5.3.3 Thermal Resistance (R-value)

Common thermal properties of materials and air spaces are based on steady state tests, which measure the heat that passes from the warm side to the cool side of the test specimen. Thermal mass of concrete, which is not based on steady-state tests, is discussed in Section 5.3.5. Daily temperature swings and heat storage effects are accounted for in thermal mass calculations. The results of steady-state tests provide the thermal resistance (R-value) of the air, material, or combination of materials tested. Tests of homogenous materials are also used sometimes to provide the thermal conductivity value. The R-value per inch of a homogenous material is equal to the inverse of its thermal conductivity. The R-value for a material with a specific thickness is its thickness divided by thermal conductivity.

The overall (total) R-value of a building wall is computed by adding together the R-values of the materials ($R_{materials}$) in the section, the indoor and outdoor air film surfaces (R_{fi} and R_{fo}) and air spaces (R_a) within the section.

$R_{total} = R_{fi} + R_{materials} + R_a + R_{fo}$ Equation 5.3.1

or

$R_{total} = R_{fi} + R_{concrete} + R_{insulation} + R_a + R_{fo}$

These equations are only applicable for layered systems where each layer is composed of a homogenous material. In framing or other systems where members or elements penetrate the insulation layer, the series-parallel or zone method from the *ASHRAE Handbook of Fundamentals* must be used.

The U-factor is the reciprocal of the total R-value ($U = 1/R_{total}$).

Tables 5.3.2 and 5.3.3 give the thermal resistances of air films and 3$^1/_2$ in. (90 mm) air spaces, respectively. The R-values of air films adjacent to surfaces and air spaces differ depending on whether they are vertical, sloping, or horizontal and, if horizontal, whether heat flow is up or down. Also, the R-values of air films are affected by the velocity of air at the surfaces and by their reflective properties.

Tables 5.3.4 and 5.3.5 provide thermal properties of most commonly used building materials. The R-values of most construction materials vary somewhat depending on the temperature and thickness. Note that expanded polystyrene and extruded polystyrene board insulation have different thermal and physical properties. Expanded polystyrene (EPS) or beadboard is composed of small beads of insulation fused together. Extruded polystyrene (XPS) is usually pigmented blue, pink, or green, and has a continuous closed cell structure. XPS generally has a higher thermal resistance, higher compressive strength, and reduced moisture absorption compared to EPS. Mineral fiber and fiberglass batt insulation are not included in the table, but are generally labeled by the manufacturer. The most common batts for walls are R11, R13, and R19, with the number following the R indicating the R-value.

Glazing thermal performance is measured by thermal transmittance (U-factor), solar heat gain coefficient (SHGC), and visible light transmission (VLT). A low SHGC will minimize solar heat gains and reduce cooling loads. Some products with low SHGC also have a low VLT that will reduce daylighting benefits. Products with a low SHGC and high VLT are often a good choice. Since glazing types have proliferated in recent years, refer to the *ASHRAE Handbook of Fundamentals* or the NFRC for glazing and fenestration properties. Table 5.3.5 provides some typical values.

Table 5.3.6 gives the thermal properties of various weight concretes in the "normally dry" condition. Normally dry is the condition of concrete containing an equilibrium amount of free water after extended exposure to room temperature air at 35 to 50 percent relative humidity. Thermal conductivities and resistances of other building materials are usually reported for oven dry conditions. However, concrete starts out wet and is rarely in the oven dry condition. Higher moisture content in concrete causes higher thermal conductivity and lower thermal resistance. However, normally dry concrete in combination with insulation generally provides about the same R-value as equally insulated oven dry concrete.

A number of typical concrete wall R-values are given in Tables 5.3.6 and 5.3.7. These wall tables can be applied to sandwich type panels, as well as single wythe panels insulated on one side. The U-factor of the wall is the inverse of the R-value with air film resistances from Table 5.3.7. To use Table 5.3.7, first determine the R-value of the insulation to be used either from Table 5.3.4 or from the insulation manufacturer. Manufacturers of insulation are required by law to provide the R-value of their material.

For concrete walls with metal furring or studs, wall R-values can be determined using Tables 5.3.7 and 5.3.8. Determine the R-value of the concrete portion from Table 5.3.7 and add it to the effective R-value from the insulation/framing layer from Table 5.3.8, page 411.

The following design example shows how to calculate R-value and U-factor for a wall using material R-values taken from Tables 5.3.2 through 5.3.7.

The R-value of walls assemblies are generally only calculated for the winter condition since the difference between the summer and winter conditions is small. This example is valid only for insulation with no metal or solid concrete penetrating the insulation layer. R-values will be impacted by the presence of these items and additional calculations will be required according to series-parallel, zone, or characteristic method.

Thermal bridges such as metal wythe connectors or a full thickness of concrete along sandwich panel edges will reduce the R-value of the wall. The net effect of metal ties is to increase the U-value by 10 to 15 percent, depending on type, size, and spacing. For example, a wall as shown in Fig. 5.3.16 would have a U-value of 0.13 if the effect of the ties is neglected. If the effect of $^1/_4$ in. diameter ties at 16 in. on center is included, U = 0.16; at 24 in. spacing, U = 0.15. Ongoing research indicates these numbers are conservative. As another example, steel ties representing 0.06 percent of an insulated panel area can reduce the panel R-value by 7 percent.[1]

Thermal bridging is minimized by the use of engineered resin, low conductivity wythe connectors in insulated concrete panel construction. These composite material connectors, along with their ability to enable edge to edge insulation coverage in the concrete sandwich panels, can significantly reduce thermal bridging and help the insulation layer to retain up to 99.7 percent of its listed R-value.

Thermal bridges may lead to localized cold areas where surface condensation can occur, particularly where the interior relative humidity is maintained at high levels. This may cause annoying or damaging wet streaks on the wall surface. Icicles have been reported on the interior side of some buildings in cold climates, see Section 5.3.6. In most cases the problem has been traced to excessive air exfiltration through major openings in the wall, often at precast concrete wythe connector locations. Since steel connectors form a high conductivity path, they offer likely locations for condensation to occur. Corrosion protection, stainless steel, or increased thickness of the connector material may provide extended service life for these steel wythe connectors.

The effect of metal tie thermal bridges on the heat transmittance may be calculated by the zone method described in the *ASHRAE Handbook of Fundamentals although the characteristic method is preferred*. With the zone method, the panel is divided into Zone A, which contains the thermal bridge, and Zone B, where thermal bridges do not occur, as shown in Figure 5.3.16. The width of Zone A is calculated as W = m + 2d, where m is the width or diameter of the metal or other conductive bridge material, and d is the distance from the panel surface to the metal. After the width (W) and area (A) of Zone A are calculated, the heat transmissions of the zonal sections are determined and converted to area resistances, which are then added to obtain the total resistance (R_t) of that portion of the panel. The resistance of Zone A is combined with that of Zone B to obtain the overall resistance and the gross transmission value U_o, where U_o is the overall weighted average heat transmission coefficient of the panel.

The effect of solid concrete path thermal bridges can be calculated by the characteristic section method. In this method, the panel is divided into two regions. The first region is treated as a perfectly insulated panel without any thermal bridge. The second region is treated as a solid concrete panel without any insulation. The total thermal resistance of the panel is calculated as the resistances of these two regions added together in parallel.

The portion of the panel that is treated as a solid concrete panel without any insulation is larger than the actual solid concrete region that exists in the panel. There is an affected zone around each solid concrete region that is added to the actual area of the solid concrete region to obtain the size of the concrete region used in the calculation. The size of the affected zone E_z is computed as:

$$E_z = 1.4 - 0.1 t_{in} \alpha + \left[0.4 t_{cf} + 0.1 (t_{cb} - t_{cf}) \right] \beta$$

Equation 5.3.2

In this equation, t_{in}, t_{cf} and t_{cb} are the thicknesses of the insulation layer, concrete face wythe, and concrete back wythe, respectively. This is an empirical equation with all dimensions expressed in inches. The parameters α and β account for the insulation and concrete conductivity values (k_{in} and k_{con}) that are used to construct the panel. Their values are computed as:

$$\alpha = 1 + 2.25 \left(\frac{k_{in} - 0.26}{0.26} \right)$$ Equation 5.3.3

and

$$\beta = 1 + 1.458 \left(\frac{k_{con} - 12.05}{12.05} \right)$$ Equation 5.3.4

1 VanGeem, M. G., "Effects of Ties on Heat Transfer Through Insulated Concrete Sandwich Panel Walls," Proceedings of the *ASHRAE/DOE/BTECC/CIBSE Conference on Thermal Performance of the Exterior Envelopes of Buildings IV*, Orlando, December 1989, ASHRAE, Atlanta, 1989, pp. 206-223. www.ASHRAE.org

In these equations, k_{in} and k_{con} have units of Btu (in/hr)(ft²)(°F).

To calculate an R-value, a panel is divided into two regions: a solid concrete region and a perfectly insulated region, as explained previously. E_z is calculated using Equation 5.3.2 and the area of each region is then calculated. The thermal resistance of the solid concrete region (R_s) is then added in parallel with the thermal resistance of the perfectly insulated region (R_p) to obtain the thermal resistance of the panel R:

$$\frac{1}{R} = \frac{A'_s}{R_s} + \frac{A'_p}{R_p} \qquad \text{Equation 5.3.5}$$

A'_s and A'_p represent the areas of the solid concrete region (A_s) and perfectly insulated panel region (A_p) divided by the total panel area A_t (i.e. $A'_s = A_s/A_t$, $A'_p = A_p/A_t$). The procedure is illustrated in Example 5.3.2.

Where:

A_p= area of insulated panel zone

A_s= area of solid concrete zone

A_t= total area of panel

A'= portion of each zone

A'_p= portion of insulated panel zone

A'_s= portion of solid concrete zone

E_z= affected zone

k_{con}= conductivity of concrete

k_{in}= conductivity of insulation

t_{cb}= thickness of back concrete wythe

t_{cf}= thickness of face concrete wythe

t_{in}= thickness of insulation layer

α= insulation conductivity coefficient factor

β= concrete conductivity coefficient factor

Problem:

Determine the R-value for the sandwich panel shown above for conductivities of 10.0 Btu·(in./hr)·(ft²)°F and 0.15 Btu·(in./hr)·(ft²)(°F) for the concrete and insulation, respectively. Face and back wythe thicknesses are 3 in., and the insulation layer thickness is 2 in.

Solution:

Calculate the parameters α and β:

$$\alpha = 1 + 2.25\left(\frac{k_{in.} - 0.26}{0.26}\right) = 1 + 2.25\left(\frac{0.15 - 0.26}{0.26}\right) = 0.05$$

$$\beta = 1 + 1.458\left(\frac{k_{con} - 12.05}{12.05}\right) = 1 + 1.458\left(\frac{10.00 - 12.05}{12.05}\right)$$

$$= 0.75$$

From the panel thicknesses, the affected zone dimension E_z is computed as:

E_z= 1.4 – 0.1(t_{in})(α) + [0.4t_{cf} + 0.1(t_{cb} – t_{cf})] β

E_z= 1.4 – 0.1(2)(0.05) + 0.4(3)(0.75)

E_z = 2.3 in.

Add E_z to the actual solid concrete areas to obtain the areas of the panel to treat as solid concrete (shown as dashed lines above).

Calculate the areas of the panel (A_t), solid concrete region (A_s), and perfectly insulated region (A_p):

A_t= panel area = (40 ft)(12 ft) = 480 ft^2 = 69,120 in.^{2}

A_s= concrete area = 2(14.3)(144) + 8(16.6)(16.6)
= 6,323 in.^{2}

A_p= insulated area = 69,120 – 6,323 = 62,797 in.^{2}

This resistance of that portion of the panel that is treated as perfectly insulated is calculated from the resistances of the concrete, insulation, and surfaces in series.

The resistance of that portion of the panel that is treated as solid concrete is calculated from the resistances of the concrete and surfaces in series.

Calculate the fractional areas of the panel that are treated as solid concrete and as insulated:

A_s/A_t = 6323/69120 = 0.091

A_p/A_t = 62797/69120 = 0.909

Compute the R-value of the panel treating the solid concrete and perfectly insulated regions in parallel.

$$\frac{1}{R} = \frac{0.909}{11.45} + \frac{0.091}{1.65} \qquad \frac{1}{R} = \frac{0.909}{11.53} + \frac{0.091}{1.73}$$

Winter:Summer:

R = 7.43 hr · ft^2 · °F/Btu R = 7.61 hr · ft^2 · °F/Btu

ASHRAE Standard 90.1 also recognizes the detrimental thermal bridging effects of steel framing within walls. For example, ASHRAE specifies an effective insulation/framing R-value of 5.1 for R13 insulation in a 4 in. metal stud cavity for concrete wall construction. For the effects of other metal framing depths and insulation R-values in precast concrete walls see Table 5.3.8.

Fig. 5.3.13
Security Insurance Group Headquarters, Farmington, Connecticut; Architect: Russell Gibson von Dohlen; Photo: Steve Rosenthal.

Fig. 5.3.14
Miami Police Station, Miami, Florida; Architect: Borrelli + Partners formerly Pancoast, Bouterse, Borrelli, Albaisa, Architects/Planners, Inc.; Photo: Borrelli + Partners.

Fig. 5.3.15 Jambs, head or sill (rotate 90º).

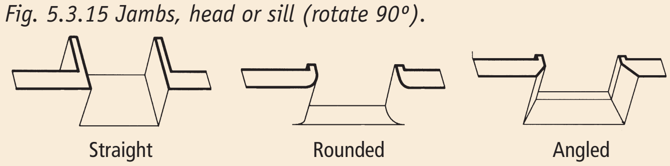


Table 5.3.2 Thermal Resistances, R_f, of Surfaces[1].

Position of surface	Direction of heat flow	Indoor – Still Air, R_{fi}			Outdoor – Moving Air, R_{fo}	
			Reflective surface		Non-reflective surface	
		Non-reflective surface	Aluminum-coated paper, polished	Bright aluminum foil	15 mph wind, winter design	7.5 mph wind, summer design
Vertical	Horizontal	0.68	1.35	1.70	0.17	0.25
Horizontal	Up	0.61	1.10	1.32	0.17	0.25
	Down	0.92	2.70	4.55	0.17	0.25

1. *ASHRAE Handbook of Fundamentals*, 2005, www.ASHRAE.org.

Table 5.3.3 Thermal Resistances, R_a, of Air Spaces[1].

Position of Air Space	Direction of Heat Flow	Air Space		Non-Reflective Surfaces	Reflective Surfaces		
		Mean temp., °F	Temp. difference, °F		One side[2]	One side[3]	Both sides[3]
Vertical	Horizontal (walls)	**Winter**					
		50	10	1.01	2.32	3.40	3.63
		50	30	0.91	1.89	2.55	2.67
	Horizontal (walls)	**Summer**					
		90	10	0.85	2.15	3.40	3.69
Horizontal	Up (roofs)	**Winter**					
		50	10	0.93	1.95	2.66	2.80
		50	30	0.84	1.58	2.01	2.09
	Down (floors)	50	30	1.22	3.86	8.17	9.60
		50	10	1.24	4.09	9.27	11.15
	Down (roofs)	**Summer**					
		90	10	1.00	3.41	8.19	10.07

1 For 3½ in. air space thickness. The values, with the exception of those for reflective surfaces, heat flow down, will differ about 10% for air space thicknesses of ¾ in. to 6 in. Refer to the *ASHRAE Handbook of Fundamentals* for values of other thicknesses, reflective surfaces, heat flow directions, mean temperatures, and temperature differentials. *ASHRAE Handbook of Fundamentals*, 2005, www.ASHRAE.org.

2 Aluminum painted paper.

3 Bright aluminum foil.

Table 5.3.4 Thermal Properties of Various Building Materials at 75°F[1].

Material	Density, lb/ft^3	Resistance, R per in. of Thickness, $hr \cdot ft^2 \cdot °F/Btu$	Specific Heat, Btu/(lb·°F)
Insulation, rigid			
Cellular glass	8.0	3.03	0.18
Glass fiber, organic bonded	4.0 – 9.0	3.1 – 4.2	0.23
Mineral fiber, resin bonded	15	3.1 – 4.2	0.17
Extruded polystyrene (XPS), extruded cont. closed cell	1.8 – 3.5	5.00	0.29
Expanded polystyrene (EPS), molded bead	1.0	3.85	—
	1.25	4.00	
	1.5	4.17	
	1.75	4.17	
	2.0	4.35	—
Cellular polyurethane/ polyisocyanurate (unfaced)	1.5	6.25 – 5.56[2]	0.38
Cellular phenolic, closed cell	3	8.2	
Cellular phenolic, open cell	1.8 – 2.2	4.4	
Polyicynene	0.5	3.6	
Miscellaneous			
Gypsum board	50	0.88	0.26
Particle board	50	1.06	0.31
Plaster			
cement, sand aggregate	116	0.20	0.20
gypsum, lightweight aggregate	45	0.63	—
gypsum, sand aggregate	105	0.18	0.20
Wood, hard (maple, oak)	38 – 47	0.94 – 0.80	0.39
Wood, soft (pine, fir)	24 – 41	1.35 – 0.89	0.39

1 See Table 5.3.6 for concrete. *ASHRAE Handbook of Fundamentals*, www.ASHRAE.org.

2 An aged value of 6.0 is currently recommended. *Environmental Building News*, January 2005, www.BuildingGreen.com.

Window System	U-Factor, Btu/hr·ft²·°F	SHGC[2]
Double glazing with low-E coating and argon gas fill in an aluminum frame with thermal break	0.36	0.36
Double glazing with a low-E coating in an aluminum frame with thermal break	0.40	0.36
Double glazing in an aluminum frame with thermal break	0.56	0.65
Single glazing in an aluminum frame with no thermal break	1.13	0.65

Table 5.3.6 Thermal Properties of Concrete[1].

Description	Concrete Density, lb/ft³	Thickness, in.	Resistance, R		Specific heat, Btu/(lb·°F)
			Per in. of thickness, hr·ft²·°F/Btu	For thickness shown, hr·ft²·°F/Btu	
Concrete including normal weight, lightweight, and lightweight insulating concretes	145		0.063		0.20
	140		0.068		0.20
	130		0.083		0.20
	120		0.10		0.20
	110		0.13		0.20
	100		0.16		0.20
	90		0.21		0.20
	80		0.27		0.20
	70		0.36		0.20
	60		0.44		0.20
	50		0.59		0.20
	40		0.71		0.20
	30		0.91		0.20
	20		1.25		0.20
Normal weight solid panels, 140 to 150 pcf, sand and gravel aggregate	145	2		0.13	0.20
		3		0.19	
		4		0.25	
		5		0.31	
		6		0.38	
		8		0.50	
Structural lightweight solid panels	110	2		0.26	0.20
		3		0.38	
		4		0.51	
		5		0.64	
		6		0.76	
		8		1.02	

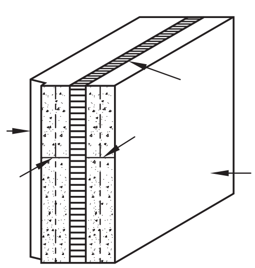
1 Based on values in the 2005 *ASHRAE Handbook of Fundamentals* and *ANSI/ASHRAE/IESNA Standard 90.1-2007*. Values do not include air film resistances. See Table 5.3.7 for R-values with air film resistances.

Table 5.3.7 R-Values for Solid Concrete and Sandwich Panel Walls[1].

Concrete Density, lb/ft^3	t,[2] in.	R-Value of Concrete No Air Films, No Insulation	R-Value of Insulation Resistance, hr·ft^2·°F/Btu												
			0 (No ins.)	1	2	3	4	5	6	8	10	12	15	16	18
145	2	0.13	0.98	2.0	3.0	4.0	5.0	6.0	7.0	9.0	11.0	13.0	16.0	17.0	19.0
	3	0.19	1.04	2.0	3.0	4.0	5.0	6.0	7.0	9.0	11.0	13.0	16.0	17.0	19.0
	4	0.25	1.10	2.1	3.1	4.1	5.1	6.1	7.1	9.1	11.1	13.1	16.1	17.1	19.1
	5	0.31	1.16	2.2	3.2	4.2	5.2	6.2	7.2	9.2	11.2	13.2	16.2	17.2	19.2
	6	0.38	1.23	2.2	3.2	4.2	5.2	6.2	7.2	9.2	11.2	13.2	16.2	17.2	19.2
	8	0.50	1.35	2.4	3.4	4.4	5.4	6.4	7.4	9.4	11.4	13.4	16.4	17.4	19.4
110	2	0.25	1.10	2.1	3.1	4.1	5.1	6.1	7.1	9.1	11.1	13.1	16.1	17.1	19.1
	3	0.38	1.23	2.2	3.2	4.2	5.2	6.2	7.2	9.2	11.2	13.2	16.2	17.2	19.2
	4	0.51	1.36	2.4	3.4	4.4	5.4	6.4	7.4	9.4	11.4	13.4	16.4	17.4	19.4
	5	0.64	1.49	2.5	3.5	4.5	5.5	6.5	7.5	9.5	11.5	13.5	16.5	17.5	19.5
	6	0.76	1.61	2.6	3.6	4.6	5.6	6.6	7.6	9.6	11.6	13.6	16.6	17.6	19.6
	8	1.02	1.87	2.9	3.9	4.9	5.9	6.9	7.9	9.9	11.9	13.9	16.9	17.9	19.9

1 Values in table are the total R-values of the walls with concrete of thickness t and insulation R-value as indicated in columns. Only for insulation with no metal or solid concrete penetrating the insulation layer. R-values will be impacted by the presence of these items and additional calculations will be required according to series-parallel or zone method. Air film resistances of 0.68 for inside and 0.17 for outside are included in R-values unless otherwise noted. These are standard air film resistances for winter conditions and are conservative for summer conditions.

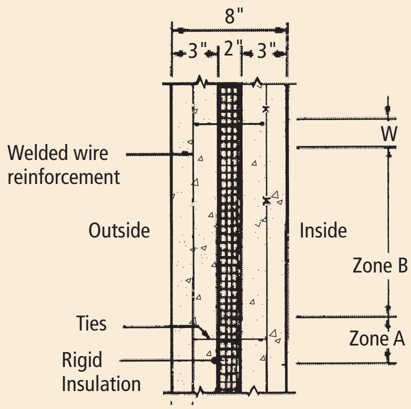
2 The thickness, t, is the sum of the thicknesses of the concrete wythes for a sandwich panel wall.



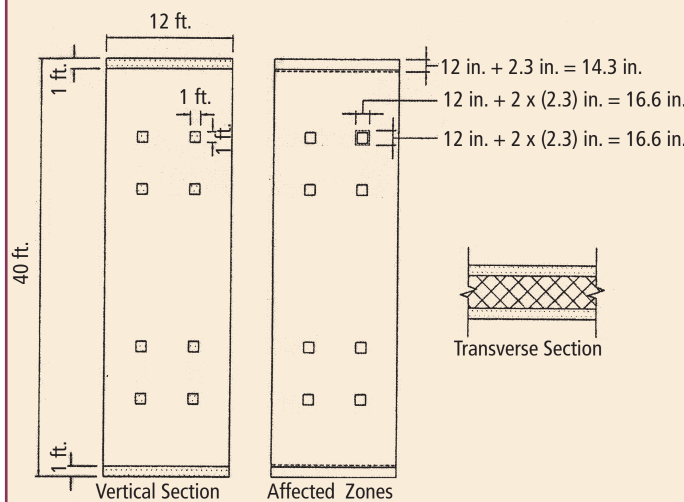
Example 5.3.1 – Calculate R-Value of Wall Assembly.

	Wall Layer	R Winter	R Summer	Table
A.	Surface, outside air film	0.17	0.25	5.3.2
B.	Concrete, 2 in. (145 pcf)	0.13	0.13	5.3.7
C.	EPS insulation (1.25 pcf), 1.5 in.	6.00	6.00	5.3.4
D.	Concrete, 2 in. (145 pcf)	0.13	0.13	5.3.7
E.	Surface, inside air film	0.68	0.68	5.3.2
	Total R =	7.11	7.19	
	U = 1/R	0.14	0.14	

Fig. 5.3.16 Metal tie thermal bridges.



Example 5.3.2 Determination of R-value for sandwich panel.



Insulated Path.

		k	Thickness	U = k/t	R = 1/U Winter	R = 1/U Summer
A	Outside surface	—	—	—	0.17	0.25
B	Concrete	10.00	3	3.33	0.30	0.30
C	Insulation	0.20	2	0.10	10.00	10.00
D	Concrete	10.00	3	3.33	0.30	0.30
E	Inside surface	—	—	—	0.68	0.68
	Total				11.45	11.53

Concrete Path.

		k	Thickness	U = k/t	R = 1/U Winter	R = 1/U Summer
A	Outside surface	—	—	—	0.17	0.25
B	Concrete	10.00	8	1.25	0.80	0.80
C	Insulation	—	—	—	0.68	0.68
	Total				1.65	1.73