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Introduction:

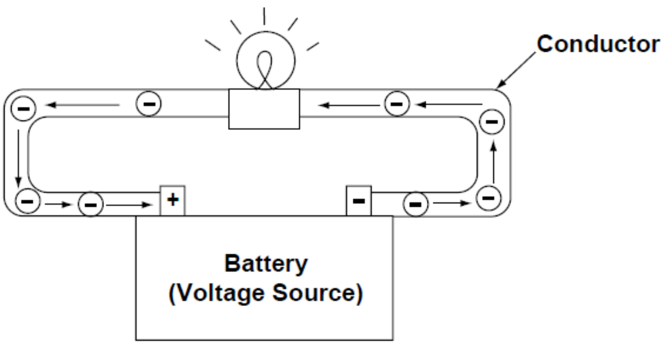
Almost nothing affects us more in our daily lives than electricity. Electricity heats and cools buildings, provides light, brings electric machinery to life and provides the "spark of life" in gasoline engines. Electricity plays an important part in Watlow heaters too. Electric current through a heater's resistance wire produces heat energy. This heat energy is used by the work load to perform some process.

Electric Circuit Relationships:

Electricity

"Electricity" usually means inserting the plug of an electric device (like a lamp) into a wall socket and turning it on. There is a lot more to it than that! When a device (such as the lamp) is connected to a power source (like a battery) a circuit is formed. The circuit in Figure 1 is composed of a battery, connection wires (conductors) and a lamp. The wires provide a path for electricity to flow.

Figure 1



Electricity is really the movement or flow of electrons through the wiring. It is more commonly called electric current. When the battery is disconnected, the electron flow (electric current) through the circuit stops.
If we install a switch in the circuit, closing the switch closes the circuit. Electric current now "flows" through the lamp filament causing it to glow (Figure 2b). Opening the switch opens the circuit (Figure 2a) and stops electric current through the lamp. The lamp now goes dark.

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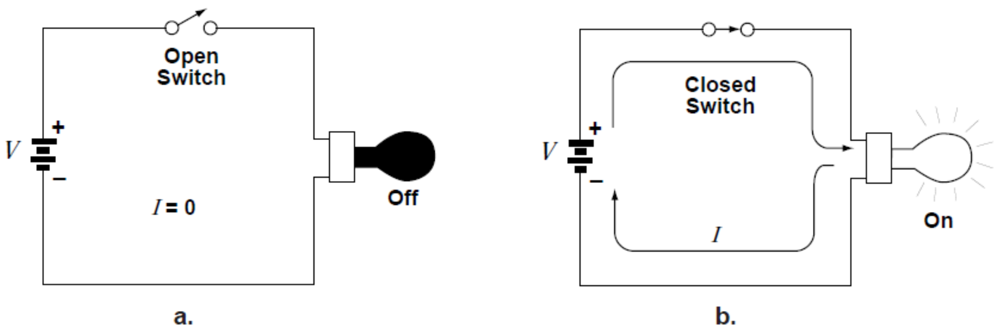
Figure 2



What is main difference between Figures 2a and 2b?
There is no electric current through an open circuit.
There is electric current through a closed circuit.

Electrical Supply

There are mainly two types of industrial power supply available: direct current (or DC) and alternating current (or AC). Voltage supplies are often given as “VDC” or “VAC.” For example, a 24VDC supply simply means a 24-volt DC voltage supply. Let’s examine DC and AC more closely.

Direct Current (DC)

Direct current (DC) is used mostly to power small, portable pieces of equipment using batteries or to operate industrial machinery at low voltages. DC is electric current which flows in only one direction. The electrons in Figure 3a move at a constant rate through the circuit (and the heater) from the negative to positive sides of the battery. Traditionally, however, the direction of current flow is shown as positive to negative. Either way, current is only in one direction.

Notice that the symbol for a heater is a resistor. This is because of the resistance element inside of the heater does the same thing as a resistor—it resists electric current.

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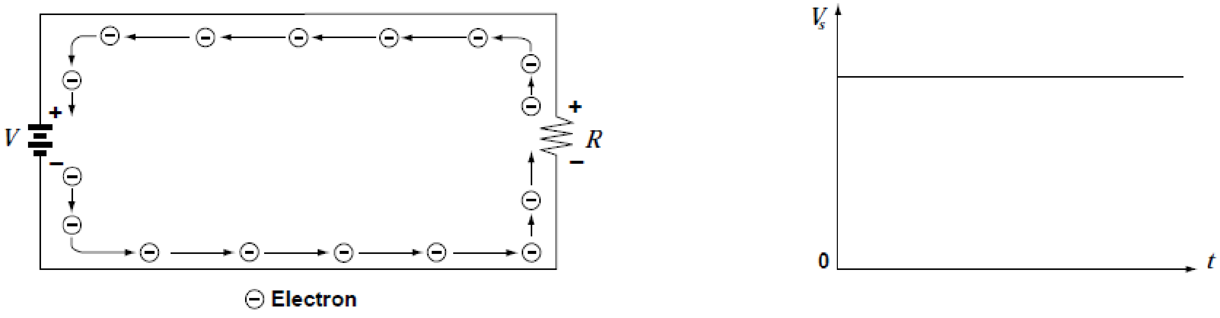
Figure 3



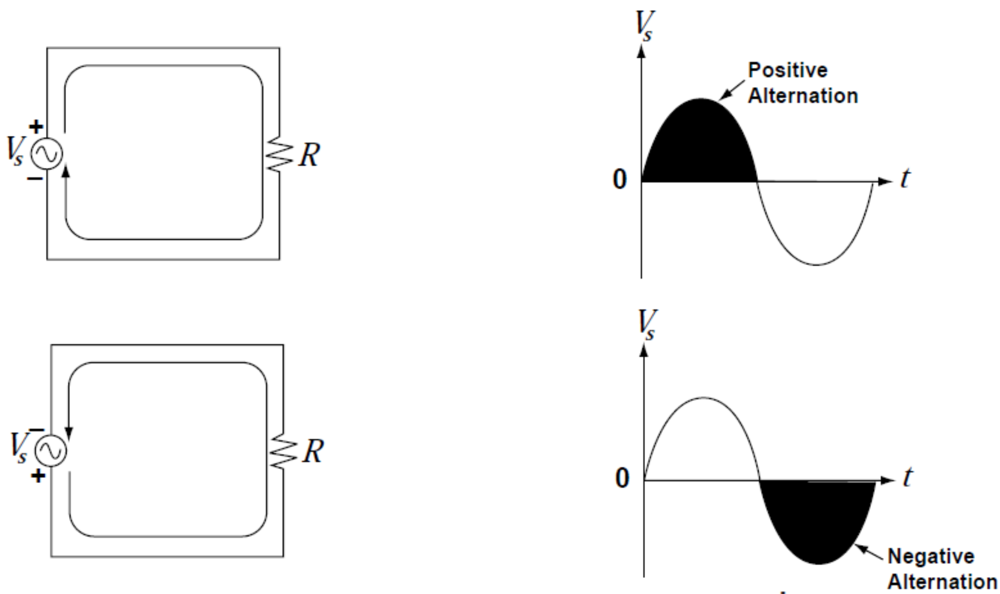
a.   b.

If we measure the voltage value across this DC power source and graph it, it looks like Figure 3b. Notice that the voltage value over time (and thus electric current) is constant and positive.

Alternating Current (AC)

The vast majority of electricity used in our homes and in industry, however, is alternating current (AC). AC flows in both directions (Figure 4a). The electrons first move in one direction through the circuit and then in the opposite direction. This is how alternating current got its name, it "alternates" directions. If we graph the voltage value of an AC power supply over time, it looks like Figure 4b. Compare Figures 3b and 4b. See any differences?

Figure 4

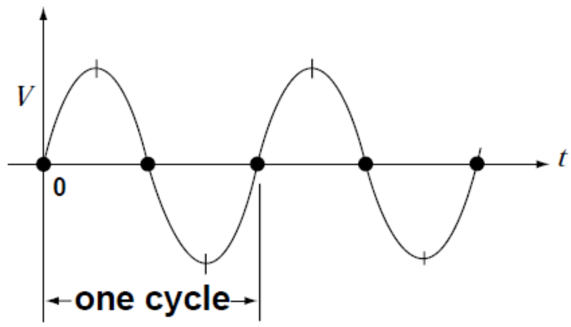


a.   b.

Notice the differences in the symbols used to show either a DC or AC voltage supply. You will see this used not only in this information sheet, but in industry as well.

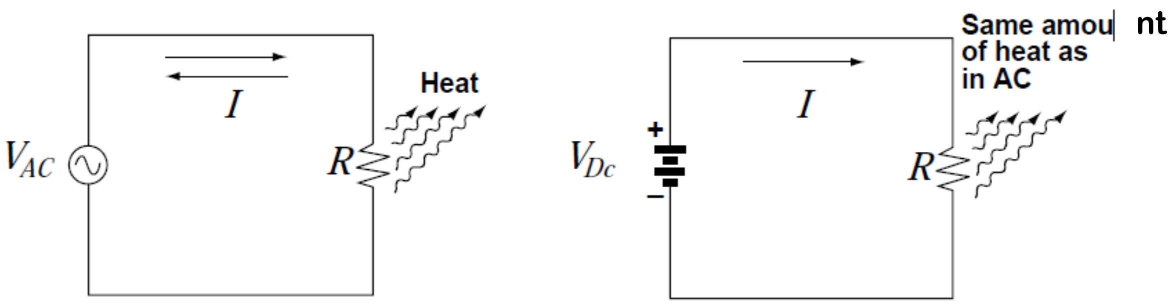
The voltage graphs look completely different! Not only is AC voltage rising and falling over time, it switches directions. Alternating current changes directions, because the positive and negative sides of the power supply change their polarity. That is, the positive side becomes negative and the negative side becomes positive (see circuit diagrams in Figure 4).
We call one complete positive to negative swing on the graph a cycle (Figure 5). The number of cycles per second are called hertz (Hz). North America has a 60 cycle per second (60Hz) power supply. Europe has a 50Hz power supply.

Figure 5



Sometimes a customer will ask if a heater can be used on AC or DC. Or they will ask if using a 50 or 60Hz power supply will affect heater performance. What do you think? Does it matter? No! Electric heaters produce the same amount of power AC or DC, 50 or 60Hz, as long as the same voltage value is used (Figure 6).

Figure 6



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Great, we know what an electric circuit is, what AC and DC power are and the net effect of using either AC or DC on a given heater. But how do we know how much resistance to put in a heater? How can we determine how much current is required to produce a certain amount of heat energy? We use a fantastic tool called Ohm's Law.

Ohm's Law

An electric heater of a certain size and material has a resistance value which remains constant. True, the resistance does change with temperature, but we will ignore temperature effects for now. For our purposes, the resistance of Watlow heaters remain constant.

Definitions

Before we proceed, however, we should define a few terms commonly used when working with electric heaters and circuits:

Current (I): The flow of electricity (movement of electrons) through any electrical conductor. It is measured in units called amperes (or amps).

Voltage (V): The force causing electric current through an electrical conductor. Voltage is also called "electrical potential." It is measured in units called volts.

Resistance (Ω): The opposition of a conductor to the movement of electrons (or electric current) through it. It is measured in units called ohms. Ohms are symbolized by the Greek letter omega (Ω).

Wattage (W): The amount of power (heat energy produced in a given time period) by a heater's resistance element. It is measured in units called watts.

Ohm's Law Relationships

The question now is: how do we calculate the effects of using heaters in an electric circuit? All of Ohm's Law values (volts, watts, amps and ohms) are mathematically related. This makes life easy, because if we know any two of the four values, we can calculate the other two as well.

There are three forms of Ohm's law that relate to voltage, current, and resistance. For a constant flow of current, the current is given by the ratio of voltage across terminals to the resistance of the resistor.

I = V/R

Ohm's law can also be written as

R = V/I

Or

V = IR

I is the current measured in Amps
V is the voltage measured in Volts
R is the resistance measured in Ohms

Power is introduced with W = VI or V = W/I or I = W/V where W = Power measured in Watts

Let's work through an example and put these simple formulas to use.

Example 1:

If 120 volts is applied to a Watlow silicone rubber heater and the current through the heater is 10 amps, how much power (wattage) is produced? How much resistance does the heater have?

Wattage: W = VI 120V X 10A = 1,200 Watts

Resistance: R = V/I 120/10 = 12 Ohms or $V^2/W = (120V)^2 / 1200W$ = 12 Ohms

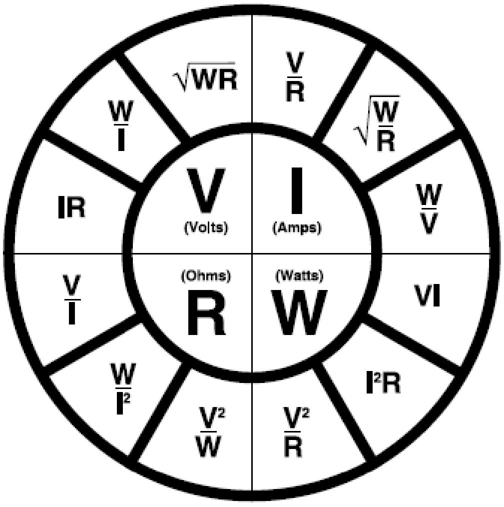
Example 2:

A Watlow MI band heater is rated at 110 volts and 400 watts. What is the heater's resistance? How much electric current will flow through the heater?

I = W/V 400w/110v = 3.6 Amps.

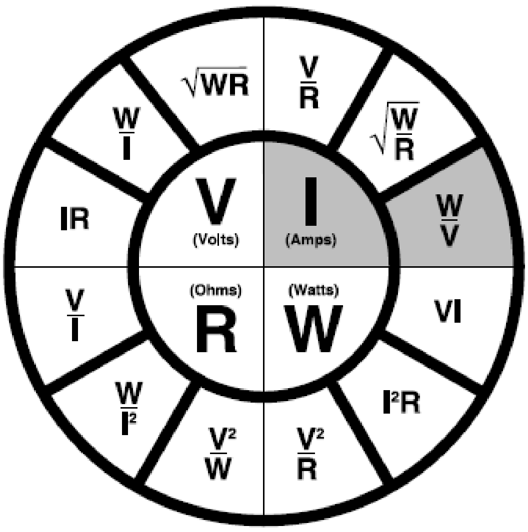
R = V/I 110/3.6 = 30.55 Ohms

Variations of calculations are available & a useful tool is Ohms law circle:



a.

For example, if you have a 115v 3600w heater and want to know its current draw you can select your required parameter in the Inner circle, in this case I or current requirement.
You can then select the parameters given in the outer circle to quickly establish the formula required, as in depiction b below & the shaded portion.
So, in this case, I = W/V or 3600/115 = 31.3 amps



b.

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Now that we know how to calculate volts, amps, watts, and ohms, we take another step forward. In many applications, more than one heater is often required. How the heaters are connected in an electric circuit determines how much total wattage the heaters produce. Therefore, in the next sections, we further explore electric circuits.

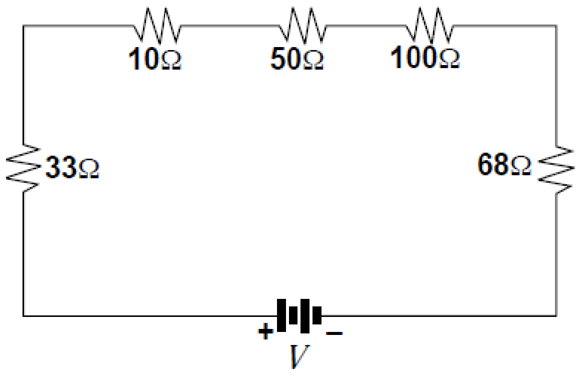
Electric Circuits:

To review, an electric circuit typically consists of a voltage source, an electric device or load (such as a heater), an electric current path (wires connecting the voltage source to the electric load) and some type of switch. When connecting heaters into a circuit, we can connect them in two basic ways: in series or in parallel. This section explores their differences and their effect on Ohm's Law relationships and calculations.

Series Circuits:

A series circuit is easy to understand and apply. A series circuit has two or more heaters connected end-to-end. An example is shown in Figure 8.

Figure 8



How do we apply Ohm's Law to a series circuit? It's actually quite easy! Since the heaters are 'connected end-to-end in the circuit, what do you think is the total resistance value of the circuit? If you said that the total resistance is equal to the sum of all heater resistances, you are absolutely right! The resistance of each heater ADDS to the total resistance of the circuit.

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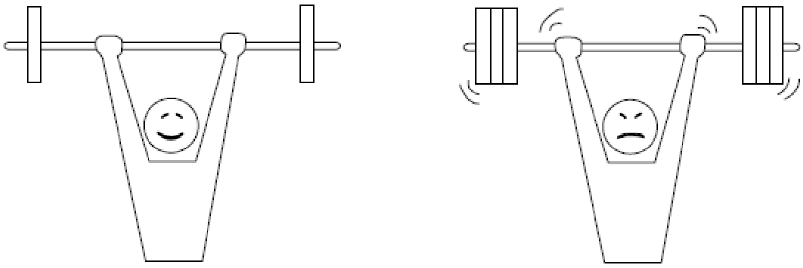
We can compare this to a man lifting heavy weights. As he lifts more and more weight, it becomes harder and harder to lift these weights (Figure 9). Why? The total weight lifted is the sum of each individual weight. The more weight added, the more the total becomes. Same thing with series circuits!

Figure 9



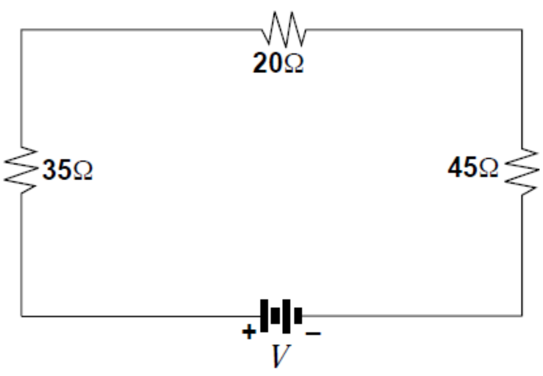
We can express this relationship in a simple formula:

$$\text{Series } R_T = R_1 + R_2 + R_3 + \ldots.$$

Where: RT = total series circuit resistance
R1, R2, R3 = the resistance values of each heater in the circuit

Example 3: What is the total resistance of the series circuit in Figure 10?

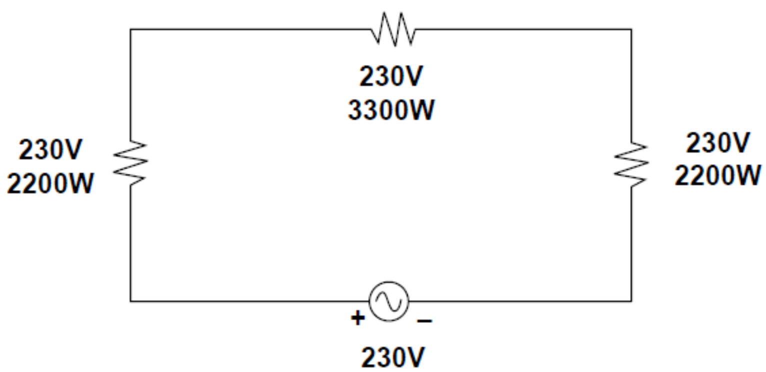
Figure 10



The heater resistance values are 20, 45 and 35 ohms.
Therefore, the total is: RT = R1 + R2 + R3 = 20 + 45 + 35Ω= 100Ω

Example 4: Several heaters are connected in a series circuit (Figure 11). Let’s calculate total resistance of the series circuit. Then we will go one step further and calculate total wattage and current for the complete circuit.

Figure 11



Since heater resistance is not given to us directly, we have to calculate it. How do we do this? Our old friend Ohm’s Law! We use the formula “R = V2/W,” because we are given the volt and watt ratings for each heater.

Resistance of heater #1 R1 = (230V) ^{2}/2200W = 24.05Ω

Resistance of heater #2 R2 = (230V) ^{2}/3300W = 16.03Ω

Resistance of heater #3 R3 = (230V) ^{2}/2200W = 24.05Ω

Now we know the resistance value of each heater. As we know, to calculate total series circuit resistance, we have to add all heater resistance values.

Series Circuit Resistance: RT = R1 + R2 + R3 = 24.05 + 16.03 + 24.05Ω RT = 64.13Ω

Now, we are ready to calculate total circuit wattage output. How? Simple. Just use one of the Ohm’s Law formulas. Make sure you use the total resistance RT.

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Series Circuit Wattage: $RT = V^2/W$

$W = V^2/RT$

$= (230V)^2/64.13\Omega$

$W = 825$ watts

What happened here? We have 3 heaters, each rated for at least 2200 watts. Yet the total wattage output of the circuit is only 825 watts! Did we do something wrong? Shouldn't the total wattage be the sum of each of the heater's wattage? We have done everything right. Let's uncover why we calculated such a low wattage output for this series circuit. Heaters in a series circuit are connected end-to-end. This, in effect, makes one big heater with a lot more resistance. The more resistance a circuit (or a heater) has, the lower the wattage output is. This is confirmed when we compare using just heater #1 in a circuit to using all the heaters in the circuit:

$R1 = V^2/W$	$RT = V^2/W$
$W = V^2/R1$	$W = V^2/RT$
$= (230V)^2/24.05\Omega$	$= (230V)^2/64.13\Omega$
$= 2200W$ (rated wattage)	$W = 825$ watts (total circuit wattage)

See the difference? Thus, a heater's voltage and wattage rating assumes it will be used by itself in a circuit, not strung together with other heaters in series. Now, let's calculate current through the series circuit.

Series Circuit Current: $W = VI$

$I = W/V$

$= 825W/230V$

$I = 3.6$ amps

Notice, that the first step was to calculate the total heater resistance. Then we used Ohm's Law to analyze the series circuit wattage and current. Now let's look at another example. Remember, first calculate circuit resistance, then calculate other total circuit values using Ohm's Law.

Exercise 4

Calculate the resistance, wattage and current of the circuit in Figure 11 when we put another heater in series (see Figure 12). The additional heater is rated at 230 volts and 2940 watts.

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Exercise 4:

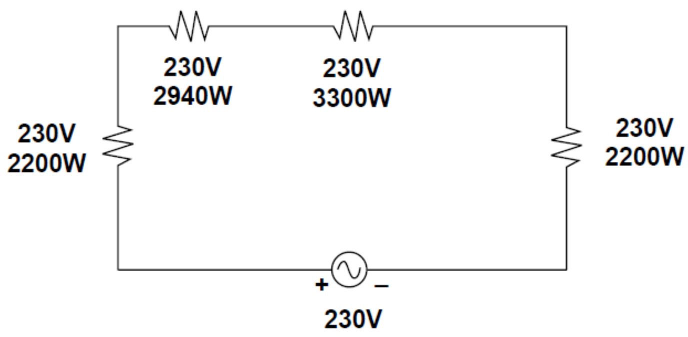
Resistance of Heater #4:
R4 = (230V) ²/2940W
= 18Ω

Circuit Resistance:
RT = R1 + R2 + R3 + R4
= 24.05 + 16.03 + 24.05 + 18Ω
= 82.13Ω

Circuit Wattage:
RT = V ²/W
W = V ²/RT
= (230V) ²/82.13Ω
W = 645 watts

Circuit Current:
V = IRT
I = V/RT
= 230V/82Ω
I = 2.8 amps

Figure 12



Compare the values calculated in Exercise Four to the values calculated in Example 4. What happened to R, W and I when we added another heater in series? Total resistance increased from 64.13 to 82.13 Ω, just as we predicted! Circuit wattage decreased from 825 to 645 watts and circuit current dropped from 3.6 to 2.8 amps.
As a result, we can say that as circuit resistance increases, wattage and current will decrease. It's that simple!

Before we move on, though, what if a customer wants to know how much current is flowing through each heater in Exercise Four? How do we calculate that? That is a good question!

Imagine a series of pipe sections connected to a tank of water (Figure 13). Each pipe section is connected end-to-end. Is the amount of water flowing through each pipe section going to be different or the same?

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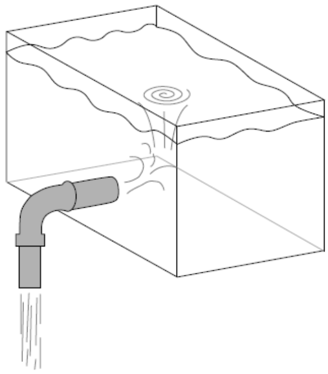
Figure 13



The same amount of water MUST flow through each pipe section in order to spill out the end of the pipe. The water flow can go nowhere else. The same thing applies to heaters connected in series! Electric current (amps) through any one of the heaters must be equal through all heaters. We can express this relationship in formula form:

Series IT = I1 = I2 = I3 = ...

Exercise Five:

Calculate the current through each heater in Exercise Four. Then calculate the actual (not rated!) wattage which each heater is producing. (Hint: Use Ohm's Law Circle to find the formula to calculate each heater's wattage, based on resistance and current.)

Since IT = 2.8 amps and IT = I1 = I2 = I3 = I4, then I1 = I2 = I3 = I4 = 2.8 amps.

Using Ohm's Law Circle (page 7), the formula is W = I2R for each heater. Thus:

$W1 = I^2R1 = (2.8A)^2 (24.05\Omega) = 189W$

$W2 = I^2R2 = (2.8A)^2 (16.03\Omega) = 126W$

$W3 = I^2R3 = (2.8A)^2 (24.05\Omega) = 189W$

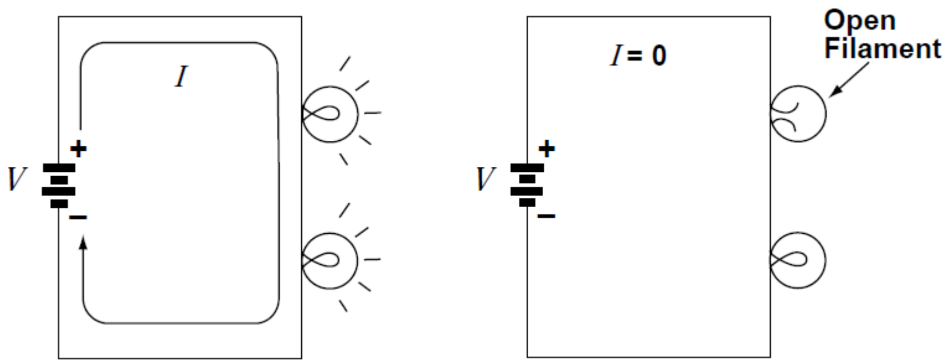
$W4 = I^2R4 = (2.8A)^2 (18\Omega) = 141W$

WT = W1 + W2 + W3 + W4 = 189 + 126 + 189 + 141W = 645W

When a Heater Burns Out

As we know, electric heaters, like light bulbs, will eventually burn out. This brings up the question of what happens when a heater in a series circuit burns out? When any one of the heaters (or in the case of Figure 14, light bulbs) fail, the circuit is broken and electric current stops. Figure 14 illustrates this effect

Figure 14



If there is no current, is any heat produced? Absolutely not. The weak point, then, in the series circuit is that if one heater fails, the entire circuit goes down. This can be very frustrating, because it shuts your entire machine down! There is a solution to this problem. The solution is to connect heaters in a parallel circuit. Before we jump into parallel circuits, however, let's review what we have discovered about series circuits.

Series Circuit Review:

Each resistor adds to the total resistance of a series circuit.
RT = R1 + R2 + R3 +...

To calculate series circuit wattage and current values, simply calculate the total resistance of the circuit and then use Ohm's Law formulas.

The current through each resistor is equal to the total series circuit current.
IT = I1 = I2 = I3 = ...

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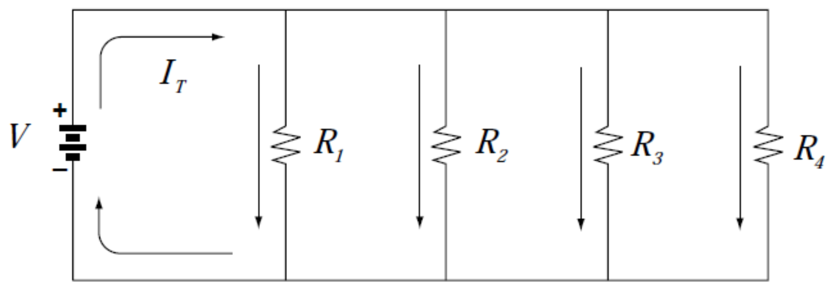
The wattage each heater produces can be summed to equal the total circuit wattage.
WT = W1 + W2 + W3 +...
When one heater in a series circuit burns out, the circuit is opened, current flow stops and all heaters stop producing heat.

Parallel Circuits:

The first thing you notice when looking at a parallel circuit in Figure 15 is its "ladder" shape. The heaters are connected like steps on a ladder. Looking back at a series circuit from previous figures, the heaters are strung together end-to-end. See the difference?

Figure 15



Also, we recently discovered that in a series circuit, there was only one path for electric current to go. Thus, the same amount of current had to flow through each heater's resistance element. A parallel circuit, in comparison, has two or more heaters connected in a parallel, ladder style. Now there are many paths through which the current may flow.

Do you think that the same amount of current will flow through a parallel circuit, compared to a series circuit? More? Less? Let's again compare water flow out of a tank with drain pipes to an electric circuit. Compare Figure 16 to Figure 13. Will more water flow from the water tank if the drain pipes are connected in series (Figure 13) or in parallel (Figure 16)?

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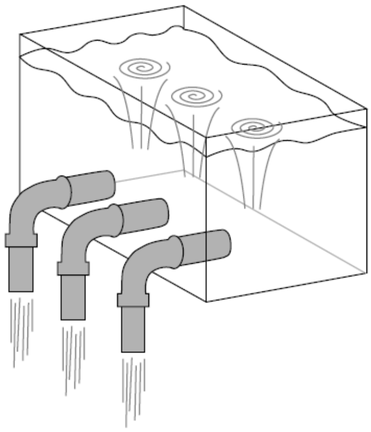
Figure 16



Do you agree that more water will flow out of the parallel pipe sections? Yes, of course, more water will flow out of 3 holes in a tank than in just one hole! If there is more water flow with parallel pipe sections, there will also be more current flow in parallel electric circuits!
So, current through parallel circuits is much greater than in a series circuit. Thus, each heater in parallel ADDS to the total parallel circuit current. We can express this in formula form:

Parallel IT = I1 + I2 + I3 + ...

Notice the difference between this current relationship and the one for a series circuit (page 13)? Now, what happens to the total circuit resistance in parallel? In the series circuit, each additional heater increased the total resistance, right? The opposite is true in parallel circuits! Each additional heater connected in parallel decreases the total resistance of the circuit! Why? Parallel circuits provide many paths for current to flow. The more paths there are, the easier it is for current to flow. Thus, the overall resistance to current drops.

We can verify this using Ohm's Law. Applying the formula "V = IR," if voltage (V) is constant and circuit current (I) increases with every additional heater, total circuit resistance (R) MUST decrease to hold V constant. Therefore, we have to use a different formula to calculate total circuit resistance:
Parallel 1/RT = 1/R1 + 1/R2 + 1/R3 + ...

The best way to really compare series and parallel is to work through an example. Let's take the series connected heaters in Figure 10 (Example 3, page 9) and connect them in parallel.

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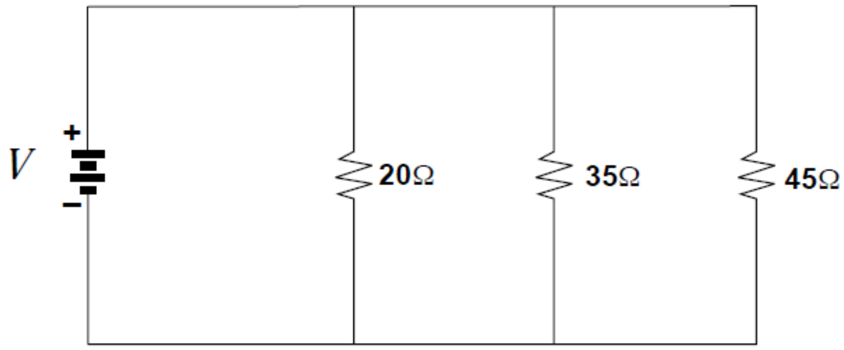
Example 6: What is the total resistance of the heaters in the parallel circuit in Figure 17?

Figure 17

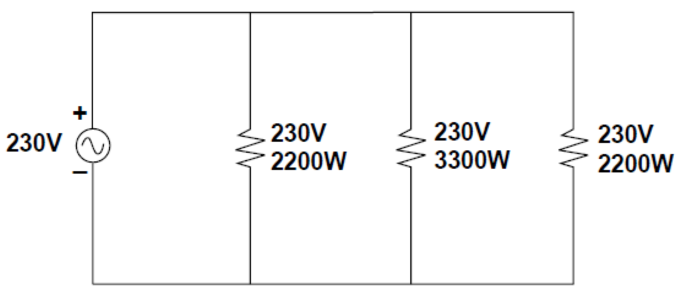


The heater resistance values are 20, 45 and 35 ohms. Therefore, the total is:
1/RT = 1/R1 + 1/R2 + 1/R3 = 1/20 + 1/45 + 1/35Ω = 0.10079
RT = 9.92Ω

Compare this to 100Ω when these same heaters were connected in a series circuit! Quite a difference! Let's do another example and compare the results from the series circuit in Figure 11 (Example 4, page 10).

Example 7: What is the total circuit resistance, wattage and current of the circuit in Figure 18? These heaters are the exact same heaters used in Example 4, Figure 11.

Figure 18



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As always, the first step is to calculate the resistance for each heater, then the total circuit resistance. The resistance value for each heater was already calculated in Example 4. We just need to plug these values into the parallel circuit resistance formula.

Parallel circuit resistance:

1/RT = 1/R1 + 1/R2 + 1/R3
= 1/24.05 + 1/16.03 + 1/24.05Ω
1/RT = 0.1456
RT = 6.87Ω

Compare the total resistance values for the series and parallel circuits:

Series circuit = 64Ω
Parallel circuit = 6.87Ω

Look what happens to the total circuit resistance! The total resistance in parallel is dramatically less than in series. Did we physically change the heaters in any way? No, we simply reconnected them from series into parallel. What a powerful tool to use!
How do we calculate parallel circuit wattage? Easy. Just use Ohm's Law exactly as you did for a series circuit. Make sure you use the total resistance RT.

Parallel circuit wattage:

RT = V^2/ W
W = V^2/ RT
= (230V)2/6.87Ω
W = 7700 watts

Compare the wattage of the series and parallel circuits.

Series circuit = 825 watts
Parallel circuit = 7700 watts

The wattage has jumped from 825 watts to 7700 watts! Why? We now see the effects of the low parallel circuit resistance (6.87Ω). Lower resistance means more current flow. More current flow means more heat is generated in each heater's resistance element.

Add the rated heater wattages together in Figure 18. What do you get? Surprise! You get 7700 watts. This means that in a parallel circuit, you can add each heater's rated wattage and get the total wattage output of the circuit.

Now, let's calculate current through the parallel circuit. What do you expect? Will the current be higher or lower than in a series circuit?

Parallel Circuit

Current: W = VI
I = W/V
= 7700W/230V
I = 33.5 amps

Compare the current of the series and parallel circuits.

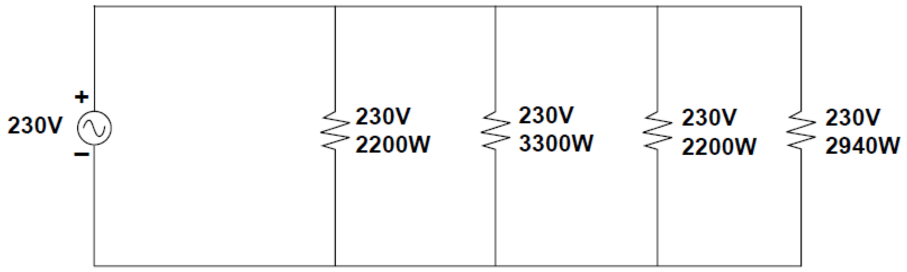
Series circuit = 3.6 amps
Parallel circuit = 33.5 amps

This confirms what we discovered at the beginning of this section. That is, current flow through a parallel circuit is much greater than through a series circuit. This makes sense, because now there are more paths for current to flow. Now it's your turn to apply parallel circuit relationships! Work through the next two exercises to get some good, hands-on practice.

Exercise Six:

Let's add another heater to the parallel circuit in Example 7. These heaters are the exact same ones used in Figure 12 (Exercise Four, page 10). Using Figure 19, calculate circuit resistance, wattage, and current. Then compare them to your answers for Exercise Four.

Figure 19



Exercise 6:
R1 = (230V) ²/2200W = 24.05Ω
R2 = (230V) ²/3300W = 16.03Ω
R3 = (230V) ²/2200W = 24.05Ω
R4 = (230V) ²/2940W = 18Ω

Parallel Circuit Resistance:
1/RT = 1/R1 + 1/R2 + 1/R3 + 1/R4
= 1/24.05 + 1/16.03 + 1/24.05
+ 1/18Ω
RT = 4.97Ω

Parallel Circuit Wattage:
RT = V2/W
W = V2/RT
= (230V)2/4.97Ω
W = 10,644 watts
OR add all heater wattages
directly to get 10,640 watts

Parallel Circuit Current:
V = IRT
I = V/RT
= 230V/4.97Ω
I = 46.3 amps

By comparing your answers to Exercise Six and Exercise Four, you can clearly see the differences between series and parallel circuits. Adding another heater into a parallel circuit has the opposite effects of adding another heater into a series circuit. In Exercise Six, circuit resistance decreases to 4.97Ω, wattage increases to 10,640 watts and circuit current increases to 46.3 amps.

Exercise Seven:

Calculate the current through each heater in Exercise Six. (Hint: Because each heater in a parallel circuit is, in effect, directly connected to the voltage supply, you can simply use the Ohm's Law formula "W = VI".

I1 = W1/V = 2200W/230V = 9.57A

I2 = W2/V = 3300W/230V = 14.35A

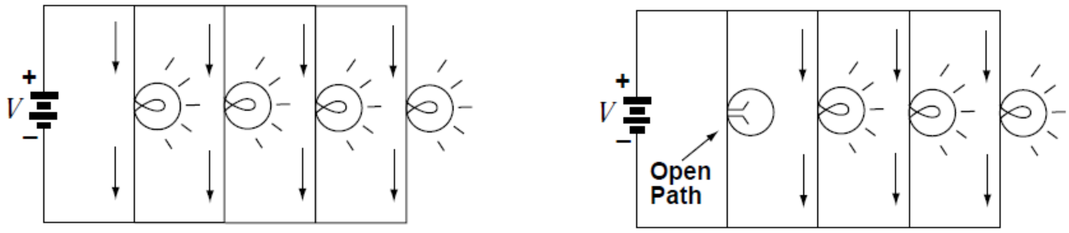
I3 = W3/V = 2200W/230V = 9.57A

I4 = W4/V = 2940W/230V = 12.78A

When a Heater Fails:

Most heaters in industrial applications are connected in parallel. Parallel has a major advantage over series. When any one heater fails, the entire circuit is NOT broken. Electric current continues to flow through the other working heaters! Notice how the burned-out light bulb in Figure 20 does not affect current flow to the other light bulbs? The other lights are still working fine.

Figure 20



Parallel Circuit Review

To review, let’s examine the highlights of parallel circuits:

Adding heaters in parallel reduces the total resistance of a parallel circuit.
1/RT = 1/R1 + 1/R2 + 1/R3 + ...

To calculate parallel circuit values simply calculate the total resistance of the circuit and then use Ohm’s Law formulas. If the supply voltage equals the heater rated voltage, then just add each heater’s rated wattage for the wattage total.

Total parallel circuit current is equal to the current through each heater.
IT = I1 + I2 + I3 + ...

When one heater in a parallel circuit burns out, the remaining heaters are not affected and continue to operate.

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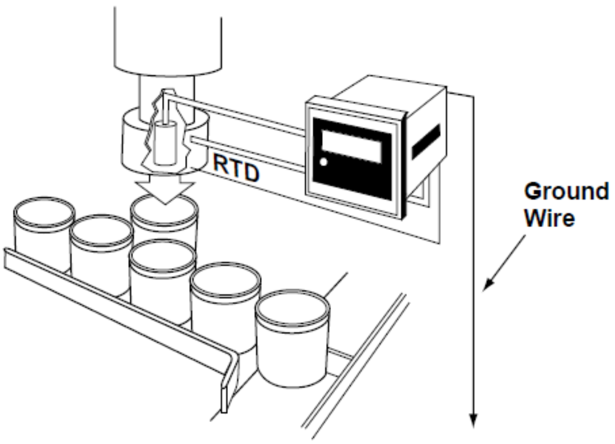
Electrical Ground

In any electrical device (including heaters), there is always the possibility that current leakage or a short circuit will occur. "Leakage current" is a small amount of electric current which passes through the electrical insulation of heaters, motors, or other electrical devices. The leakage current may be strong enough to cause a shock or to cause sensitive electronic devices not to operate properly. A short circuit occurs when some part of an electric circuit contacts metal parts of a machine. This shortens (or "shorts") the electric circuit, because the resistance which is normally in a circuit is bypassed. This creates a high current which eventually blows a fuse somewhere in the circuit. If the short circuit causes electric current to come in contact with someone, that person will get an electric shock.

An electrical or safety ground is used to protect people from being hurt and/or equipment damaged. As the name implies, it "grounds" electrical current in case of a short circuit. It is basically a wire attached to the metal part of an electric device and connected to a metal rod which is driven into the earth (ground).

Now the ground functions as an alternate return path for electricity. The ground path effectively "drains" off any leakage current or short circuit current into the earth. Figure 21 shows an example of a thermal system with a ground.

Figure 21



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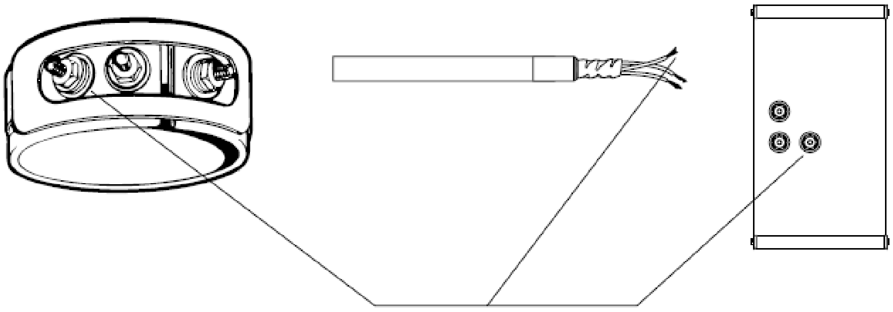
Many heaters ordered from Watlow are manufactured with a ground wire or a ground terminal as an added safety feature (Figure 22). The third lead or terminal on the heater is where the connection is made.

Figure 22



You can easily tell which terminal or lead is the ground. It is either color coded green (or green with a yellow stripe) or labeled with a tag or ground symbol (⏚). If you are not sure which terminal is the ground, measure the resistance between all terminals (or all leads). The ground will measure "open" or a very high resistance between one terminal and the two other terminals. The resistance measured between the two remaining terminals will measure near the heater's rated resistance value (based on rated volts and watts). If still unsure, please contact the factory to verify the heater specifications.

Three phase power:

For many people, three phase (3ph) power tends to be somewhat mysterious. However, working with heaters in 3ph circuits is actually quite simple! Don't take our word for it, you will discover this yourself! As usual, we apply Ohm's Law formulas to calculate volts, watts, etc. For 3ph, however, we adjust the formulas slightly. We give you these formulas and work through several examples step-by step to get you comfortable applying them. Three phase power is one of the most widely used sources of electrical power in industrial machinery. As with single phase AC power, it is rated in volts (for example, 480V, 3ph). We see the difference between single and 3ph power by graphing their voltage values over time. In Figure 23, notice how 3 phase voltage has 3 distinct "waves" of power for every 1 "wave" of single-phase power. That is how "3 phase" power got its name.

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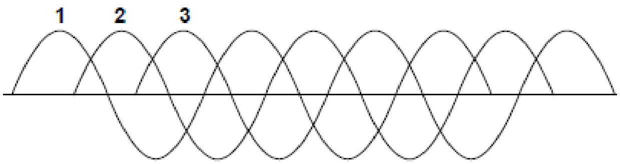
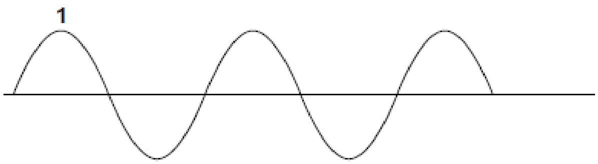
Figure 23



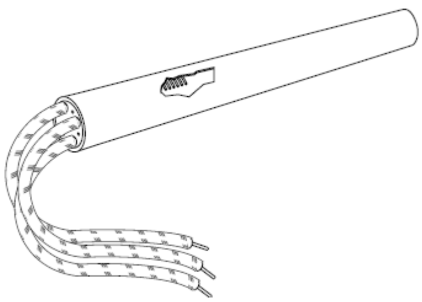
a. Three-phase sine wave



b. Single-phase sine wave

One other difference between single phase and 3ph power is that 3 power lines are required versus only 2 for single phase (Figure 24).

Figure 24
A Three Phase Firerod Cartridge Heater



Internal 3ph Connection:

Many heaters are designed for use on 3 phase voltage. A 3-phase heater typically has 3 lead wires or three terminals for connection to the power supply (see Figure 24). There is one simple formula for working out the volts, watts and amps on a three-phase heater.

Ohm's Law Formula for 3 Phase
$W = 1.73\ V_L I_L$

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Where: VL = Line Voltage, IL = Line Current

What is the difference between this formula and the one on page 8 for a single-phase heater? Notice the multiplier (1.73)? We will not discuss why 1.73 is used. The important thing is to use the formula for calculations! Let's go through two examples to see how really easy this formula is to use.

Example 8: A customer requires a 3ph heater, 480VAC, 5000W. What is the current draw of this heater? Compare this to a single-phase heater with the same volt and watt rating

Three Phase Current:	Single Phase Current:
W = 1.73VLIL	W = VI
IL = W/(1.73VL)	I = W/V
= 5000W/ [(1.73) (480V)]	= 5000W/480V
IL = 6 amps	IL = 10.4 amps

Notice the big reduction in current required to produce 5000 watts on a three-phase heater! As a result, high wattage heaters are almost exclusively 3ph heaters.

Example 9: A customer wants to use a 3ph heater on a 50-amp circuit in his factory. At 440VAC, what is the maximum wattage he can get and still not exceed the 50-amp circuit limit?

W = 1.73VLIL
= 1.73(440V) (50A)
W = 38,000 watts

The largest heater which the customer can use is 38,000 watts. If the circuit is upgraded to 100 amps, can the customer use a larger heater? Sure! He can use a heater about twice as large or 76,000 watts. Let's look at another example in exercise 8.

Exercise 8:
A customer calls and says she bought a 240VAC, 3ph, 8000W heater. She is concerned that it is over rated for her factory circuits. The max. is 30 amps. Can she use this heater?

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There are two ways to solve this problem. One is to compare heater current to maximum current. One is to compare heater wattage to the maximum possible wattage which the circuit could safely handle. Either way, the heater will work
fine on the existing circuit!

W = 1.73VLIL
IL = W/(1.73VL)
= 8000W/ [(1.73) (240V)]
IL = 19.3 amps

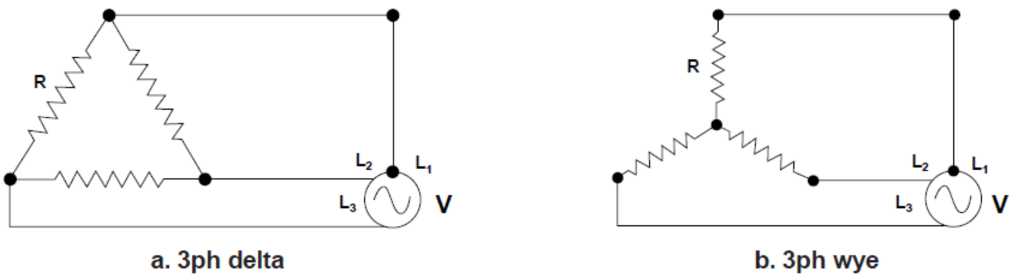
W = 1.73VLIL
= 1.73(240V) (30A)
W = 12,460 watts

External 3ph Connection

The 3ph heaters we examined in the previous section have their resistance elements connected internally for 3ph operation. However, there are also many cases when we must connect individual (single phase) heaters into a 3ph circuit.

There are two main connection schemes for 3 phase circuits: delta and wye. What are the similarities and differences you see between the delta and wye heater circuits in Figure 25? Think about it for a while, then read on.

Figure 25



For similarities, delta and wye both require 3 heaters. Also, each has three power lines going to a 3ph power source. They are also connected in ways that allow electric current to flow through multiple paths. The difference between delta and wye is in how they are connected to the 3 power lines. Heaters are connected end-to-end in delta. In wye, one end of each heater is

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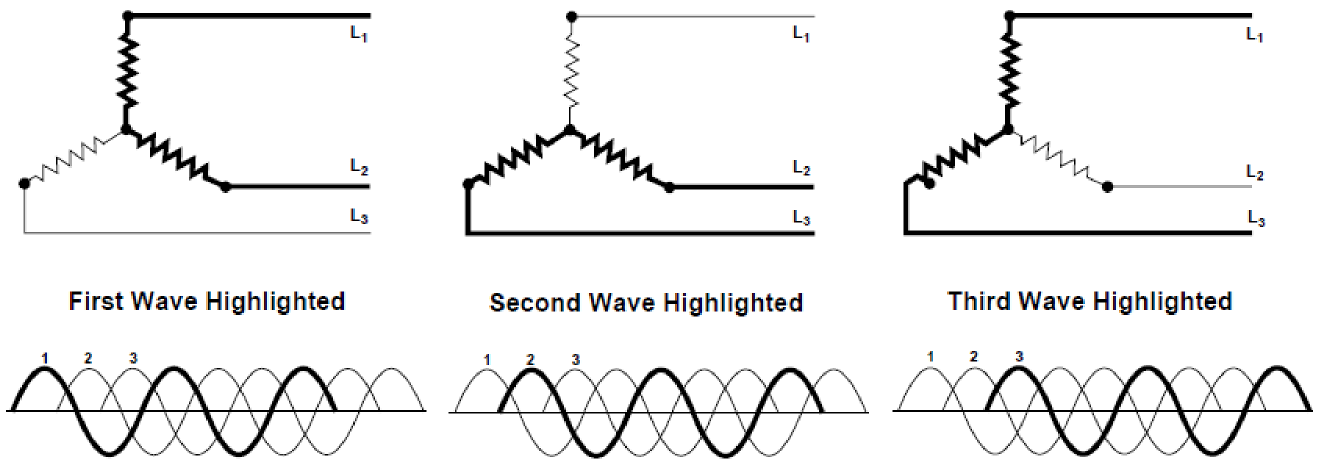
connected at a common point, then each remaining end is connected to a power line. How does 3 phase work in these circuits? Excellent question! In Figure 26, we see that each “phase” of electricity (remember Figure 23) passes through each phase or leg of the 3-phase heater circuit. That’s why we will ALWAYS need at least 3 heaters or some multiple of 3 (like 6, 9, etc.) to connect the heaters into a 3ph circuit.

Figure 26
Phase Current Flow



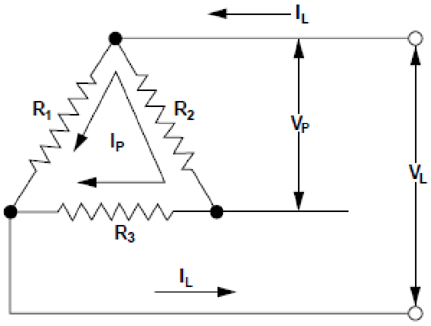
Now we are set to begin defining the Ohm’s Law formulas for 3 phase circuits. As we learned in the previous section, a heater with internal 3ph connections just needs the formula W = 1.73VLIL. This still applies for delta or wye three phase circuits! However, we start encountering differences as we get inside the 3ph circuit. The formulas for each type of 3ph circuit are shown in Figure 27.

Figure 27
Three Phase Circuit Formulas

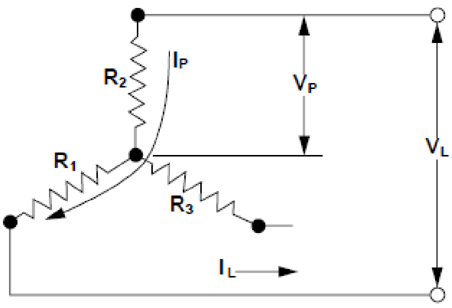
For Both Wye and Delta:

V_P = Phase Voltage
V_L = Line Voltage
I_P = Phase Current
I_L = Line Current
R = Resistance of each branch
W = Wattage

Three-Phase Delta



Three-Phase Wye



Wye and Delta Equivalents

$W_{DELTA} = 3W_{WYE}$

Equations For Delta Only

$I_P = I_L/1.73$
$V_P = V_L$
$W_{DELTA} = 3(V_L^2)/R$
$W_{DELTA} = 1.73\ V_L I_L$

Equations For Wye Only

$I_P = I_L$
$V_P = V_L/1.73$
$W_{WYE} = V_L^2/R = 3(V_P^2)/R$
$W_{WYE} = 1.73\ V_L I_L$

The difference between “phase” values and “line” values, is that line values are measured from power line to power line. Phase values are measured inside the 3ph circuit between heaters. Also notice that the resistance of each heater is equal. This is called a “balanced” load. We will only work with balanced loads.
Just as when we used Ohm’s Law for single phase circuits, if we know 2 values, (like volts and watts), we can calculate the other two values! The best way to do this is to work through some examples.

Example 10:

A customer has purchased 3 heaters, each rated for 480VAC, 4,000W. The maintenance person wants to connect these heaters up to a 480VAC, 3ph power supply (Figure 28). If he connects the heaters in a 3ph delta circuit, answer the questions on the following page.

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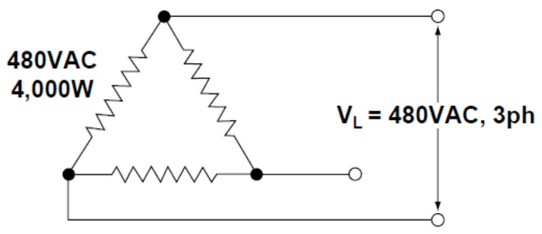
Figure 28



a) What is the resistance value (R) of each heater?
This one is easy! Three phase or single phase, a heater's resistance always stays the same! We use the rated volts and watts in one of Ohm's Law formulas.

Resistance: $R = V^2/W$
$= (480V)^2/4000W$
$R = 57.6\Omega$

b) What is the total wattage output of all 3 heaters?
Wattage in a delta circuit is calculated using the formula given in Figure 27
WD $= 3(VL)^2/R$
$= 3(480V)^2/57.6\Omega$
WD = 12,000 watts
Notice that the total wattage output is equal to the rated wattage of each heater multiplied by 3 (for 3 heaters).

c) What is the phase voltage (VP) of each heater? This one is easy! The voltage measured across the heater (phase voltage) is the same as that measured across two power lines.
VP = VL
VP = 480V

d) What is the line current (IL) through the circuit?
WD = 1.73VLIL
IL = WD/1.73VL
= 12,000W/ (1.73) (480V)
IL = 14.45 amps

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e) What is the phase current (actual amount of current IP) through each heater?

IP = IL/1.73
= 14.45A/1.73
IP = 8.35 amps

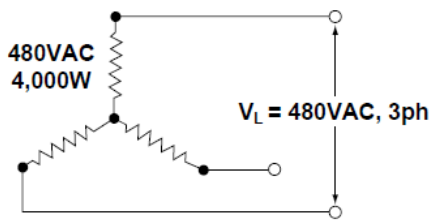
Notice how the phase current value is less than the line current draw. This is in contrast to the phase and line voltages which are equal.

f) What is the wattage output of each heater?

Do you need a formula for this one? No! If you have 3 heaters and the total wattage is 12,000 watts, then obviously each heater is producing 1/3 of this, or 4,000 watts!
Wow! You have just worked your way through a three-phase circuit problem! It isn't that tough, is it?
What do we do if the same customer wants to wire up the heaters for a 3ph wye circuit? That is your next challenge!

Using the information given in Example 10, calculate the same current, wattage, etc. values for the 3ph wye circuit shown in Figure 29. Simply follow the order of calculations used in Example 10. Make sure you use 3ph wye formulas!

Figure 29



a) What is the resistance value (R) of each heater?
This one's easy! Heater resistance isn't going to change just because you wire up the circuit differently! Thus, the resistance of each heater is still 57.6 ohms.

b) What is the total wattage output of all 3 heaters?
Wattage in a wye circuit is calculated using the formula given in Figure 29.
WW = $(VL)^2/R$

$= (480V)^2/57.6\Omega$
WW = 4,000 watts
What a big decrease in wattage from the delta circuit (12,000W)!

c) What is the phase voltage (VP) of each heater?

VP = VL/1.73
= 480V/1.73
VP = 277V

Notice that the voltage across each heater also decreased substantially compared to the delta connected circuit! This explains the big drop in total wattage output.

d) What is the line current (IL) through the circuit?

WW = 1.73VLIL
IL = WD/1.73VL
= 4,000W/ (1.73) (480V)
IL = 4.8 amps

e) What is the phase current (actual amount of current IP) through each heater?

IP = IL
IP = 4.8 amps

f) What is the wattage output of each heater?

Do you need a formula for this one? No! If you have 3 heaters and the total wattage is 4,000 watts, then obviously each heater is producing 1/3 of this or 1,333 watts! This is 1/3 of the rated wattage of each heater.
Do you see the complete contrast in wattage, current and voltage results of delta and wye 3ph connections? When a customer wires up heaters in 3-phase, it is really important that it is done correctly! If not, wattage output may be 1/3 of (or 3 times) what was actually desired.

Three Phase-4 Wire and 5 Wire Heaters

How can a 3-phase circuit have 4 wires or even 5? Figure 30a shows a circuit diagram of a typical 3 phase 4 wire heater. Figure 30b shows what a 4-wire radiant heater might look like.

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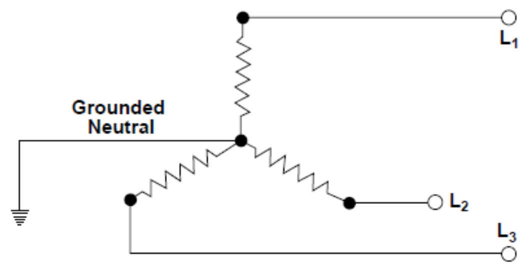
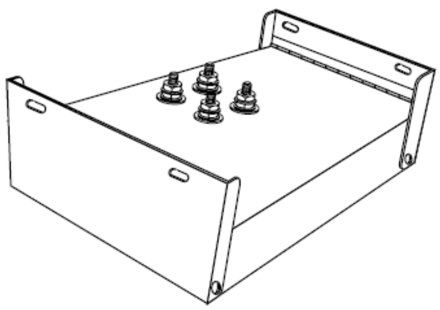
Notice how the "4th wire" is attached to the center point of the 3-phase wye circuit and grounded? What is the purpose of this wire?

Figure 30



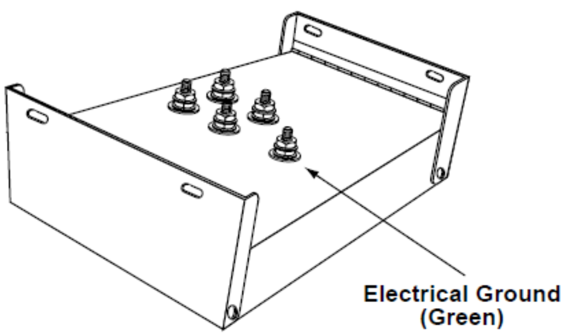
a. A 3ph-4 wire circuit



b. A 3ph-4 wire radiant panel

If one of the heaters (or resistance elements) should fail open, the 4th wire or neutral reduces the wattage drop in the remaining heaters. It also provides an outlet for balancing current when the resistance loads are unbalanced. Finally, it serves as a ground when a short within the circuit (as opposed to a short to the heater sheath) occurs.
Three phase-four wire heaters typically have a white neutral lead or terminal marked for easy identification of the neutral. If a terminal, however, is green in color, this indicates that it is the electrical or safety ground for the sheath or metal case of the heater.
What then is a 3 phase-5 wire heater? As you might have guessed, it is a 3 phase- 4 wire heater with an electrical safety ground. This makes a total of 5 connection points (Figure 31). Again, you know which terminal is the electrical ground and which is the neutral, because they are either clearly marked or color coded.

Figure 31
A 3 Phase-5 Wire Radiant Panel



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What do you do if a customer requests a 3 phase-4 or 5 wire heater? Simply ask that person what the 4th (and 5th) wire functions as. If it still is not clear, it may be simplest to just fax a copy of the above figures. Then the customer can tell you specifically what is required.

How can you use your knowledge of single and three phase circuits to make yourself valuable to customers? A very good question! There are hundreds of ways that your ability to apply electric heating circuits can make you valuable. In the next section we give you the answers to some of the more commonly asked customer questions.

Q: What happens if one of the heaters fail in a series circuit?
A: All the heaters operating in that series "string" of the circuit shut down.

Q: What happens when one of the heaters fail in a parallel circuit?
A: All other heaters continue operating as before.

Q: Can I use all of these heaters on my present circuit?
A: Calculate the current which heaters will use and compare to existing circuit limits.

Q: What happens to wattage output, watt density and current when I use this heater at a voltage value other than rated voltage?
A: We can manipulate Ohm's Law formulas to give us a new formula:

$$W_{NEW} = W_{RATED}(V_{NEW}/V_{RATED})^2$$

Example: What is the new wattage output if a heater is rated for 110 volts, 1000 watts, but will be operated on 120 volts. What is the new current and watt density?

WNEW	$= WRATED(VNEW/VRATED)^2$	$I = W/V$
	$= 1000W(120V/110V)^2$	$= 1190W/120V$
WNEW	= 1190 watts	I = 9.92 amps

Watt density changes proportionally with any wattage changes. If wattage

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increases from 1000W to 1190W, then watt density also increases by 1.19 times (1190/1000). So, if the watt density was 10, now it is 11.9W/in2.

Q: What happens if I rewire my circuit from 3ph delta to 3ph wye?
A: Multiply rated wattage in the delta circuit by 1/3. Adjust current, etc. values per the formulas in Figure 27 (based on the new wattage value).

Q: What happens if I rewire my circuit from 3ph wye to 3ph delta?
A: Multiply rated wattage value in the wye circuit by 3. Adjust current, etc. values per the formulas in Figure 27 (based on the new wattage value).

Q: What happens to the wattage output of a three-phase heating system if one of the heaters (or resistance element phases) burns out?
A: Use "Open 3 Phase Circuits" formulas to calculate values required.
These are found in the Watlow catalog's Application Guide.
Formulas are reprinted below.

Open 3 Phase Circuit Formulas:

Open Delta Wattage = $\frac{2}{3} W_{DELTA}$
Open Wye Wattage = $\frac{1}{2} W_{WYE}$
Open 4 Wire Wye Wattage = $\frac{2}{3} W_{WYE}$

To summarize & further examples:

1/ An electric circuit typically consists of a voltage source, wiring, electrical load (like a heater) and some type of switch.

2/ Electric current is the flow of electrons through circuit wiring when a voltage is applied to a circuit.

3/ Direct current (DC) has a positive, constant voltage value. Alternating current flows in both directions due to polarity changes. Voltage value varies continuously, going first positive, then negative and continuing to alternate in this manner.

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4/ If a heater operating on 24VDC produces 1000 watts. How many watts will the heater produce if operated on 24VAC, 50Hz power?
1000 watts. If the voltage value is the same, so is the current output.

5/ If a Watlow heater rated 120 volts, 500 watts is connected to a 120 volt, single phase power supply. Calculate the resistance and current through the heater.

Resistance: $R = V^2/W$
$= (120V)^2/500W$
$R = 28.8\Omega$

Current: $I = W/V$
$= 500W/120V$
$I = 4.17$ amps

6/ a) Calculate the wattage output and current if the heater in problem #1 is connected to a 240V, single phase power supply. b) If the circuit can handle up to 10 amps, can this heater be used on 240V?

Wattage: $W = V2/R$
$= (240V)^2/28.8\Omega$
$W = 2000$ watts

Current: $I = W/V$
$= 2000W/240V$
$I = 8.33$ amps

Yes, heater can be used because it draws less than 10 amps.

7/ Two Watlow heaters are connected in series. Draw the circuit diagram if the heaters are rated 240V, 2500W and 240V, 3000W. Calculate a) circuit resistance, b) circuit current and c) total wattage if the power supply is 230VAC (1ph).

$R1 = (240V)^2/2500W = 23.04\Omega$
$R2 = (240V)^2/3000W = 19.2\Omega$
$RT = R1 + R2 = 23.04 + 19.2 = 42.24\Omega$
$W = V^2/RT = (240V)^2/42.24\Omega = 1363.6$ watts
$I = W/V = 1363.6W/240V = 5.7$ amps

8/ If the above heaters are connected in parallel, calculate the circuit resistance, current, and total wattage.

$1/RT = 1/23.04\Omega + 1/19.2\Omega$; $RT = 10.47\Omega$
$W = V^2/RT = (240V)^2/10.47\Omega = 5500$ watts (or 2500W + 3000W = 5500W)

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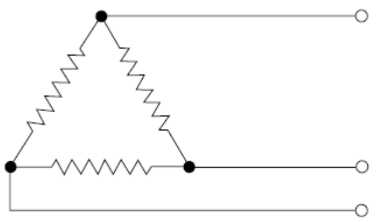
I = W/V = 5500W/240V = 22.9 amps

9/ Electrical ground is basically a wire attached to the metal part of a heater or other electrical device. This wire is attached to a metal pole driven into the ground. When stray currents or a short circuits occur, the ground serves as a "drain" for the excess current. In this way people will not get shocked.

10/ A 3 phase heater is rated for 480V, 3ph. However, the wattage rating is not readable. When operating on a 480V, 3ph power supply, you measure the line current as 38.5 amps. Calculate the wattage of this heater (round off to nearest thousand).
W = 1.73VLIL = 1.73(480V) (38.5A) = 32,000 watts

11/ A customer has purchased an immersion heater with 3 heating elements. The heater is rated for 415VAC, 3ph, 15,000W. The wiring diagram for connecting the heater elements is shown in Figure 32. Calculate the following:

Figure 32



a) What is the resistance value (R) of each heater?

b) What is the total wattage output of all 3 heaters?

c) What is the phase voltage (VP) across each heater?

d) What is the line current (IL)?

e) What is the phase current (IP) through each heater?

f) What is the wattage output of each heater?

11/
a) $WD = 3(VL)^2/R$
$R = 3(VL)^2/WD = 3(415V)^2/15{,}000W$
$R = 34.45\Omega$
b) Total is the rated 15,000 watts.

c) VP = VL = 415V

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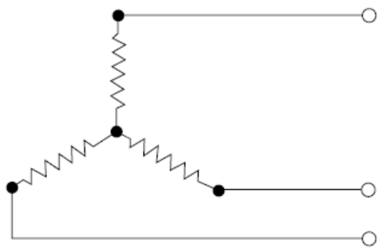
d) WD = 1.73VLIL
IL = WD/1.73VL
= 15,000W/ (1.73) (415V)
IL = 20.9 amps

e) IP= IL/1.73
= 20.9A/1.73
IP = 12.1 amps

f) 15,000W/3 = 5,000W per heater.

12/ By mistake, the customer wires the immersion heater in problem #13 incorrectly. Figure 33 shows how it was accidentally wired. What effect will this have on wattage output of the heater? (Hint: Use the wye-delta short cut equivalents in Figure 27 on page 28.)

Figure 33



WD = 3WW
WW = WD/3 = 15,000W/3 = 5,000 watts

13/ Calculate the actual wattage output if a heater rated 240V, 3000W is operated on a) 120 volts and b) 480 volts? (Hint: Use short cut formulas on p. 29).

$W_{NEW} = W_{RATED}(V_{NEW}/V_{RATED})^2$
$= 4000W(120V/240V)^2$
$W_{NEW} = 1{,}000$ watts

$W_{NEW} = W_{RATED}(V_{NEW}/V_{RATED})^2$
$= 4000W(480V/240V)^2$
$W_{NEW} = 16{,}000$ watts