The Case of the
OVERLOADED ELECTRICAL CIRCUIT

By Mitch Ricketts

Math Toolbox is designed to help readers apply STEM principles to everyday safety issues. Many readers may feel apprehensive about math and science. This series employs various communication strategies to make the learning process easier and more accessible.

Using a real-world example of a home electrical fire, this article presents a variety of ways to apply mathematical tools to explore how a safety professional might predict and prevent similar incidents.

Figure 1 depicts events that took place during a fatal home fire caused by an electrical overload. Fires such as this occur when electrical resistance generates heat in wires and other conductors. Heating will be minimal if the electric current does not exceed the rated load of the electrical system. Excessive currents, in contrast, may heat conductors to temperatures capable of igniting wood and other building materials.

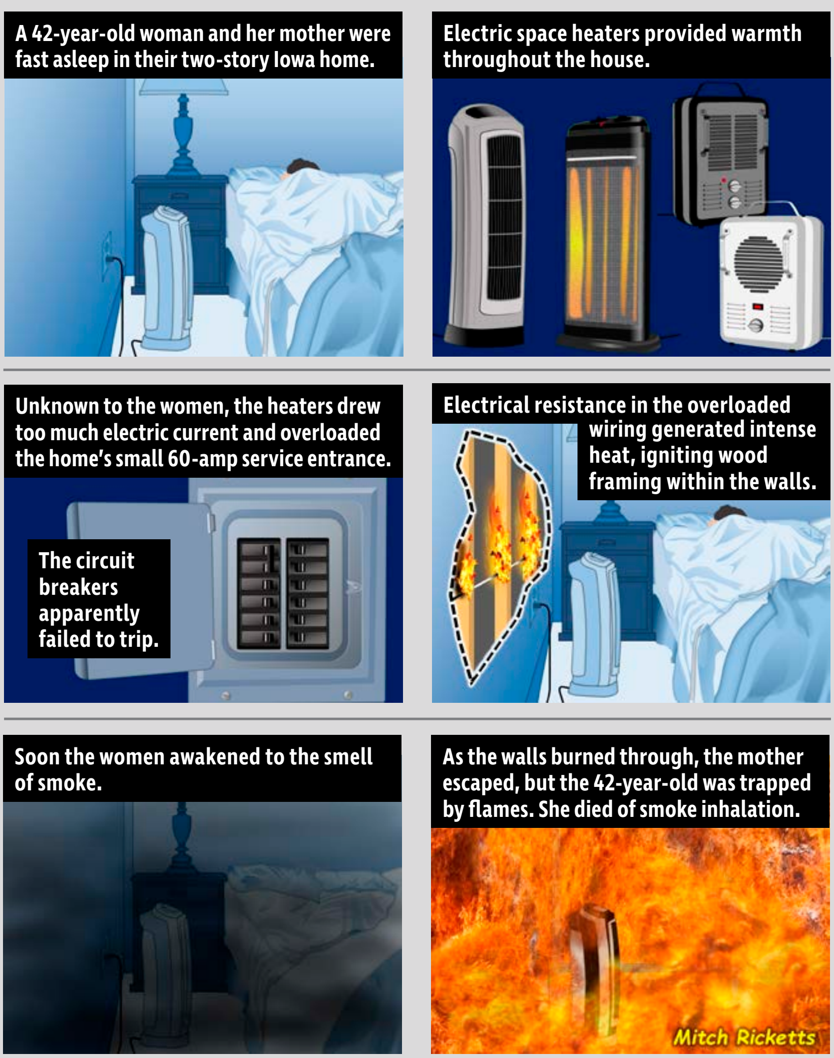
Safety professionals can help prevent electrical fires by learning to recognize potential overloads. Lessons from the fatal Iowa fire will serve as the basis for a series of exercises to help readers identify overloaded electrical circuits.

As a Safety Professional, How Can I Predict & Prevent Fires From Electrical Overloads?

Wires and other electrical components are rated by the maximum current they can safely carry. Excess current may cause electrical components to overheat (Figure 2). Although breakers and fuses are designed to disconnect circuits during overloads, fires can occur if breakers and fuses fail to operate due to improper sizing or mechanical defects. When breakers and fuses function properly, fires may still occur if extension cords are overloaded. This is because the current rating of cords often falls far below the loads necessary to activate breakers and fuses.

To predict overheating, we calculate the total current and determine whether the electrical load exceeds the current rating (i.e., ampacity) of the components (i.e., conductors). We do this by relating

FIGURE 1
HOME ELECTRICAL FIRE, OSKALOOSA, IA, 2013



Note. Adapted from "Woman Dies in Electrical Fire," by K. Tremblay, 2014, *NFPA Journal, 108*(4), 30.

FIGURE 2
ELECTRICAL EQUIPMENT DAMAGED BY OVERHEATING FROM EXCESSIVE CURRENT

Figure 2a (left): Plug burned and bubbled around blades (from an overloaded extension cord). Figure 2b (right): Overloaded outlet melted around terminal screws.

FIGURE 3
ELECTRICAL SYMBOLS CROSSWORD PUZZLE

Symbols for the electric power equation. Complete the crossword using terms designated by the symbols. Answers are on p. 63 of this issue.

Down

1) Term designated by "V" in the power equation

4) Term designated by "P"

5) Term designated by "I"

Across

2) Term designated by "W"

3) Term designated by "A" (formal)

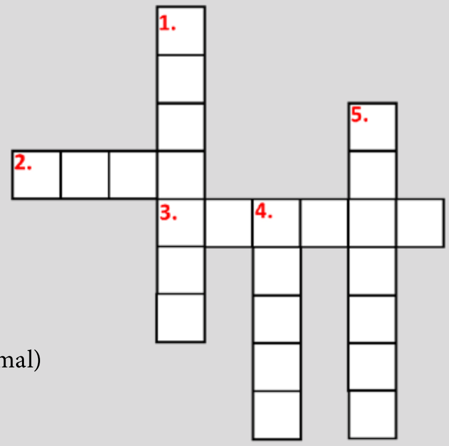


FIGURE 4
ELECTRICAL LOAD

Home electrical service panel with additional load from four electric space heaters.

current (in amperes, A) to power (in watts, W), using the equation for electric power:

$$P = V \cdot I$$

where:

P = power (energy transfer rate), in watts (W)

V = voltage, in volts (V)

I = current, in amperes (amps, A)

Note: This formula was designed for direct current (DC). It also applies to alternating current (AC) in simple circuits that involve only an AC power source and resistors. Engineers use more advanced equations when AC circuits include inductors and capacitors, but those calculations are beyond the scope of work for most safety professionals.

Before practicing this formula, let's consider some important terms and concepts.

The Language of Electricity

You'll encounter electrical symbols and terms in codes, certification exams and discussions with other professionals. Check your knowledge by matching the concepts with their definitions in questions 1 through 5, presented in Figure 3. Answers are on p. 63 of this issue.

Matching Questions

This exercise will help readers evaluate and refine their knowledge of concepts related to electrical loads. Match each concept with the appropriate definition. If you have trouble, you can look up the concepts in resources such as NFPA 70E and the NIOSH electrical safety student manual (see references). Answers are on p. 63 of this issue.

Concepts

6) Ampacity
7) Circuit breaker
8) Conductor
9) Current (I)
10) Fuse
11) Overcurrent (a.k.a., overload)
12) Power (P)
13) Resistance (R)
14) Voltage (V)

Definitions

a) A difference in electric potential or electric tension between two conductors, measured in volts (V). It creates an electric field that can drive current.

b) Amount of energy used each second (or the rate of doing work), measured in watts (W).

c) Any material through which electric current will flow.

d) Any flow of electrically charged particles, measured in amperes (a.k.a., amps, A). For alternating current, this concept usually refers to electrons flowing through wires or other conductors.

e) A material's ability to decrease or stop electric current, measured in ohms (Ω).

f) Maximum current a wire or other conductor can carry continuously without overheating or exceeding its temperature rating.

g) Current that exceeds the ampacity of a wire or electrical part.

h) Overcurrent protection device that shuts off power to a circuit manually (through a switch) and automatically (when a maximum current is exceeded).

i) Overcurrent protection device that shuts off power to a circuit when excessive current causes part of the device to melt.

How Do I Calculate the Effects of an Electrical Load on a Service Entrance or Breaker Box?

As in the fatal house fire that introduced this topic, imagine a home with an electrical service that enters through a breaker box containing several appropriately sized breakers (Figure 4). Also imagine the total ampacity (maximum current rating) for the breaker box and the entire electrical system is 60 amps (60 A).

The home already has the usual appliances such as a refrigerator, microwave, lights and vacuum cleaner. For the purposes of this exercise, we will say the total current drawn by existing appliances (not including the space heaters) is 40 A.

Now we add an additional load of four electric space heaters. Imagine that each heater uses 1,500 watts (W) of power at a voltage of 120 volts (V), as indicated by the product labels. Is the building's electrical system overloaded? Stated another way, does the addition of these four space heaters create a high risk of electrical fire if the 60 A main breaker fails to trip?

To summarize this problem, here is what we know:

•The home's electrical system has an ampacity of 60 A.

•Existing appliances already draw a current of 40 A.

•We add four space heaters, each using 1,500 W of power at 120 V.

•To keep the exercise simple, we will ignore the impact of any capacitors and inductors that may be present.

We use the electrical power formula to determine whether the overall electrical load exceeds the 60 A maximum rating of the electrical system, as follows:

Step 1. Determine the current (I) of each space heater, based on the known voltage (120 V) and power usage (1,500 W):

a) Start with the equation for power:

$$P = V \cdot I$$

Since we wish to solve for current (I), we rearrange the original formula.

Begin rearranging by dividing both sides of the formula by V:

$$\frac{P}{V} = \frac{V \cdot I}{V}$$

Since

$$\frac{V}{V} = 1$$

we can cancel the Vs on the right side:

$$\frac{P}{V} = \frac{\cancel{V} \cdot I}{\cancel{V}}$$

Simplify by removing the canceled *V*s:

$$\frac{P}{V} = I$$

Since we are solving for *I*, we'll finish by reversing the equation:

$$I = \frac{P}{V}$$

Remember:
I = current, in amperes (amps, *A*)
P = power, in watts (*W*)
V = voltage, in volts (*V*)

b) For each space heater, insert the known values for power (1,500 *W*) and voltage (120 *V*). Then solve for current (*I*):

$$I_{Per\ Heater} = \frac{1{,}500}{120} = 12.5\ A$$

Step 2. We learned in Step 1b that each heater draws a current of 12.5 *A*. Now, we multiply by 4 to find the total current of all four space heaters:

$$I_{All\ 4\ Heaters} = 12.5 \cdot 4 = 50\ A$$

Step 3. We learned in Step 2 that the total current drawn by the four space heaters is 50 *A*. Now we add the space heaters' 50 *A* to the 40 *A* current drawn by other, existing appliances. The new total will be the current drawn by the home's entire electrical system, including the heaters:

$$I_{Entire\ System} = 40 + 50 = 90\ A$$

Step 4. Our calculations indicate the total current drawn by all appliances (including the four space heaters) is 90 *A*. This far exceeds the 60 *A* ampacity of the service entrance. We conclude the service entrance is overloaded. Thus, the main breaker is likely to trip if all appliances are used at once. Alternatively, overheating and fire may occur if the main breaker fails to trip.

Step 5. Correcting the issue: The short-term solution is to unplug at least three of the space heaters immediately to reduce the load to 60 *A* or less. In the long term, we may decide to upgrade the electrical system with a new service entrance rated for the higher current (along with additional branch circuits, if necessary).

Note: Service entrances come in many different ampacities (ranging from less than 60 *A* to far more). Be sure to check the labels or main breakers in the service entrance to determine the actual ampacity.

You Do the Math

Apply your knowledge to the following question. Answers are on p. 63.

15) What current (*I*) is drawn by one space heater that consumes 1,410 *W* of power at a voltage of 120 *V*? Assume there are no inductors or capacitors. Use the equation:

$$I = \frac{P}{V}$$

How Do I Calculate the Electrical Load of a Single Branch Circuit?

Imagine a 120 *V* household electrical circuit (Figure 5). The circuit is protected by a 15 *A* breaker. To keep the exercise simple, we will imagine the circuit is confined to three electrical outlets. Outlet 1 is loaded with a single space heater. This heater consumes 1,200 *W* of power. Outlet 2 is loaded with a single floor lamp, consuming 100 *W*. Outlet 3 is loaded with an 840 *W* vacuum cleaner.

Is this circuit overloaded when all appliances operate at the same time? Assume there are no inductors or capacitors.

Step 1. Use the equation for electric power:

$$I = \frac{P}{V}$$

where:
I = current, in amperes (amps, *A*)
P = power, in watts (*W*)
V = voltage, in volts (*V*)

Step 2. For each outlet, insert the known values for power (heater = 1,200 *W*; lamp = 100 *W*; vacuum = 840 *W*). Also insert the voltage (120 *V*). Find the current (*I*) of each appliance:

$$I_{Heater} = \frac{1{,}200}{120} = 10\ A$$

$$I_{Lamp} = \frac{100}{120} = 0.83\ A$$

$$I_{Vacuum} = \frac{840}{120} = 7\ A$$

Step 3. Add the current from each appliance to determine the total load for the circuit:

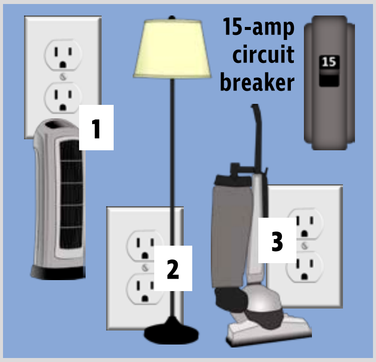
$$I_{Circuit} = 10 + 0.83 + 7 = 17.83\ A$$

Step 4. The total current is 17.83 *A*. This exceeds the 15 *A* ampacity of the circuit. The circuit is overloaded, and we expect the breaker to trip. If the breaker fails to trip, the circuit may overheat and cause a fire.

Step 5. Correcting the issue: Immediately move the space heater or vacuum cleaner to a different circuit (one with enough unused ampacity to handle the load).

FIGURE 5
SINGLE BRANCH CIRCUIT

Electrical branch circuit with three outlets and plug-in appliances.



You Do the Math

Apply your knowledge to the following questions. Answers are on p. 63.

16) What current (*I*) is drawn by one lamp that consumes 60 *W* of power at a voltage of 120 *V*? Assume no inductors or capacitors. Use the following equation:

$$I = \frac{P}{V}$$

17) What total current (*I*) is drawn by four lamps that consume 60 *W* of power each, at a voltage of 120 *V*? Since there are four lamps, take your answer for Question 16 and multiply by 4.

How Do I Calculate the Electrical Load of an Extension Cord?

Imagine a 120 *V* light-duty extension cord (Figure 6) labeled with a maximum load (ampacity) of 10 *A*. We use the extension cord to power a 120 *V* circular saw that consumes 600 *W* of power. Is the extension cord overloaded? Assume no inductors or capacitors.

Step 1. Use the equation:

$$I = \frac{P}{V}$$

where:
I = current, in amperes (amps, *A*)
P = power, in watts (*W*)
V = voltage, in volts (*V*)

Step 2. Insert the known values for power (saw = 600 *W*), and voltage (*V* = 120). Solve for current (*I*):

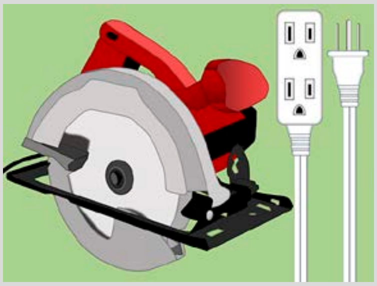
$$I_{Saw} = \frac{600}{120} = 5\ A$$

Step 3. The total current drawn through the extension cord is 5 *A*. This result is less than the 10 *A* ampacity of the extension cord. The extension cord is not overloaded, and there is no increased risk of overheating from this load.

Step 4. We can use the extension cord with this circular saw, but we must recalculate if we add additional appliances to the cord.

FIGURE 6
EXTENSION CORD

Light-duty extension cord with circular saw.



You Do the Math

Answers are on p. 63.

18) What current (I) is drawn by one saw that consumes 550 W of power at a voltage of 120 V? Assume there are no inductors or capacitors. Use the following equation:

$$I = \frac{P}{V}$$

How Do I Calculate Power in Watts When Current and Voltage Are Known?

This time let's use the electric power equation in its original form (not rearranged). Imagine a 120 V extension cord (Figure 7) with a label indicating a maximum power usage of 620 W. We use the extension cord to power a 120 V saber saw that draws current of 3 A and a 120 V drill that draws a current of 4 A. Assuming there are no inductors or capacitors, is this extension cord overloaded?

Step 1. Use the original equation for electric power, and solve for P:

$$P = V \cdot I$$

where:
P = power, in watts (W)
V = voltage, in volts (V)
I = current, in amperes (amps, A)

Step 2. For each appliance, insert the known values for current (saw = 3 A; drill = 4 A). Also, insert voltage (120 V). Solve for power (P):

$$P_{Saw} = 120 \cdot 3 = 360\ W$$

$$P_{Drill} = 120 \cdot 4 = 480\ W$$

Step 3. Add the wattage from each appliance to determine the total power.

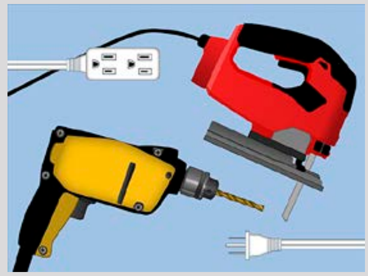
$$P_{Total} = 360 + 480 = 840\ W$$

Step 4. The total power consumption is 840 W. This exceeds the rated wattage of the extension cord (620 W). The extension cord is overloaded, and the cord may overheat if we use both tools at the same time.

Step 5. We must immediately move one of the tools to a different extension cord (one with enough unused ampacity to handle the load).

FIGURE 7
CALCULATING POWER

Light-duty extension cord with drill and sabre saw.



You Do the Math

Answers are on p. 63.

19) What power (P) is consumed by one drill that draws 4.4 A of current at a voltage of 120 V? Assume no inductors or capacitors. Use the equation:

$$P = V \cdot I$$

What If the Voltage Isn't 120 V?

If the voltage is not 120 V, no problem. Just insert the actual voltage into the equation. For example, if the voltage is 240 V, and the current is 8 A, the equation for power is:

$$P = V \cdot I = 240 \cdot 8 = 1{,}920\ W$$

If the voltage is 240 V, and the power is 960 W, the equation for current is:

$$I = \frac{P}{V} = \frac{960}{240} = 4\ A$$

You Do the Math

Assume there are no inductors or capacitors. Answers are on p. 63.

20) What power (P) is consumed by one appliance that draws 7 A of current at a voltage of 240 V? Use the equation:

$$P = V \cdot I$$

21) What current (I) is drawn by one appliance that consumes 390 W of power at a voltage of 240 V? Use the equation:

$$I = \frac{P}{V}$$

How Much Have I Learned?

Try these problems on your own. Assume there are no inductors or capacitors. Answers are on p. 63 of this issue.

22) What is the total current (I) of a 120 V circuit that consumes 300 W of power?

23) What is the total current (I) of a 240 V circuit that consumes 1,100 W of power?

24) What is the total power consumption (P) of a 240 V circuit that draws 5.7 A of current?

25) What is the total power consumption (P) of a 120 V circuit that draws 2.2 A of current?

26) Imagine a house in which the electrical service enters through a breaker box containing several appropriately sized breakers. The service entrance has a total ampacity of 100 A for the entire electrical system. Also, imagine the following appliances are operating at the same time: refrigerator (120 V, 720 W); washing machine (120 V, 600 W); microwave oven (120 V, 680 W); lights (120 V, 700 W); and water heater (240 V, 4,500 W). Assuming no other power usage, is the building's electrical system overloaded?

27) Imagine a 120 V light-duty extension cord, with a label indicating a maximum load of 5 A. We use the extension cord to power a 120 V leaf blower that consumes 880 W. Is this extension cord overloaded?

For Further Study

Learn more about electrical safety from these sources:

•Electrical Safety Foundation International, **www.esfi.org**.

•*ASSP's ASP Examination Prep: Program Review and Exam Preparation*, edited by Joel M. Haight, 2016.

•National Electrical Code (NFPA 70E) free access: **http://bit.ly/2sO7TAR**.

•*NIOSH Electrical Safety Student Manual*: **www.cdc.gov/niosh/docs/2009-113/pdfs/2009-113.pdf**. PSJ

References

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doing, but also must continue to grow and not become complacent. This growth can be accomplished through the use of leading indicators such as work observations and feedback sessions.

For the other five Acme locations, management should evaluate what lagging indicators are being used. If the lagging indicators being used are just the basics (e.g., injuries, safety infractions, near-hits, regulatory actions), these indicators might not be presenting the full picture and other lagging indicators may need to be examined to assess the overall culture. For example, the use of absences along with turnover and transfer rates could show the bigger picture, since those who do not want to be at work rarely give their full potential. Acme should still use leading and lagging indicators to evaluate each location's culture, but that is all these metrics should be used for. If a culture change is needed, it must be made at each location through cultural interaction, which cannot occur by checking boxes and filing forms.

Compliance-based safety programs fail by their nature since they attempt to remove the human element from a human-based system and replace it with a paper-based system. When designing safety programs, individuality must be considered if we are to regulate the human component of a varied group, because individuality is inherent to human behavior, and human behavior dictates the core actions of any group. **PSJ**

IPOPBA/ISTOCK/GETTY IMAGES PLUS

References

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Cooper, M.D. (2006). Exploratory analyses of the effects of managerial support and feedback consequences on behavioral safety maintenance. *Journal of Organizational Behavior Management, 26*(3), 1-41.

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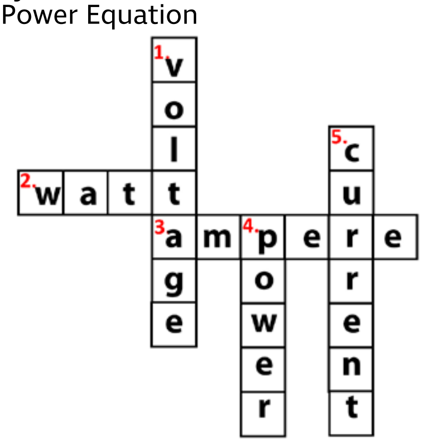
Math Toolbox, continued from pp. 52-55

Answers: The Case of the Overloaded Electrical Circuit

Symbols for the Electric Power Equation



The Language of Electricity

6) f; 7) h; 8) c; 9) d; 10) i; 11) g; 12) b; 13) e; 14) a.

You Do the Math

Your final digits may be different due to rounding.

15) $I = \frac{P}{V} = \frac{1{,}410}{120} = 11.75\ A$

16) $I = \frac{P}{V} = \frac{60}{120} = 0.5\ A$

17) $I_{Total} = 0.5 \cdot 4 = 2.0\ A$

18) $I = \frac{P}{V} = \frac{550}{120} = 4.58\ A$

19) $P = V \cdot I = 120 \cdot 4.4 = 528\ W$

20) $P = V \cdot I = 240 \cdot 7 = 1{,}680\ W$

21) $I = \frac{P}{V} = \frac{390}{240} = 1.63\ A$

How Much Have I Learned?

Your final digits may be different due to rounding.

22) $I = \frac{P}{V} = \frac{300}{120} = 2.5\ A$

23) $I = \frac{P}{V} = \frac{1{,}100}{240} = 4.58\ A$

24) $P = V \cdot I = 240 \cdot 5.7 = 1{,}368\ W$

25) $P = V \cdot I = 120 \cdot 2.2 = 264\ W$

26) $I_{Refrigerator} = \frac{P}{V} = \frac{720}{120} = 6.0\ A$

$I_{Washing\ Machine} = \frac{P}{V} = \frac{600}{120} = 5.0\ A$

$I_{Microwave} = \frac{P}{V} = \frac{680}{120} = 5.67\ A$

$I_{Lights} = \frac{P}{V} = \frac{700}{120} = 5.83\ A$

$I_{Water\ Heater} = \frac{P}{V} = \frac{4{,}500}{240} = 18.75\ A$

$I_{Service\ Entrance} = 6 + 5 + 5.67 + 5.83 + 18.75 = 41.25\ A$

The total current of 41.25 A is less than the 100 A ampacity of the service entrance. We conclude the service entrance is not overloaded. We do not expect the main breaker to trip, and there is no increased risk of fire.

27) $I_{Leaf\ Blower} = \frac{P}{V} = \frac{880}{120} = 7.33\ A$

The leaf blower draws a current of 7.33 A, which is greater than the rated ampacity of the extension cord (5 A). The cord is overloaded and presents an increased risk of fire. Immediately move the leaf blower to a cord rated for the current.