Chapter

2

Energy Transfer

In this chapter, you will learn the following to World Class standards:

- **Energy Transfer**
- **Specific Heat of a Material**
- **Heat Transfer Calculations**
- **Heat Transfer through Barriers**
- **Calculating Energy Losses with R-Values**

Energy Transfer

One of the largest usages of energy in the world is heating or cooling of a building, whether that structure is a home or business. Even if people would tolerate a daily range of temperatures from lets say 40°F (4.4°C) to 80°F (26.7°C), where they would just turn off the furnace and the air conditioner, the products they purchase would not fare well, because they also work best or last longer when they reside in a nominal ambient temperature. Using a different strategy, we could just heat or cool ourselves using an environmental suit which would take far less energy, since a family of four would only have to hold the average comfortable heat or temperature they desire against their own skin, and then the furniture, kitchen appliances and the bedroom articles would have to survive the weather with their own protection. So unless we want to change the design of all our household or business possessions, we will need to heat or cool the entire dwelling to maintain our accustomed 70°F (21.1°C) temperature.

So whether we wish to control the temperature with a macro or micro system, we first need to understand how we gain heat or then how heat is lost. If we place a pot that contains a gallon of water on a gas stove, we could add energy to the water by heating the base of the pot with a fire. By igniting the fossil fuel (methane gas) coming from the burners on top the stove, a flame heats the atoms in the stainless steel container, exciting the electrons which cause motion and vibration by radiation. Radiation is one of three methods that heat energy flows, where the energy is transmitted to the container through electromagnetic waves which can travel through space. We can measure the amount of thermal energy the container is receiving by measuring the temperature of the pot.

Some of the heat will dissipate away from the exterior of the containing through conduction, the second method of energy flow. However, since the molecules in the air next to the pot are not very dense, the transfer of the hotter temperature to the lower temperature in this region is not substantial. The thermal energy from the stainless steel container will transfer or conduct more effectively to the water in the pot where the liquid was at ambient temperature. Through conduction, the excited atoms of the metal pot are in direct contact with the water molecules, and the excited molecules in the pot interact with the atoms of the water. We also can measure the temperature of the water at the bottom of the pan to detect the transfer of thermal energy.

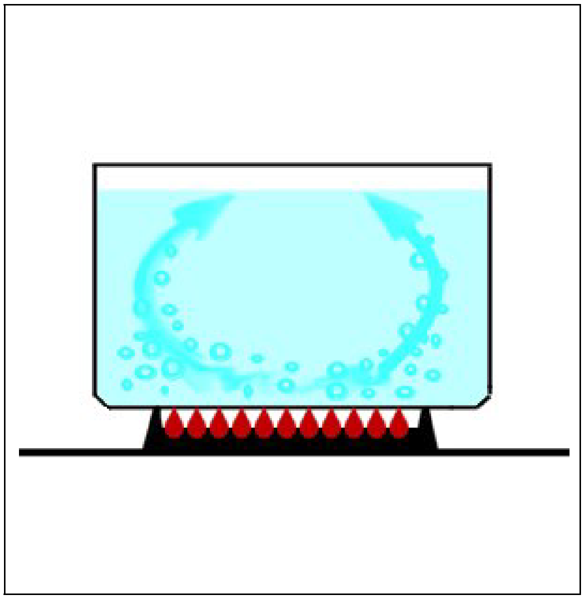


Figure 2.1 – 3 Types of Energy Flow

The last method of energy flow we will examine in our example is what is happening in the water. At the bottom of the container, the water is becoming extremely energized or as we would remark, "hot". Most often in fluids, convection takes over as the main method of heat transfer. As the water is heated, the density of the liquid, which is the amount of molecules per given volume gets smaller, and in this case the hotter and lighter water will rise to the surface, being replaced by the heavier and colder water. After just a few moments, we can observe the fluid in the container moving from bottom to top and from top to bottom. Convection of heat energy will take place is phases of matter that are fluid and are able to move freely.

In any system we observe, all energy is conserved and never destroyed. However, we may want that energy to be directed efficiently in the direction we choose and that may not always happen. As technicians, we need to know how to use and contain energy by design.

Radiation	**The transfer of thermal energy through space by electromagnetic wave**
Conduction	**The transfer of thermal energy from one body of matter to another by contact**
Convection	**The transfer of thermal energy mainly in fluids by motion**

When we heat a building to levels that are comfortable to people, very often the outside temperatures are different than the interior nominal temperature of 70°F (21.1°C). If the outside air temperature is 20°F (-6.7°C), then the differential between the two levels of heat is 50°F (10.0°C). The pathway to equilibrium in the system is for the energy in the building to reach a balance with the outside environment. In most cases that we observe, the hotter elements release energy to the cooler until they reach symmetry. In this study, we need to understand how different substances gain or lose heat, and so we need to comprehend Specific Heat.

Specific Heat of a Material

The specific heat of a material is the amount of energy to raise an amount of substance 1 degree. The measurement is made in three major systems, Joules per kilogram degree Celsius, Calorie per gram degree Celsius and BTU per pound degree Fahrenheit.

We know from studying the last chapter, the Nature of Energy, that the Joule is the amount of energy to lift a one Newton (4.4 pounds) weight the distance of one meter (3.28 feet). A Joule can also raise a kilogram of water one degree Celsius. The Joule is the most prevalent mode of measuring energy; however some industries still use the BTU. The British Thermal Unit (BTU) is the amount of energy to increase one pound of liquid water one Fahrenheit degree. Another unit we may see in a specific heat table is the calorie. This is the amount of energy to raise a gram of matter one degree Celsius. When we can also observe the amount of Watts in an energy formula or in a set of data. Remember that a Watt is one joule per second.

The table in Figure 2.2 shows the specific heat of common materials. We can find the specific heat of materials in product data sheets in catalogs or on web pages. Depending on the purity of the material and the accuracy of the test, the quantities recorded can vary slightly between published tables. We included the density of some of the materials for the problems in this chapter.

Substance	Joules/kg °C	Calorie/g °C	BTU/lb °F	Density (lb/in³)
Air (50° C)	1006	0.240	0.240	
Aluminum, 6061-T6	963	0.230	0.230	0.098
Concrete	1000	0.239	0.239	
Glass	837	0.200	0.200	
Granite	790	0.190	0.190	
Ice (-10°C to 0°C)	2093	0.500	0.500	
Iron	440	0.105	0.105	
Marble	858	0.205	0.205	
Soil	1046	0.250	0.250	
Steam (100° C)	2009	0.480	0.480	
Steel C1020	419	0.100	0.100	0.284
Water	4186	1.000	1.000	0.023
Wood	1674	0.400	0.400	

Figure 2.2 – Table of Specific Heats for Common Materials

Heat Transfer Calculations

To understand heat transfer of larger problems, we will start by examining the transfer of heat energy from small objects to the surrounding environment.

The amount of heat energy transferred equals the mass of the object times the change in temperature times the specific heat of the material. In the formula below, Q is the amount of heat energy, m is equal to the mass of the body, ΔT is the change in temperature and Cp is the specific heat of the material.

$$Q = m(\Delta T)Cp$$

In our first heat transfer problem, we have a 1.0 inch cast aluminum cube at a temperature of 200°F in a foundry that surrounding air temperature of 72°F. How much heat energy is released when the cube cools to the surrounding temperature?

The volume of the cube is 1 in. × 1 in. ×1 in. or 1 in³. The density of aluminum is 0.098 pounds per cubic inch, so 1 in³ × 0.098 lbs / in³ equals 0.098 lbs.

$$Q = w(\Delta T)Cp$$

$$Q = 0.098(200°F - 72°F)0.230BTU/lb - °F = 0.098 \times 128 \times 0.230 = 2.88512 \text{ BTU}$$

The aluminum cube transferred 2.88 BTUs of energy into the room. Now, we can do another problem using the metric units.

In our second heat transfer problem, we have a 3.5 kg aluminum casting at a temperature of 180°C in a foundry that surrounding air temperature of 22°C. How much heat energy is released when the cube cools to the surrounding temperature?

$$Q = m(\Delta T)Cp$$

$$Q = 3.5kg(180°C - 22°C)963J/kg - °C = 3.5 \times 158 \times 963 = 532{,}539 \text{ Joules}$$

The 3.5 kg aluminum casting emits 532,539 Joules of energy into the room. What if we made hundreds of these castings a day? Could we figure a way to use the heat from the foundry to warm the office?

*** World Class CAD Challenge 12-7 * - Find the amount of heat energy released in each problem in the table below. The information in the table can be in various systems of measurement, so you may have to convert the data prior to placing the amount into the heat energy formula. Complete each record in 2 minutes and record the answers in the table.**

	Heat	**Mass or Weight**	**Heated Object**	**Room Temperature**	**Material**
	Q	Kg or lbs	°C or °F	°C or °F	Aluminum
1		10 kg	150 °C	20 °C	Iron
2		1.5 kg	100 °C	22 °C	Steam
3		100 lbs	90 °F	70 °F	Water
4		2000 lbs	85 °F	40 °F	Concrete
5		250 lbs	50 °C	10 °C	Wood
6		200 kg	50 °F	15 °C	Marble
7		10 lbs	35 °C	18 °C	Glass
8		400 kg	60 °C	21 °C	Granite
9		3 tons	85 °F	62 °F	Soil
10		9 tons	800 °F	80 °F	Iron

By familiarizing ourselves with specific heat quantities, we recognize that the process to raise the temperature of aluminum one degree requires more energy than increasing the temperature of an equal mass of steel one degree. We see that we can measure energy transfer by accurately recording the temperature of the surrounding air temperature. However, you might have already noticed in this simple equation, that in a smaller room, the heat from the hotter mass could be so great that the surrounding air temperature may increase significantly and therefore change the temperature in the equation throughout the transfer process. Then our answer would not be correct and the mass will not cool to our original projections. If the surrounding air temperature increases then the material will equalize above the initial air temperature reading and the observing the entire system, the temperatures balance out and the mass will no longer cool.

The next equation we will study will look not just at heat loss, but at heat gain. In this formula, we state that heat loss equals heat gain, which matches the Law of Conservation of Energy.

Heat loss = Heat gain

By investigating both the emitting material and the receiving matter, we can determine the temperature of the entire system when the transference of heat energy is complete. Before doing any calculations, we will have to think about what is changing as the heat energy transfers; that is what masses are losing heat energy and what matter is gaining energy. We will calculate how much energy causes a substance to change phases, from solid to liquid and from liquid to gas. We will continue to isolate our problem and ignore the affects of the outside world on the system we are investigating, such as the temperature outside the walls.

When we examine problems where heat energy is transferred, we must understand that a large amount of energy is used to cause matter to change phases, such as from ice to water or from water to steam. There is an expenditure of energy in causing these phase transitions. In heat transfer problems where the mass changes phases from solid (ice), the temperatures can essentially remain the same but we require energy to change the state of matter. The Specific Latent Heat of Fusion for ice is 0.336 Mega Joules per kilogram, so if we want to melt 10 kg of ice, we would add 3.36 Mega Joules to the ice to have ice water. The Specific Latent Heat of Vaporization for water is 2.26 Mega Joules per kilogram. We would need 22.6 Mega Joules of energy to transition boiling water to steam. The graph in Figure 2.3 shows what is actually happening to the water as energy is spent to bring ice to steam.

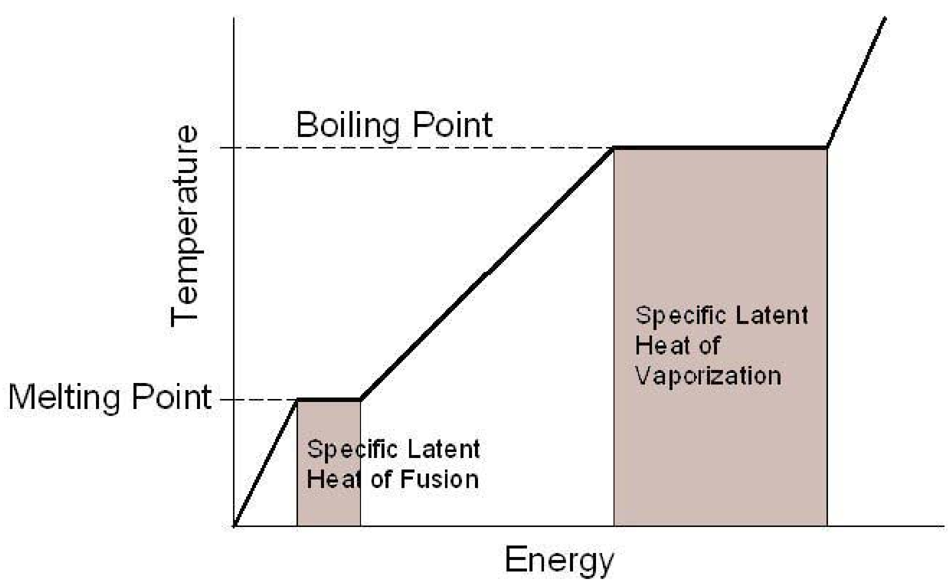


Figure 2.3 – Graph Showing Energy Usage to Transform a Material through States

So in our first problem, we will melt ice in a large amount of water and discover the final temperature of the liquid, thus examining both concepts; heat loss equals heat gain and the applying the Specific Latent Heat. We will neglect examining any energy loss or gain from the surrounding environment. The formula to calculate the energy spent to change the state of matter such as ice to water is Mass times the Specific Latent Heat.

$$Q = mL$$

Now, can you imagine that we can place 1 kilogram (2.2 pounds) of ice in container holding 10 kilograms (22 pounds) of water at 21.1°C (70°F). What is the final temperature of the water when the ice melts? Ignore any other surrounding conditions.

We begin with the equation:

Heat loss = Heat gain

The heat loss in the experiment is in the surrounding water that initially was 21.1°C (70°F). As the warmer water melts the ice, two energies are spent. The first energy gain is in the ice, where a large amount of energy is used to transition the ice to water. The second amount of energy is in stabilizing the ice water to the final temperature of the mixture. Below, we see the breakdown displaying heat loss and gain.

Heat loss	**=**	**Heat gain**		
Heat lost by surrounding water	=	Heat gained by the ice	+	Heat gained by the warming ice water

Now, we use our first formula, $Q = mCp\Delta T$ and our new formula showing energy for transformation of a phase of matter, $Q = mL$ in the calculation. The heat loss is on the left of the equation and the heat gains are on the right side. In the table, we found that the specific heat of water is 4186 Joules per kilogram degree Celsius. We are also utilizing the 3.36×10^5 Joules per kilogram in the conversion of ice to water.

$$m_w Cp_w \Delta T_w = m_{ice} L_f + m_{icewater} Cp_{icewater} \Delta T_{icewater}$$

$$10kg \times \frac{4186J}{kg°C} \times (21.1°C - T_f) = 1kg \times \frac{3.36 \times 10^5 J}{kg} + 1kg \times \frac{4186J}{kg°C} \times (T_f - 0°C)$$

$$41860(21.1 - T_f) = 3.36 \times 10^5 + 4186 T_f$$

$$883{,}246 - 41860\ T = 336{,}000 + 4186\ \mathrm{T}$$

$$883{,}246 - 336{,}000 = 4186\ \mathrm{T} + 41860\ T$$

$$547246 = 46046\ \mathrm{T}$$

$$T = \frac{547246}{46046} = 11.88°\mathrm{C}$$

The final temperature of the water will be 11.88 °C.

If we were observing the experiment, we would have 11 kg of water at 11.88 °C, with no ice remaining. We can see that this approach gives us more information concerning an actual event, where we can see the balancing of heat energy and determine the final temperature. Now we will place a large block of ice in a small room and determine the final temperature.

Can you imagine that we can place 5 kilogram (11 pounds) of ice in a room that is 10 ft by 12 foot and has an 8 ft high ceiling at 22.2°C (72°F). What is the final temperature of the room when the ice melts and the room temperature and the water stabilize? Ignore any other surrounding conditions.

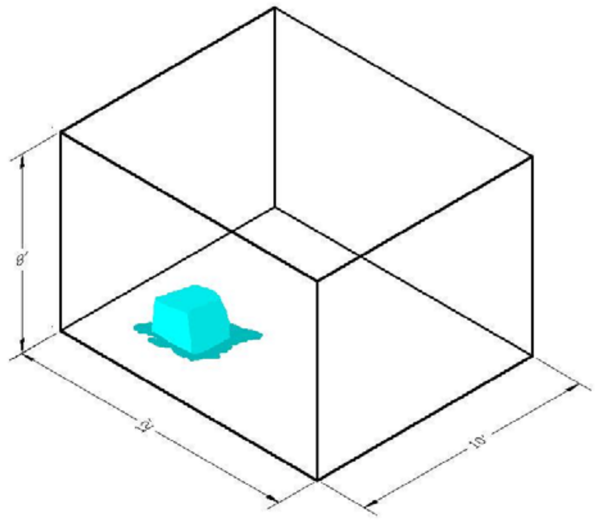


Figure 2.4 – Melting Ice in a Room

In this problem, we need to get the cubic feet of the air in the room and convert the number to a mass using the density of air of 1.2 kilogram per cubic meter.

The 10 ft by 12 ft by 8 ft room is 960 cubic feet. 960 cubic feet is 27.18 cubic meters. Multiply the 1.2 kilogram per cubic meter times 27.18 cubic meters, which equals 32.616 kilograms.

Heat loss	=	**Heat gain**		
Heat lost by surrounding air	=	Heat gain by the ice	+	Heat gained by the warming ice water

$$m_{air} Cp_{air} \Delta T_{air} = m_{ice} L_f + m_{icewater} Cp_{icewater} \Delta T_{icewater}$$

$$32.616kg \times \frac{1006J}{kg°C} \times (22.2°C - T_f) = 5kg \times \frac{3.36 \times 10^5 J}{kg} + 5kg \times \frac{4186J}{kg°C} \times (T_f - 0°C)$$

$$32811.696(22.2 - T_f) = 3.36 \times 10^6 + 41860 T_f$$

$$728{,}419.6512 – 32811.696\ T = 1{,}680{,}000 + 20930\ \mathrm{T}$$

$$728{,}419.6512 - 1{,}680{,}000 = 32811.696\ T + 20930\ \mathrm{T}$$

$$-951580.3488 = 53741.696\ \mathrm{T}$$

$$T = \frac{-951580.3488}{53741.696} = -17.71°\mathrm{C}$$

The final temperature of the water will be -17.71°C.

*** World Class CAD Challenge 12-8 * - A 50 kg iron stove is turned off in a 20 ft by 12 ft room with a 10 ft ceiling The iron stove's temperature is 200°F and the current temperature in the room is 60°F. Compute the final temperature in a room when the air temperature and the iron stove reach equilibrium. Ignore the surrounding conditions outside the room.**

Heat Transfer through Barriers

In the two types of problems we did, we either isolated the hot object from a ever changing surrounding environment while the material is cooling or in the second case we transferred energy from one system to another. In the real world, heat energy does leave the hotter object and transfer to the cooler room, but the next we discover that the walls or barriers that enclose our specific space also are transferring or receiving heat energy. If the temperature outside the building is colder, the heat energy from the room will transfer to the outside. In the summer, the greater heat energy is outside and the exterior walls act as a barrier to the transfer of energy. Now, we need to examine the materials ability to insulate or conduct heat energy.

To calculate the energy transfer through a wall, we will use Fourier's Law of Conductivity, which states that the rate of heat flow, dQ/dt through a homogenous solid barrier is directly proportional to the area of the barrier, the thermal conductivity of the material and the change of temperature from outside to inside and inversely proportional to the thickness of the barrier. The formula is shown below.

$$\frac{Q}{t} = -kA\frac{\Delta T}{\Delta x}$$

Where:
- Q = Heat energy
- t = time
- k = Thermal conductivity
- A = Area of the barrier (wall)
- ΔT = Change of temperature
- Δx = Thickness of the barrier (wall)

We need to discuss an example of transferring heat energy through a barrier. For instance, some concrete buildings are built with two inch polystyrene forms that are left in place. If the concrete's temperature is 4.4°C (40°F) and the room temperature is 21.7°C (71°F), what is the amount of energy loss in a 20 foot long by 10 foot tall wall?

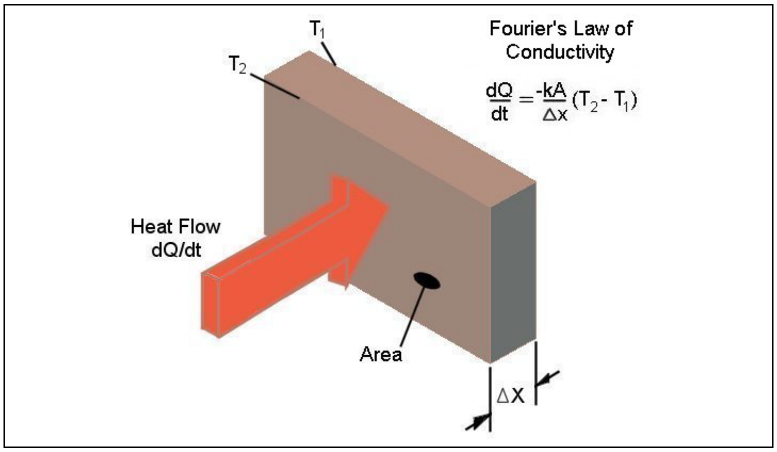


Figure 2.5 – Fourier's Law of Conductivity

After writing the formula, we look up the thermal conductivity of polystyrene (Styrofoam) in the table in Figure 2.6, which is 0.019 BTU per hour foot degree Fahrenheit. Next, the area is 20 ft times 10 ft. The delta T or the change of temperature is 71°F minus 40°F. To compute the thickness of the wall, we divide 2 inches by 12 inches per foot to obtain 0.167 feet. Place the quantities in the equation as shown.

$$\frac{Q}{t} = -kA\frac{\Delta T}{\Delta x}$$

$$\frac{Q}{t} = \frac{-0.019BTU}{hr \times ft \times {}^\circ F}(20\,ft \times 10\,ft)\frac{71^\circ F - 40^\circ F}{0.167\,ft}$$

$$\frac{Q}{t} = \frac{-0.019BTU}{hr \times ft \times {}^\circ F}(200\,ft^2)\frac{31^\circ F}{0.167\,ft} = 705.4\,\text{BTU/hr}$$

The energy loss from the wall is 705.4 BTU per hour, which is a small amount of energy loss, and the quantity is better than if we were using a non-insulated eight inch block or brick wall that we see in use throughout older buildings in the United States. Using the table in Figure 2.6, to compute the energy loss in a wall using four inch red brick. The outside temperature is 4.4°C (40°F) and the room temperature is 21.6°C (71°F). The wall is still 20 foot long by 10 foot tall.

Substance	**Watts/m °C**	**BTU/hr ft °F**
Air (0° C)	0.024	0.014
Aluminum, 6061-T6	205	118.5
Concrete	0.8	0.46
Glass	0.8	0.46
Brick, red	0.6	0.347
Ice (-10°C to 0°C)	1.6	0.925
Iron	79.5	46.0
Polystyrene	0.033	0.019
Fiberglass	0.04	0.023
Steel	50.2	29.0
Water	0.6	0.347
Wood	0.12-0.04	0.069-0.023

Figure 2.6 – Table of Thermal Conductivity for Common Materials

Begin by setting up the formula.

$$\frac{Q}{t} = -kA\frac{\Delta T}{\Delta x}$$

$$\frac{Q}{t} = \frac{-0.347BTU}{hr \times ft \times {}^\circ F}(20\,ft \times 10\,ft)\frac{71^\circ F - 40^\circ F}{0.167\,ft}$$

$$\frac{Q}{t} = \frac{-0.347\,BTU}{hr \times ft \times {}^\circ F}\left(200\,ft^2\right)\frac{31^\circ F}{0.167\,ft} = 12{,}883\text{ BTU/hr}$$

The calculation shows that we lose 12,883 BTU per hour or 18 times more energy than with the 2 inch polystyrene barrier.

*** World Class CAD Challenge 12-9 * - A commercial building has 8 inch concrete walls. The building is 100 foot by 40 foot rectangle with 10 feet high walls. The temperature is 20°F and the current temperature in the room is 70°F. Ignoring the three doors, the front windows, and the ceiling, compute the energy loss through the building's walls.**

Calculating Energy Losses with R-Values

Most of us have all heard of R values. In the building industry, they represent an inverse to the amount of heat energy loss through a wall, window, door or ceiling. There is relationship to the Fourier's Law of Conductivity is that one R-value equals one degree Fahrenheit, square foot, hour per BTU, so rewrite Fourier's Law of Conductivity, substituting $\frac{-k}{\Delta x}$ with $\frac{1}{R}$ as shown in the formula below.

$$\frac{Q}{t} = -kA\frac{\Delta T}{\Delta x} = \frac{A \times \Delta T}{R}$$

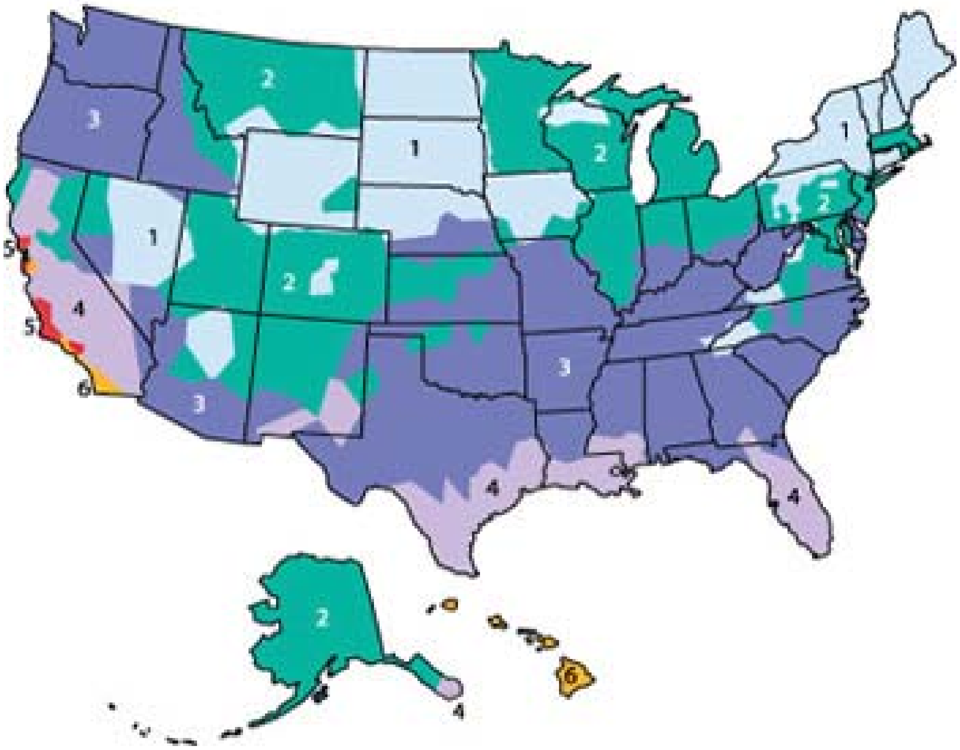
Therefore, the higher the R-value the better when trying to save the heat energy in the building or keep the hot summer temperatures outside in the warmer weather. Recommendations from the U.S. Department of Energy for how much insulation do you need are in Figure 2.6.

If we insulate a 200 square foot wall in central to northern Ohio to R22, and examine the energy loss on the 4.4°C (40°F) day when the room temperature is 21.6°C (71°F), what is the energy loss?

$$\frac{Q}{t} = -kA\frac{\Delta T}{\Delta x} = \frac{A \times \Delta T}{R}$$

$$\frac{Q}{t} = -kA\frac{\Delta T}{\Delta x} = \frac{200\,ft^2 \times 31^\circ F}{22\,\frac{{}^\circ F \times ft^2 \times hr}{BTU}} = 281.8\text{ BTU / hr}$$

Now, we can calculate the energy loss for a 100 ft by 40 ft building built on a concrete slab in zone 2 of the U.S. Department of Energy recommended insulation value map. The walls are 10 feet high. The temperature is 20°F and they keep the temperature set at 70°F. The ground temperature is 50°F. The building has an electric furnace. Ignoring the doors and windows, what is the energy loss?



Zone	Gas	Heat pump	Fuel oil	Electric furnace	Ceiling		Wall	Floor	Crawlspace	Slab edge	Basement	
					Attic	Cathedral					Interior	Exterior
1	X	X	X		R-49	R-38	R-18	R-25	R-19	R-8	R-11	R-10
1				X	R-49	R-60	R-28	R-25	R-19	R-8	R-19	R-15
2	X	X	X		R-49	R-38	R-18	R-25	R-19	R-8	R-11	R-10
2				X	R-49	R-38	R-22	R-25	R-19	R-8	R-19	R-15
3	X	X	X	X	R-49	R-38	R-18	R-25	R-19	R-8	R-11	R-10
4	X	X	X		R-38	R-38	R-13	R-13	R-19	R-4	R-11	R-4
4				X	R-49	R-38	R-18	R-25	R-19	R-8	R-11	R-10
5	X				R-38	R-30	R-13	R-11	R-13	R-4	R-11	R-4
5		X	X		R-38	R-38	R-13	R-13	R-19	R4	R-11	R-4
5				X	R-49	R-38	R-18	R-25	R-19	R-8	R-11	R-10
6	X				R-22	R-22	R-11	R-11	R-11	-	R-11	R-4
6		X	X		R-38	R-30	R-13	R-11	R-13	R4	R-11	R-4
6				X	R-49	R-38	R-18	R-25	R-19	R8	R-11	R-10

Figure 2.7 – Recommended Total R-Values for New Houses in Six Climate Zones

Our insulation for the zone 2 construction will be as follows:

Concrete slab	**R-8**
Wall	**R-22**
Ceiling	**R-49**

The calculation for the 100 ft by 40 ft concrete slab is:

$$\frac{Q}{t} = \frac{A \times \Delta T}{R} = \frac{4000\,ft^2 \times 20°F}{8\,\frac{°F \times ft^2 \times hr}{BTU}} = 10{,}000 \text{ BTU / hr}$$

The calculation for the 280 ft of 10 ft high walls is:

$$\frac{Q}{t} = \frac{A \times \Delta T}{R} = \frac{2800\,ft^2 \times 50°F}{22\,\frac{°F \times ft^2 \times hr}{BTU}} = 6364 \text{ BTU / hr}$$

The calculation for the 100 ft by 40 ft ceiling is:

$$\frac{Q}{t} = \frac{A \times \Delta T}{R} = \frac{4000\,ft^2 \times 50°F}{49\,\frac{°F \times ft^2 \times hr}{BTU}} = 4082 \text{ BTU / hr}$$

Our total energy loses are:

Area	**BTU / hr**
Concrete slab	**10000**
Wall	**6364**
Ceiling	**4082**
Total	**22728**

*** World Class CAD Challenge 12-10 * Now, we can calculate the energy loss for a 250 ft by 75 ft building built on a concrete slab in zone 3 of the U.S. Department of Energy recommended insulation value map. The walls are 9 feet high. The temperature is 20°F and they keep the temperature set at 70°F. The ground temperature is 55°F. The building has an electric furnace. Ignoring the doors and windows, what is the energy loss?**

The study of heat transfer is as complex as the number of transitions we want to include into the problem and there are many. There are numerous textbooks and guides that entirely investigate the subject of heat transfer. In the next chapter, we will learn about selecting prefabricated assemblies such as doors and windows that will save energy.