
(6) Fiberglass insulation	11.00
(7) Gypsum board interior	0.45
(8) Interior air film	0.68

A The parallel path correction factors may be used for this type of construction. This calculation method is available for wall sections with non-metal skin attached to metal stud framing. It is a modified form of the equivalent circuit method. It uses the parallel path correction factors listed in Table 402.1.2.1b. The correction factor for a 2×4 metal stud framing at 24 in. o.c. with R-11 fiberglass cavity insulation is 0.60. The thermal transmittance of this assembly is given by the following equations:

$$R_e = R_{insulation} \times F_c = 11.0 \times 0.60 = 6.6$$

The thermal resistance of the framing and insulation with thermal bridging accounted for. The parallel path correction factor of 0.60 is taken from Table 402.1.2.1b of the code.

$$\sum_i R_i = 0.17 + 0.21 + 4.00 + 0.45 + 6.60 + 0.45 + 0.68 = 12.56$$

The thermal resistance of the materials in "series"

$$U_t = \frac{1}{R_t} = \frac{1}{12.56} = 0.0796$$

The overall thermal transmittance of the assembly

Two Dimensional Heat Flow

Two-dimensional heat flow analysis may be used to accurately predict the U-factor of a complex construction assembly. While the series-parallel path calculation method assumes that heat flows in a straight line from the warm side of the construction to the cooler side, with two dimensional models, heat can also flow laterally in the construction, following the path of least resistance. Calculating two-dimensional heat flow involves advanced mathematics and is best performed with a computer. A model is set up by dividing the construction into a large number of small pieces, and defining the thermal resistance between each piece. The result is analyzed with electric circuit theory. The network consists of a rectangular array of nodes connected by resistances. As in the real material, the energy flow will take the path of least resistance. The computer can perform the complicated calculations necessary to solve the network, yielding the U-factor for the unit at steady state. It can also solve the network for dynamic energy conditions. Short of performing laboratory tests, this is the most accurate method available for determining the U-factors of concrete and masonry walls.

Zone Method

For conditions for which there are no parallel path correction factors, the zone method may be used. It may be used for construction assemblies with metal framing and non-metallic sheathing, such as concrete or masonry. The use of this method is documented in the ASHRAE Fundamentals Handbook (1985) and involves dividing the construction assembly into zones. Heat flow in the zone near the metal framing is assumed to be conducted toward the framing and the thermal resistance is smaller.

Compressed Insulation

Insulation that is compressed must be derated in accordance with Table 402T or the reduction may be calculated in accordance with the procedures in the ASHRAE Fundamentals Handbook (1985).

Table 402U Effective R-value of Fiberglass Batts Compressed in Various Depth Cavities (h-ft^2-°F/Btu)

Nominal Lumber Size	**Actual Depth of Cavity**	**Insulation R-values at Standard Thickness**													
		38C	**38**	**30C**	**30**	**25**	**22**	**21**	**19**	**15**	**13**	**11**	**8**	**5**	**3**
2" × 12"	11-1/4"	38	37												
2" × 10"	9-1/4"		32	30											
2" × 8"	7-1/4"		27		26	24									
2" × 6"	5-1/2"				21		20	21	18						
2" × 4"	3-1/2"						14		13	15	13	11			
2" × 3"	2-1/2"										10				
2" × 2"	1-1/2"										6.5	6.0	5.7		
2" × 1"	1/2"													3.2	3.0

The standard thicknesses are as follows: 10-1/4" for R-38C, 12" for R-38, 8-1/4" for R-30C, 9-1/2" for R-30, 8" for R-25, 6-3/4" for R-22, 5-1/2" for R-21, 6-1/4" for R-19, 3-1/2" for R-15, 3-1/2" for R-13, 3-1/2" for R-11, 2-1/2" for R-8, 1-1/2" for R-5 and 3/4" for R-3.