

THE PHYSICS OF HEAT TRANSFER FROM ELECTRICAL FAULTS

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ABSTRACT

Electrical faults release energy into the surrounding environment because electrical current flowing in the fault drops through a potential difference. This release of energy can raise the temperature of combustible materials near the site of the fault to the point where ignition of the combustible material occurs. The basic physics of heat transfer from electrical faults to surrounding combustible materials is presented so that the fire investigator can properly analyze the release of fault energy and subsequent ignition of combustible materials.

Types of faults are reviewed and discussed. These include low-impedance faults (short circuits), high-impedance faults, open circuits and high-resistance connections.

The concepts of fault energy release rates and time durations of fault energy release are presented. Equations are given so that the fire investigator can calculate energy release rates from the fault and total energy release over the duration of the fault. Energy release rates from the different types of electrical faults are presented and examples of energy release rate calculations are illustrated.

The heat transfer properties of combustible materials are presented. Concepts of mass, density, specific heat, and heat conduction rates within the material are discussed in the context of heat transfer from electrical faults.

Using the concepts of fault energy release and combustible material heat transfer properties, workable approximate models are developed so that the fire investigator can assess the probability of fire cause from an electrical fault. Specific examples of low- and high-impedance faults are presented and analyzed.

The probability of fire caused by specific types of faults is discussed. Low-impedance, short duration faults are contrasted with long duration high-impedance faults. Specific conclusions are presented with regard to classes of electrical faults and their potential to ignite fires.

TYPES OF ELECTRICAL FAULTS

An electrical fault is any change in an electrical circuit that causes the interruption of current or re-routing of current such that a problem occurs. Interruption of current occurs when a conductor breaks such as when a power line is down and one end has broken away from the system. The fault is not a short-circuit in this case but is an open-circuit. This condition rarely causes fires as the interruption of current leaves much of the circuit un-energized. Ground faulting may occur at the energized broken end of the conductor such as when a downed power line is arcing to the ground.

A ground fault is a condition where an energized conductor comes into contact with a grounded object. Current flows rapidly into the grounded object provided that the electrical system is also connected to ground. Most electrical systems are grounded systems, so the rapid development of fault current is the usual case for ground faults. These ground faults sometimes occur on circuits protected by ground fault current interrupter (GFCI) devices. These devices

sense the flow of current to ground at very low current levels and open the circuit before any harm is done. A GFCI device will generally operate at low ground fault current levels (below 5 milli-amperes). If a GFCI device is in the circuit, insufficient energy will be released to start a fire, provided that the device is working properly.

Line-to-line faults occur when one conductor comes into contact with another conductor, either metal-to-metal contact, or contact through some other conducting material, and current flows between the two conductors. The conductors may both be hot conductors, or one can be hot and the other neutral. Conductors in close proximity to each other are insulated; therefore, the current must pass through either damaged or altered insulation. Sometimes, the insulation on the wires can be damaged to the point where there is metal-to-metal contact between the two conductors allowing higher currents to flow during the fault.

Faults involving short-circuits (line-to-line and ground faults) can be further characterized as either high-impedance or low-impedance faults. First, the subtle difference of impedance versus resistance must be discussed. Strictly speaking, alternating current (AC) systems should be modeled using impedance instead of resistance. Impedance takes into account not only resistance, but also the other two AC circuit characteristics of inductance and capacitance. Even though one may be addressing resistance in an AC circuit, one may still use the term impedance because it is correct to do so when discussing AC systems. For purposes of this presentation, the reader may assume that impedance means the same as resistance.

A low-impedance fault is a typical “bolted short-circuit” where the conductors come into close contact and large currents flow during the fault. Because circuit over-current protection devices are designed to clear these faults quickly, the fault will usually clear in about one cycle or approximately 0.016 seconds. Clearance times vary from device to device and some devices act more quickly than other devices. For purposes of this study, a clearance time for low-impedance faults of 0.016 seconds will be assumed. If the specific over-current device that protected the circuit in question can be examined, then specific time-current relationship curves can be obtained.

Faults that are not bolted short-circuits are characterized as high-impedance faults. These faults do not involve the direct contact between conductors as discussed above for low-impedance faults. High-impedance faults have some other conducting medium between the two conductors that serves to limit current flow between the two conductors. For example, in the fire investigation field, the fire investigator is likely familiar with the char that forms on wires exposed to heat and flame from the fire. The char is rich in carbon, a conductor of electricity. Arcing through char is recognized as one way that faults can occur during a fire. The arcing path through the char may have high enough impedance to the flow of electrical current that circuit breakers will not trip during the fire. Similarly, pyrolysis of wire insulation can change the electrical properties of insulation such that current will begin to flow through the insulation. Such a flow of current would be termed a high-impedance fault.

Another type of fault is a high resistance connection (HRC). Conductor connections that corrode, are contaminated or are improperly made can have substantial resistance to current flow. These connections will increase in temperature due to resistance heating. Over time, a HRC can cause pyrolysis of wood framing and other combustibles, ultimately leading to a fire.

FAULT ENERGY RELEASE RATES

Electrical faults that involve short-circuits or high-resistance connections (HRCs) release energy in the form of heat. Open circuits, in general, do not release energy. HRC type faults release energy because a current is flowing through a resistance in the connection. The energy release rate can be calculated using Ohm's Law:

$$P = I^2 R$$

Where P is the energy release rate in watts, I is the current flowing in amperes and R is the resistance present in the connection. One can readily see that a 1-ohm resistance in a circuit with 10 amperes of current can release 100 watts of heat. If the HRC is at the back of duplex receptacle outlet, such a release of heat will eventually start a fire in the wall cavity.

Low-impedance faults release energy as a function of the fault current and the voltage between the two objects that have been brought together at the fault site. The fault current is limited by the overall impedance of the electrical system that includes the transmission lines, the transformer feeding the area, the service drop, and the branch circuit affected by the fault. The fault currents can be very large, on the order of 4000% or more of the normal current flow. Electrical circuit breaker panels are rated as to their ability to withstand fault currents. Typical household panels are usually rated at 10,000 amperes interrupting current (AIC). In a typical 20-ampere household circuit, instantaneous current flows can be expected to exceed 1,000 amperes. Heat release rates are calculated as follows:

$$P = E_{\text{system}} I_f$$

Where E_{system} is the system voltage in volts and I_f is the fault current flow in amperes. For a typical 120-volt system, heat release rates can be well in excess of 100 kilowatts.

High-impedance faults have a built-in limiter for the fault current flow. That limiter is the fault impedance, Z_f . The fault impedance may limit the fault current flow to values well below the trip setting of the circuit over-current protection device. As such, the fault can be a prolonged event. Recent changes in the National Electrical Code recognize that such faults occur and have mandated that arc fault detector type circuit breakers be used for circuits in the sleeping areas of dwellings. Heat release rates for high-impedance faults are calculated as follows:

$$P = E_{\text{system}}^2 / Z_f$$

For purposes of this discussion, the fault impedance term is assumed to be pure resistance. If one has a fault impedance of 100 ohms, the fault current in a 120-volt system will be limited to 1.2 amperes. However, that fault current will result in a heat release rate of 144 watts. That heat release rate is a competent ignition source, especially if buried in an insulated wall cavity.

FAULT DURATIONS AND TOTAL FAULT ENERGY RELEASE

Different types of faults have different fault durations. Low-impedance faults are typically short-duration faults. A typical circuit breaker will clear a low-impedance fault in about one cycle, or 0.016 seconds. When calculating the total energy released during a fault, the investigator must consider the heat release rate, P , and the duration of the fault, T_{fault} . The total fault energy released, W_{fault} , is approximated by:

$$W_{\text{fault}} = P T_{\text{fault}}$$

One can readily see that a 100 kilowatt fault energy release rate will only release about 1600 joules of heat energy assuming that the fault clears in about one cycle. To understand this amount of energy in common sense terms, one joule is equal to 0.239 calories. A calorie is the amount of heat energy needed to raise the temperature of one gram of water one degree Celsius. So, 1600 joules equals 382 calories. If a container of 10 grams of water (about equal in mass to two U.S. nickel coins) absorbs that heat energy, its temperature will rise only 38 degrees Celsius. Smaller masses of water will increase in temperature more, provided that the mass is well enough isolated or insulated to actually absorb all of the fault energy.

A longer duration fault will release vastly more energy than a short duration fault. Consider a HRC in a residential building. Assume that a wiring connection became contaminated and corrosion occurred at the connection causing a HRC of 1 ohm. Further consider a current of 10 amperes flowing through the HRC. The fault heat release rate is given by:

$$P = (10 \text{ amperes})^2 \times 1 \text{ ohm} = 100 \text{ watts.}$$

Next, assume that the fault duration is 10 days. The total time duration of the fault in seconds is given by:

$$T_{\text{fault}} = 10 \text{ days} \times 24 \text{ hours/day} \times 60 \text{ minutes/hour} \times 60 \text{ seconds/minute} = 864,000 \text{ seconds.}$$

The total fault energy released is given by:

$$W_{\text{fault}} = 100 \text{ watts} \times 864,000 \text{ seconds} = 86,400,000 \text{ joules (86.4 mega-joules).}$$

That is enough energy to bring to a boil (assuming no losses to the surrounding environment) about 250 kilograms of water! Such a release of heat in a confined space, such as an insulated wall cavity, would have a profound effect on combustible materials within the wall cavity.

Next, consider a high-impedance fault. Assume a fault current of 10 amperes in a 120-volt system. Clearly, the 10-ampere fault current would not trip a 15- or 20-ampere circuit breaker. The fault could go on indefinitely. The heat release rate is given by:

$$P = 10 \text{ amperes} \times 120 \text{ volts} = 1,200 \text{ watts.}$$

A fault duration of just one day would release about 103 mega-joules of energy. This amount of energy is on the same order of magnitude as the energy released by the HRC in the previous example. The difference is the shorter fault duration of only one day.

SPECIFIC HEAT

The specific heat of a substance is defined as the heat capacity per unit mass of a body. That is, it defines how much heat is required to raise the temperature of a substance per unit mass. Specifically,

$$c = \text{heat capacity} / \text{mass} = dQ / m dT,$$

where m is the mass in grams. The units are usually given in Joules / gram C°. The following table lists some values for specific heat capacities of common substances:

Table 1 – Typical Values for Specific Heat Capacity¹

Material	J / g C
Asbestos	0.84
Brick	0.92
Carbon	0.71
Concrete	0.80
Glass	0.84
Marble	0.88
Plaster	0.84
Steel	0.452
Wood	1.34 to 2.01

These values allow the investigator to test a hypothesis against the known physics of the situation. For example, the investigator may be faced with evaluating the hypothesis that a low-impedance short-duration fault ignited a nearby wooden wall stud in a wall framing cavity. Without knowing the exact values of all the parameters, some good estimates can still be obtained by applying the elementary physics of the situation.

In this hypothetical case, there is a wooden stud in a wall cavity. The stud will have a specific heat of between 1.34 to 2.01 J / g C. For purposes of this example, a value of 1.7 J / g C will be used. A small section of the stud, approximately 10 cm long (enough to match up with an electrical outlet box) will have a mass of approximately 170 grams. The ignition temperature of the wood is approximately 200 C. The change in temperature required to bring about ignition is approximately 180 C (assuming a room temperature wall stud). The quantity of heat energy required to bring that portion of the wall stud to ignition is then computed as follows:

$$dQ = m dT c = 170 \text{ g} \times 180 \text{ C} \times 1.7 \text{ J} / \text{g C} = 52,020 \text{ Joules}$$

Comparing this quantity of heat with that released in a low-impedance fault is instructive. As calculated above, a low-impedance fault may release about 1600 joules of heat energy. Even if all of that fault energy could be instantaneously transferred to the stud with no losses, the heat from the fault would only amount to about three percent of that required to ignite the small section of wall stud. Therefore, the hypothesis should be rejected, as it is very difficult for a low-impedance fault to ignite nearby wood framing as shown in the simple calculations above.

Consider the hypothesis of a wad of steel wool, one-gram total mass, next to a low-impedance fault catching fire and igniting other nearby combustibles. Steel has a specific heat capacity of 0.452 J / g C. If one gram of steel wool accepts the 1600 Joules of fault energy, then the steel will reach a temperature as computed below:

$$1600 \text{ Joules} = 1 \text{ g} \times dT \times 0.452 \text{ J / g C, or}$$

$$dT = 3,540 \text{ C}$$

This temperature is much higher than the ignition temperature of steel wool, which is known to ignite with an ordinary match. The steel wool would ignite if it accepted all of the heat energy from the fault. If the burning steel wool was a competent ignition source for the other combustibles, then the investigator could not reject this hypothesis.

CONCEPTS OF HEAT TRANSFER

The fault energy released will ultimately transfer to the surrounding materials. Heat transfer is accomplished by three well-defined modes:

- Conduction
- Convection
- Radiation

Electrical faults that cause fires are usually in confined spaces with some sort of close contact between the ignition source (the fault) and the material first ignited. Radiative and convective heat transfer under such conditions are not significant as compared to conductive heat transfer when computing the approximate temperatures within the confined space. Convective heat transfer plays only a small role in a confined space since there is not much of a flow of air into or out of the confined space. Movement of heat out of the space by convection is limited since the air in the space is trapped and cannot readily escape. Convective heat transfer plays a role within the space itself, but only to aid in evenly warming the space. Similarly, radiative heat transfer is significant once the heat energy reaches the outside surface of the confined space. However, within the space itself, the radiation mode of heat transfer simply serves to even out temperatures within the space. For purposes of this study, only conduction will be considered as a significant mode of heat transfer from within the confined space to the exterior regions outside the confined space.

Long-term faults will develop into a steady state condition that is readily analyzed using the Fourier Equation of conductive heat transfer:

$$Q = k A dT / dX$$

where

A = surface area across which heat is transferred (square meters)

dT = difference in temperature (Celsius)

dX = thickness of the material (meters)

k = thermal conductivity of the material (W/m C)

Q = rate of heat flow across the area (Watts)

Some typical values of thermal conductivity of use to the fire investigator are listed in the table below.

Table 2 – Typical Values for Thermal Conductivity²

Material	Thermal Conductivity W / m C
Asbestos Cement Board	0.744
Brick work	0.69
Concrete	0.90 to 2.0
Cotton Wool Insulation	0.029
Fiberglass Insulation	0.04
Glass	1.05
Gypsum or plaster board	0.17
Marble	3.0
Plaster with metal lath	0.47
Plaster with wood lath	0.28
Plywood	0.13
Soft woods	0.12

A typical value of thermal conductivity for white pine (across the grain) is 0.12 W/m C and that of gypsum plaster board is 0.17 W / m C. These values can be used to obtain some characteristic temperature ranges under fault conditions for steady state heat transfer out of a wall cavity.

For example, assume there is a high-impedance fault of 10 amperes in a 120-volt system in an electrical box right next to a wall stud. The total heat production rate is 1,200 watts. Assume that the electrical box is surrounded by insulation such that most of the heat is conducted away through the gypsum wallboard on each side of the wall and the adjacent studs. There are two heat flow rates which can be called $Q_{\text{wall board}}$ and Q_{stud} . These two rates have to add up to equal 1,200 watts. The objective is to calculate the temperature in the wall cavity such that the heat generated by the fault will flow into the adjacent spaces. Assuming that the adjacent spaces are at 20 C and the portion of the cavity that is involved is 37 cm (14.5 inches) wide by 37 cm tall, the system can be modeled as follows:

$$\text{Area of the studs} = 0.37 \text{ meters high} \times 0.089 \text{ meters wide} \times 2 \text{ sides} = 0.066 \text{ sq meters}$$

$$\text{Area of wall board} = 0.37 \text{ meters high} \times 0.37 \text{ meters wide} \times 2 \text{ sides} = 0.27 \text{ sq meters}$$

$$\text{Thickness of wall board} = 0.0127 \text{ meters (1/2 inch)}$$

$$\text{Thickness of wall stud} = 0.0381 \text{ meters (1 - 1/2 inches)}$$

$$\text{Total heat flow} = 1,200 \text{ watts} = Q_{\text{stud}} + Q_{\text{wall board}}$$

$$1,200 \text{ watts} = 0.12 \text{ W/m C} \times 0.066 \text{ sq m} \times dT / 0.0381 \text{ m} + 0.17 \text{ W/m} \times 0.27 \text{ sq m} \times dT / 0.0127 \text{ m}$$

Solving for dT yields a value of 314 C for the wall cavity temperature difference, or 334 C as the computed cavity temperature. It is interesting to note that the heat flow through the studs is only 65 watts. Compared to the gypsum wallboard (1,135 Watts), the heat flow through the adjacent studs is insignificant. This is why most small wall cavity fires do not spread into the adjacent stud spaces.

One can readily see that the wall cavity temperature of 334 C far exceeds that required to ignite the wood framing (approximately 200 C). If the hypothesis under consideration is that of a high-impedance fault in a wall cavity igniting the framing in the wall cavity, then the analysis shown above would require that the hypothesis be retained.

Consider another example of a high-impedance fault in a non-metallic sheathed cable run in an attic where the cable is stapled to a ceiling joist and then covered with 25 centimeters (10 inches) of fiberglass insulation. Assume that the fault current is only 500 milli-amperes. The heat release rate is just 60 watts. The insulation area affected by the fault is assumed to be 0.25 square meters. This area was assumed to be a rectangle encompassing one ceiling joist space with one side twice as long as the other (36 cm x 72 cm). Assume that the ambient temperature in the attic is 30 C. What would the steady state temperature be at the face of the joist assuming that only an 18 cm (7 in) by 18 cm (7 in) patch of the joist is affected?

$$60 \text{ Watts} = 0.12 \text{ W / m C} \times (0.18 \text{ m})^2 dT / 0.0381 \text{ m} + 0.04 \text{ W / m C} \times 0.25 \text{ sq m} \times dT / 0.25 \text{ m, or}$$

$$dT = 422 \text{ C and } T = 422 \text{ C} + 30 \text{ C} = 452 \text{ C}$$

Again, the temperature at the face of the joist is much higher than the ignition temperature of the wood. Another question to ask regarding this hypothetical model is, what fault current would produce a temperature of 200 C at the face of the ceiling joist? The calculations to answer that question are:

$$dT = 200 \text{ C} - 30 \text{ C ambient} = 170 \text{ C}$$

$$Q = 0.12 \text{ W / m C} \times (0.18 \text{ m})^2 170 \text{ C} / 0.0381 \text{ m} + 0.04 \text{ W / m C} \times 0.25 \text{ sq m} \times 170 \text{ C} / 0.25 \text{ m}$$

$$Q = 17.3 \text{ Watts} + 6.8 \text{ Watts} = 24.1 \text{ Watts}$$

$$I = 24.1 \text{ Watts} / 120 \text{ volts} = 0.200 \text{ amps or } 200 \text{ milli-amps}$$

The example illustrated above shows how, in one hypothetical scenario, a small fault can start an attic fire. Such a fire would very likely smolder for days until the fire broke out of the immediate area of ignition and engulfed the entire attic.

LOW-IMPEDANCE VERSUS HIGH-IMPEDANCE FAULTS

Evidence of low-impedance faults is found frequently in the course of fire investigation. Such evidence may include re-melting of the copper conductors forming globules of metal on the conductors. As documented in NFPA 921, not all of these copper globules can be attributed to arcing from a low-impedance fault. However, as illustrated above, the amount of heat released from such short-duration, low-impedance faults rarely can be shown as a competent ignition source for solid fuels. Only if the material first ignited is of low mass, low specific heat capacity, and in close proximity to the fault, will a fire occur. The exceptions to this statement are fuel gases within the flammable limits, which are readily ignitable with a short-duration arc.

The existence of high-impedance faults and high-resistance connections is well documented.³ Insulation on wiring that is organic in nature will degrade and carbon arc tracking will occur. Absorption of moisture by wiring insulation can cause small current paths to form, leading to pyrolysis of the insulation (carbon arc tracking). Application of unwanted heat to the wiring will also lead directly to pyrolysis. The carbon arc tracking produces a high-impedance fault in the wiring system leading to possible ignition of a fire. High resistance faults develop due to corrosion or improperly made connections. Investigators need to focus on high-impedance electrical faults and high-resistance connections, as opposed to low-impedance faults, when evaluating possible fire causes.

In summary, high-impedance faults are likely to be of long duration and are a much more competent ignition source for solid fuels than low-impedance faults. High-impedance faults may leave no trace of their occurrence since the original fault current path may be completely burned away in the fire. The temperatures reached during a high-impedance fault may not reach the melting point of copper. The conductors left at the site of the high-impedance fault may not show any trace of the fault when they are examined after the fire.

ABOUT THE AUTHOR

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ENDNOTES

¹ www.engineeringtoolbox.com

² www.engineeringtoolbox.com

³ DeHaan, John D., Kirk's Fire Investigation, Prentice Hall (1997)