

## FORMULA HYBRID SAFETY TUTORIAL

# FUSING

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### *Purpose of Fusing*

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Fuses interrupt current in a circuit when the current exceeds a safe limit. When you work on a circuit in a lab, with a power supply as a power source, the power supply limits the current, and a fuse is not needed. Failures are rarely dangerous. However, when you work with power sources such as batteries, ultracapacitors, or the power grid, the available current can be in the kA range, and it is essential to provide some way to interrupt current in the event of a fault. The hazards that fuses can help control include:

- Fires: with a high fault current, circuit components and wiring can overheat to the point that they start a fire. A fire in a car that has a tank of gasoline and, in many cases, a flammable accumulator, can be very dangerous.
- Shock hazards: Fuses don't directly protect against shock hazards—50 mA can be lethal and it is rare to have a fuse that would limit current to such a low value. However, overcurrent might be caused by a short circuit which is also creating a shock hazard. And overcurrent could overheat and melt insulation on wires or other components, creating a shock hazard.
- Arc flash: A short in a high current circuit can lead to a high-energy arc that can injure or kill people, damage equipment and start fires. The hazards include blinding light, intense heat, acoustic shock waves, and flying molten metal and shrapnel. Proper fuses can limit the energy in an arc flash, reducing this hazard to some extent.
- Damage to wiring and circuitry: With a fuse, repair after a fault often requires only correcting the fault and replacing the fuse. Without a fuse, the entire electrical system may be destroyed.

### *Protecting a Circuit*

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Consideration of the current ratings of the various fuses, conductors, and loads in a circuit is called coordination. In a simple circuit, you have a power source, a fuse, some wire, and a load. Clearly, the fuse and the wire both need to be rated for at least the maximum continuous current that you expect the load to draw. For example, for an 8 A load, you might choose a 10 A fuse and wire rated for 12 A continuous current. But it's also essential to coordinate the fuse rating and the wire rating. The purpose of the fuse is to protect the wire from overheating. So the current rating of the wire needs to be at least the current rating of the fuse.

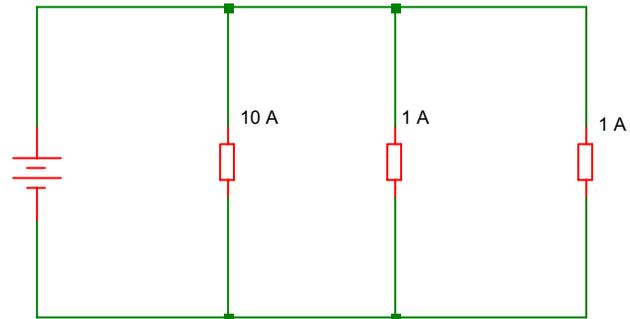
If the fuse is too small for the load, the fuse may blow during normal operation. But if the wire is too small for the fuse, the wire may overheat during a fault condition, before the fuse blows, producing the unsafe conditions that the fuse was meant to prevent.

	Good (fuse rating below)	Unreliable (fuse rating below load current)	Unsafe (wire rating below fuse rating)
Load current	8 A	8 A	8 A
Fuse rating	10 A	6 A	12 A
Wire rating	12 A	10 A	10 A

A good guideline (that is in some cases a legal requirement) is to use a fuse rating 25% larger than the expected maximum continuous load current, in order to leave some margin to avoid blowing a fuse when there is not a serious fault condition.

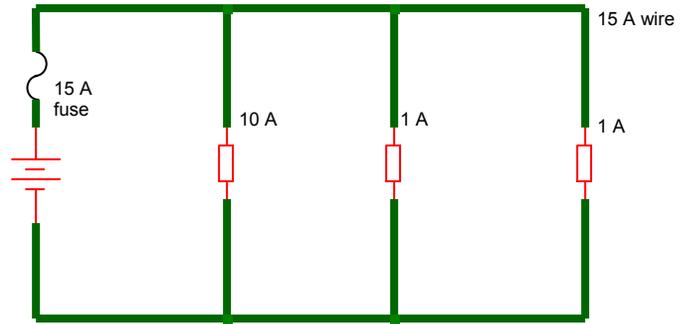
## Branch Circuits

Consider fusing for this circuit, with one source and three loads.

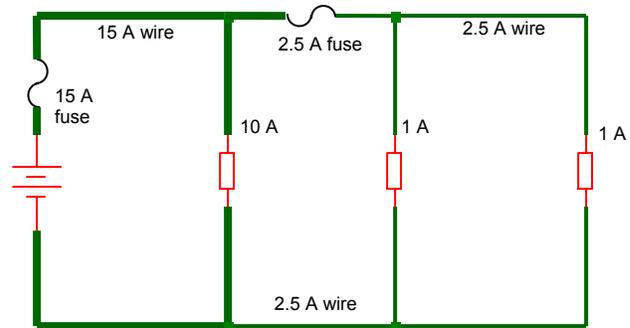


One option is to use a fuse 25% larger than the total current ( $12\text{ A} \times 1.25 = 15\text{ A}$ ), and use wire rated for 15 A throughout the circuit, as shown, right.

Note that the fuse should be adjacent to the power source. Any wiring between the power source and the fuse is unprotected—if a short occurs in that part of the system, the fuse cannot offer any protection.

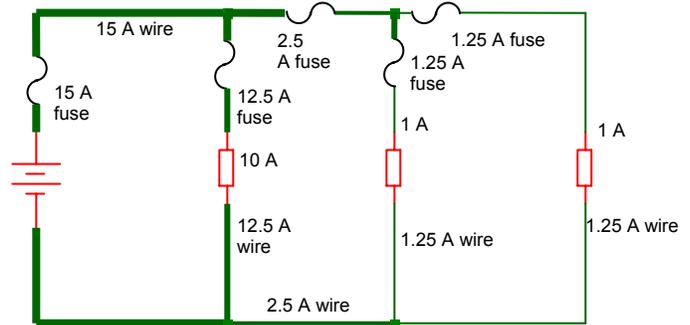


The disadvantage of the single-fuse approach is that it requires big wire everywhere, even for circuits that only use 1 A. An alternative is to use smaller wire for the low-current part of the circuit, and to include a fuse to protect that part of the circuit, as shown, right.

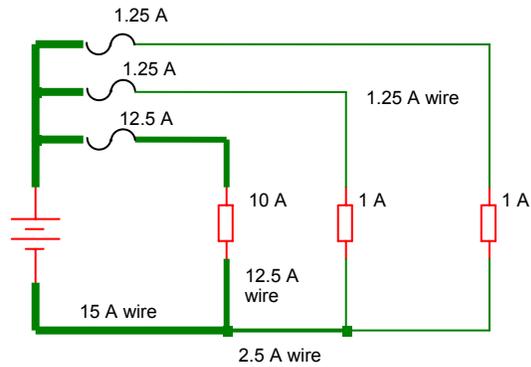


We could even go crazy with that approach and put fuses in each branch of the circuit, so as to be able to use wire as small as possible in each branch, as shown, right.

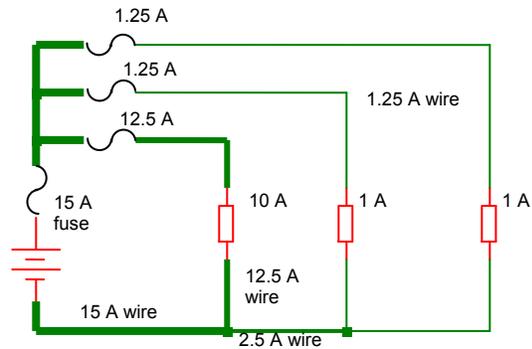
But that would be a terrible design! Not only does it have more fuses than loads, but it also has fuses everywhere in the system. If one of them failed, it would be a nightmare to find it.



A better design is to put all the fuses in one spot. For 12 V automotive and marine systems, inexpensive fuse blocks are readily available in various sizes and configurations; they can make constructing a safe, convenient, and reliable 12 V power system very easy.



If locating the fuse block away from the power source is necessary, a master fuse is needed protect the wiring between the power source and the fuse block. Other reasons for including a master fuse are discussed under fuse ratings.



## Fuse Ratings

A fuse’s current rating, the maximum current it can continuously carry without blowing, might seem like the only parameter you need to know. However, fuses also have voltage ratings, interrupting capacity ratings, and various ratings related to the speed at which they blow.

If a fuse is used in a circuit with a higher voltage than its rating, or if the short-circuit current in the circuit exceeds the interrupting capacity of the fuse, it might not be able to safely open the circuit even after the element melts. An arc can continue the current through the fuse even after the element melts—in this case the fuse does not succeed in stopping current flow. Or, the fuse may explode, spewing hot metal around and starting a fire rather than preventing one.

The voltage rating must be at least the maximum voltage in the system. Multiple fuses in series do not help—each one must be rated for the full voltage. That’s because one will trip first, and the full voltage can appear across that one fuse<sup>1</sup>. The voltage rating of a fuse for ac voltage is often higher than the voltage rating of the same fuse for dc voltage. That’s because the zero crossing of an ac voltage can help extinguish an arc, whereas with dc the arc is more likely to continue. The dc rating may be less than half the ac rating; some fuses are not rated for interrupting dc at all. Formula Hybrid rules require that dc systems use fuses rated for dc.

The interrupting rating of the fuse must be greater than the possible short circuit current in the circuit. With grid-powered systems, calculating the short-circuit current is complex, but with battery and ultracapacitor systems, the short-circuit current of a cell is the cell voltage divided by the series resistance of the cell. When cells are combined in series, the short circuit current remains the same; when they are connected in parallel the short circuit currents increase. For example, for a Maxwell BCAP3000 ultracap, the cell voltage is 2.7 V, and the ESR is 0.37 ohms. That means the short-circuit current is 7300 A. An A123 ANR26650 Li-ion cell is rated 3.3 V and 10 milliohms (for a 1

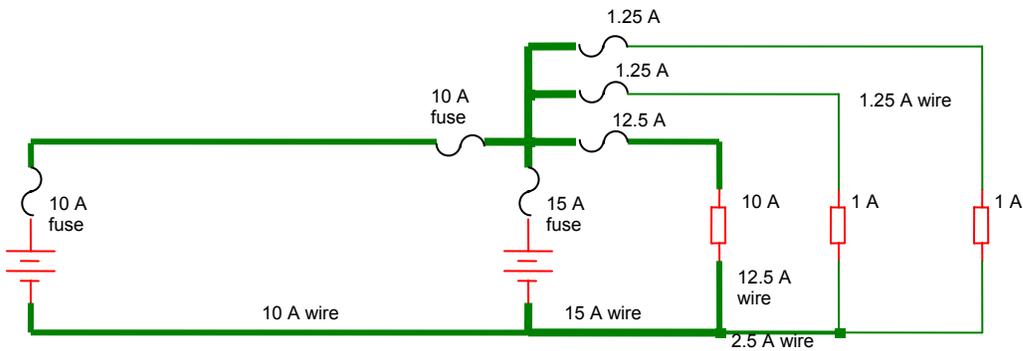
<sup>1</sup> [http://www.ferrazshawmut.com/en/pdf/edupack/GB110\\_Fuses\\_in\\_series.pdf](http://www.ferrazshawmut.com/en/pdf/edupack/GB110_Fuses_in_series.pdf)

second dc pulse). That means a 330-A short-circuit current. The interrupting rating may be lower for dc than for ac.

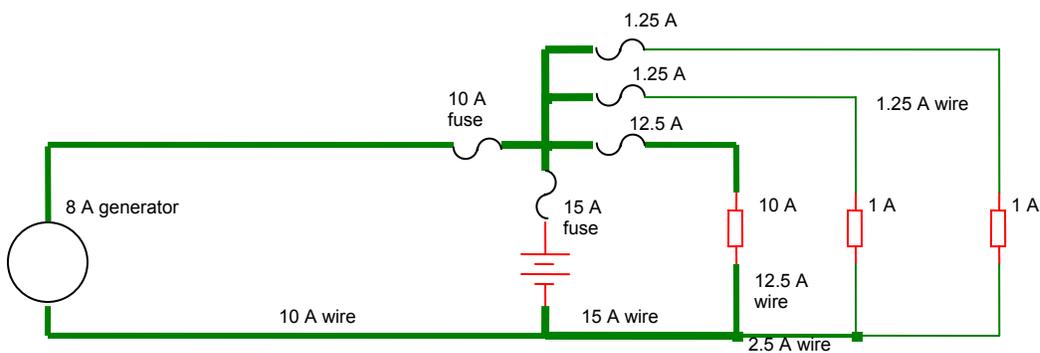
In a system with a master fuse and additional branch-circuit fuses, the interrupting capacity of the branch-circuit fuses need only be equal to the rating of the master fuse. This can help you avoid buying many exotic high-interrupting capacity fuses for a system with a high-current source.

### Fusing Multiple Sources

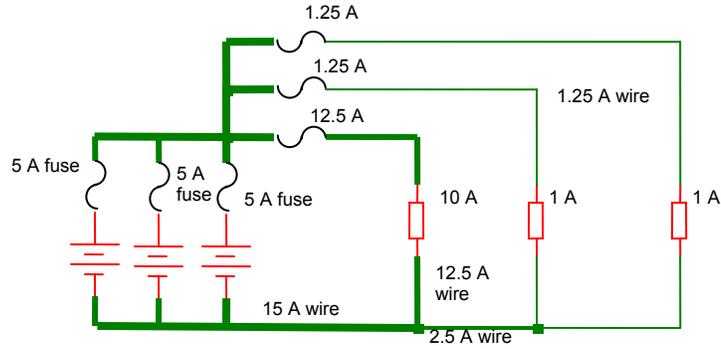
With multiple power sources, each power source needs to be fused, unless a source has inherently limited current capability, and the wire size is adequate for that current. In some cases, this may require fuses at both ends of a particular wire run. For example, in the drawing below, the left battery, which is intended to put out 8 A, has a 10 A fuse and 10 A wire. It needs fuses at both ends of the run of 10 A wire, because the 10 A wire wouldn't be protected by the 15 A fuse on the main battery.



If a source is inherently current-limited, and the wire is rated for at least that current, no fuse is required at the source. However, a fuse might be required at the end of the wire that connects to other parts of the system. For example, if we replace the battery on the left in the above example with a generator, inherently limited to 8 A, the left 10 A fuse may be omitted, but the right one is still needed, because current could flow from the main system back into the generator wires if they were to short out.



Sometimes a battery or ultracapacitor bank has multiple cells or strings of cells connected in parallel. In that case, it is necessary to fuse each string separately, even if there is no run of wire outside the battery box (see next page). These fuses protect against overcurrent from one string charging another string, as could happen if a cell shorted.



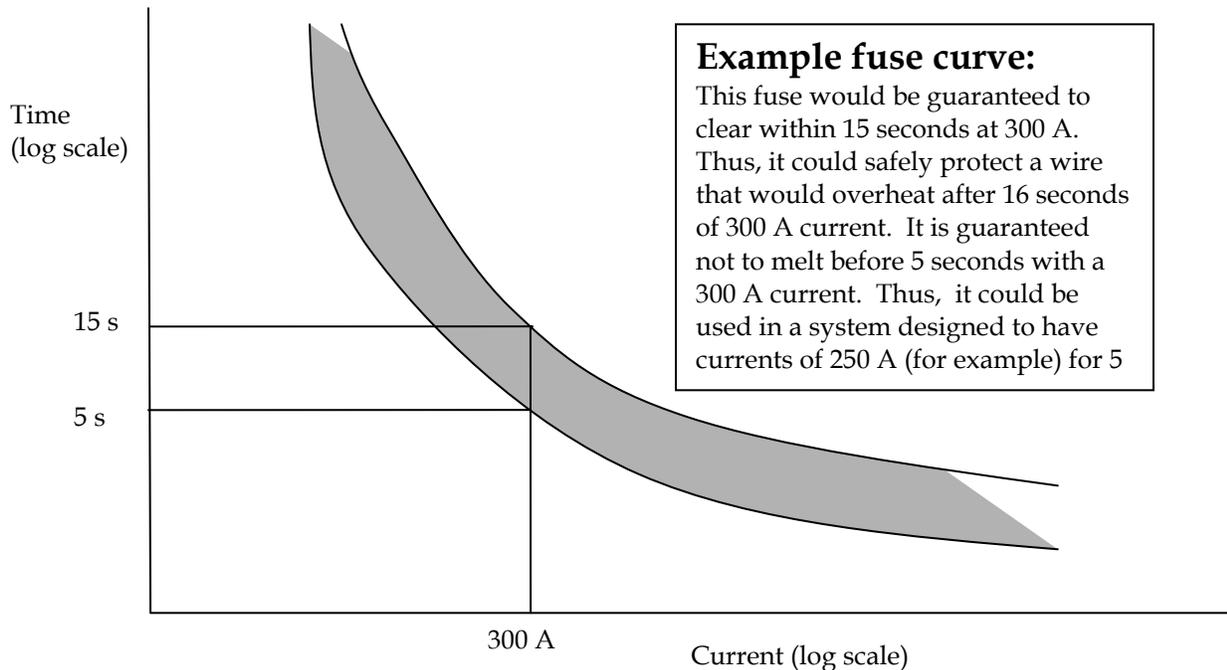
## Measurement circuits

Often there is a need to connect some small wires to a power circuit in order to make measurements, power a small auxiliary circuit, or connect balancing circuits to a battery or ultracapacitor bank. Since these are not power circuits, it's easy to forget that they might need fusing. A 24 AWG wire connected to a 100 A circuit will likely act as a fuse itself if it is shorted, which might seem to obviate the need for a fuse, but fuses safely encase their hot metal inside a glass or ceramic tube, sometimes filled with sand. A plastic-insulated wire that melts could start a fire and/or cause another insulation failure that might cause a higher-current short, or produce a shock hazard.

The straightforward solution is to do exactly as we did before and add a fuse each place that a smaller wire connects to a high-current system. One other solution is to place a resistor in the same place the fuse would go, with the resistor value chosen to limit the short-circuit current to a level that is safe for the wires.

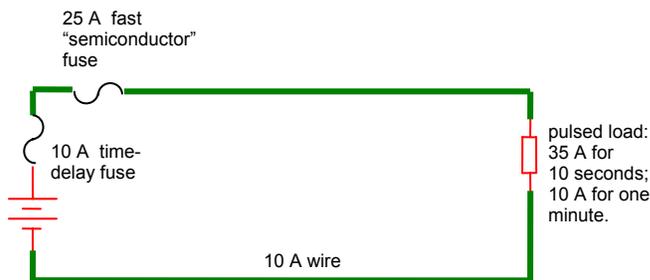
## Time Dependence

Fuses take time to blow. The further they are over the current limit, the faster they blow. This characteristic can work well for protecting wire from overheating, because wire also takes time to heat up. Each fuse time has a different characteristic, described by a time-current curve. A good time-current curve will show a shaded area. Below the shaded area, the fuse is guaranteed not to blow; above it, it is guaranteed to interrupt the circuit.



Protecting semiconductors with fuses is, however, harder than protecting wire, as semiconductors can heat up and fail very rapidly in an overcurrent situation. For this purpose, special very fast blowing fuses are available. They often are not fast enough to protect the semiconductor from failing, but may prevent the failure from being as violent, allowing repair to be more feasible.

On the other hand, a slow-blowing fuse can be very useful in a system such as a vehicle, where high currents are often expected to last only a short time (e.g., 10 seconds during acceleration). A very fast fuse would need to be sized for that full current (although even a fast fuse might take double its rated current for 10 seconds). But a slow (“time-delay”) fuse might be able to carry as much as five times its rated current for 10 seconds. Using a fuse rated for a lower current isn’t in and of itself an advantage, but doing so could allow using smaller wire. Using wire rated for 50 A for a short 100 A pulse is fine as long as it is for a short enough time that the wire won’t overheat. Here’s an example using this approach:



The 10 A time-delay fuse protects the 10 A wire. The 25 A fast fuse is only needed if the load itself has semiconductors that need protection that is not already built into the load. For example, some motor controllers do not have internal fuses and recommend external fast fuses.

Although the use of time-delay fuses can make it safe to use wire rated for lower currents, doing so is not necessarily the best choice for high performance: the added power loss and voltage drop in thinner wire could degrade efficiency and acceleration capability of the vehicle. Comparing these effects to the effect of greater weight and cost in larger wire could lead you to a good choice of wire size.

## Other Protection Devices

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Circuit breakers—switches that automatically open upon an overcurrent condition—can be an attractive alternative to fuses. Similar ratings apply, and as for fuses, it is essential to find ones that are rated for dc if they are used in a dc application, for the same reason as with fuses. The advantages of circuit breakers are that they can be reset rather than replaced after they trip, and, in many cases, they can provide a useful switching function as well as a protection function.

PTC (positive temperature coefficient) resistors rapidly increase in resistance if too much current makes them get hot. This can provide similar protection to a fuse or circuit breaker. In the case of a fault, the circuit won’t be completely interrupted—a smaller current will continue to flow, maintaining the temperature of the PTC. After the fault is removed, it will cool and effectively reset itself. PTCs are available only for currents and voltages that are low compared to the electric drive system in a hybrid vehicle, but they can be useful for the low-voltage (e.g. 12 V) system in a vehicle. Note that they generally have higher resistance (even when not tripped) than fuses or circuit breakers.