

A Brief Description of the Construction and Function of Common Electric Matches

Lawrence Weinman

Schneier/Weinman Consultants, LLC, Huntsville, AL USA

and

K. L. Kosanke

PyroLabs, Inc., Whitewater, CO USA

ABSTRACT

A simple description of the construction and the physical principles governing the function of common electric matches and some implications of these principles for testing and firing them are presented.

Keywords: electric match, heat resistance, current, volt, pyrogen

Introduction

This article offers a brief and not overly technical description of how typical electric matches function. It is hoped that this information will be of assistance to those who use them. As a general aid to readers with somewhat limited technical experience, a series of definitions have been included at the end of this article. Because the information presented in this article can be found in numerous texts, except for some direct quotes included in the definitions, specific references are not cited in this article.

In concept, the basic operation of an electric match is quite simple. An electric current is passed through the resistance of the bridgewire. Over time, as energy is dissipated in the bridgewire, it heats-up. A portion of that heat is transferred to the chemical composition (pyrogen) of the electric match. When the pyrogen reaches its ignition temperature, it reacts to produce the desired output of fire from the electric match.

An Idealized Electric Match

Figure 1 is an illustration of a cross sectioned idealized (i.e., imaginary) electric match. The adiabatic barrier is meant to imply that, for the purposes of this example, no thermal energy (heat) may flow through the barrier, not even into the electrical conductors by means of conduction through the ends of the bridgewire. In the center of the bridgewire is a *very small* amount of pyrogen in intimate contact with the bridgewire. It will be assumed that the contact is sufficiently good such that the temperature of the pyrogen is always equal to the temperature of the bridgewire. It will also be assumed that the amount of pyrogen is so small that its heat capacity is a negligible addition to that of the bridgewire.

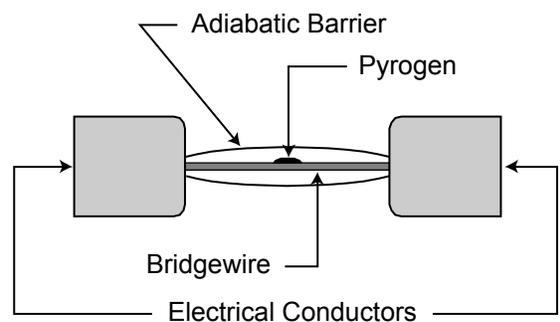


Figure 1. Illustration of an idealized (i.e., imaginary) electric match.

Given the conditions described above, and after providing somewhat typical physical characteristics for the system, it is possible to calculate the minimum energy needed to function (fire)

this ideal device. Specifically, it will be postulated that:

- The bridgewire:
 - Diameter (d_{bw}) is 0.025 mm
 - Length (l_{bw}) is 2.0 mm
 - Density (ρ_{bw}) is 8.0 g/cm³
 - Specific heat capacity (C_{bw}) is 0.46 J/g°C (independent of temperature)

The ambient temperature (T_a) is 27 °C (81 °F).

- The ignition temperature for the pyrogen (T_{ig}) is 327 °C

Using this information some useful calculations can be performed. First, the mass of the bridgewire (m_{bw}) is simply the product of its density and its volume (V_{bw}),

$$\begin{aligned} m_{bw} &= \rho_{bw} \cdot V_{bw} = \rho_{bw} \left(\pi \cdot \frac{d_{bw}^2}{4} \cdot l_{bw} \right) \\ &= \left(\frac{8.0 \text{ g}}{\text{cm}^3} \right) \pi \frac{(0.0025 \text{ cm})^2}{4} (0.20 \text{ cm}) \quad (1) \\ &= 0.0000079 \text{ g (i.e., } 7.9 \times 10^{-6} \text{ g)} \end{aligned}$$

The amount of energy (J_{bw}) required to raise the bridgewire temperature by one degree Celsius (1 °C) is just the product of its specific heat capacity (C_{bw}) and its mass (m_{bw}),

$$\begin{aligned} J_{bw} &= C_{bw} \cdot m_{bw} \\ &= (0.46 \text{ J/g°C}) (7.9 \times 10^{-6} \text{ g}) \quad (2) \\ &= 3.6 \times 10^{-6} \text{ J/°C} \end{aligned}$$

Since the pyrogen needs to be raised from ambient temperature to its ignition temperature to cause its ignition, the electrical energy required for ignition is (J_{ig}),

$$\begin{aligned} J_{ig} &= (T_{ig} - T_a) J_{bw} \\ &= (327 \text{ °C} - 27 \text{ °C}) (3.6 \times 10^{-6} \text{ J/°C}) \quad (3) \\ &= 1.1 \times 10^{-3} \text{ J (i.e., } 0.0011 \text{ J)} \end{aligned}$$

In calculating the *minimum* energy required to function this idealized electric match, note that no consideration needed to be given to bridgewire resistance, the voltage applied, the current flowing, or time to ignition. When performing this type of analysis only the mass, specific heat capacity, and ignition temperature are

needed to determine the minimum firing energy. Any combination of the applied voltage, total circuit resistance, electric current and time that provides the minimum firing energy will cause the functioning of this idealized electric match.

A More Nearly Real World Electric Match

Figure 2 is an illustration of a cross section of a more nearly real world electric match, and for which there are both similarities and differences from the ideal case. The most important differences are that there is no adiabatic barrier to preclude the escape of thermal energy and by no means does the pyrogen present a negligible contribution to the heat capacity of the bridgewire. (Complicating the situation is that typically the thermal characteristics of the pyrogen are not well known.) There also exists a heat transfer path out the ends of the bridgewire into the electrical contacts. However, this path is generally considered to be negligible, provided that the length of the path is a minimum of approximately 6–12 wire diameters to each of the electrical contacts. Thus, allowing for an additional distance of 5–10 bridgewire diameters at the center of the electric match, if the total bridgewire length is approximately 25 times its diameter, then the loss of heat through its electrical contacts will be negligible.

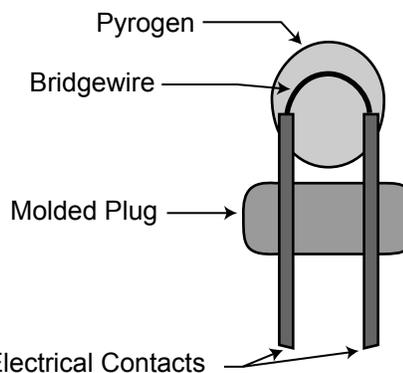


Figure 2. An illustration of a more realistic electric match.

For this more realistic electric match, the primary added consideration is the additional energy required to heat that portion of the pyrogen in immediate contact with the bridgewire while

at the same time this thin layer of pyrogen is transferring heat further outward into the bulk of the pyrogen. Taking a somewhat simplified approach to the problem, at any given time the net amount of thermal energy having accumulated in the thin layer of pyrogen in immediate contact with the bridgewire (J_{net}) is simply the difference between the energy into (J_{in}) and the energy out of (J_{out}) that pyrogen layer.

$$J_{net} = J_{in} - J_{out} \quad (4)$$

The total energy into (or out of) the layer is the rate of energy (i.e., power) being supplied (or leaving) multiplied by time. However, because the rates of energy into and out of the pyrogen layer are not constant over time, this problem must be treated as an integral equation from calculus. While this approach could be taken, it would not be consistent with the “not overly technical” approach promised for this article.

Instead, consider the following analogy, pouring water into a bucket with a hole in its bottom. At any time the amount of water in the bucket will be the difference between the amount of water that has been put into the bucket, minus the amount that has leaked out. (In this analogy, the amount of water in the bucket represents the amount of thermal energy in the layer of pyrogen closest to the electric match bridgewire.) If one adds water very slowly to the bucket, because the water is leaking out as fast as it is being added, only an insignificant amount of water will accumulate in the bucket no matter how long the process continues. If the rate of pouring into the bucket is increased, more water will begin to accumulate in the bucket (i.e., the pyrogen will get hotter). However, as the level of the water in the bucket increases, so does the rate at which it leaks out of the hole. Accordingly, even after adding water for a long time, it may not continue to accumulate to the point of the bucket becoming full (i.e., the pyrogen may not get so hot as to ignite). At some further increased rate of adding water to the bucket, continuing to add water will eventually cause the bucket to fill completely. However, the length of time required to fill the bucket depends on the size of the bucket and the size of the hole. In this analogy, the way to fill the bucket using the least amount of water, is to pour the water into the bucket very rapidly, before much water has a chance to leak out.

For an electric match, the rate of adding thermal energy (W) is equal to the current through the bridgewire (I_{bw}) times the voltage drop across the bridgewire (E_{bw}). However, from Ohm’s law, the voltage drop across any resistance is equal to the current through the resistance times the value of the resistance ($E = I \cdot R$). Thus, in the case of the bridgewire, the rate of adding thermal energy equals the current through the bridgewire squared (I^2), times the resistance of the bridgewire (R_{bw}).

$$W = I_{bw} \cdot E_{bw} = I_{bw}^2 \cdot R_{bw} \quad (5)$$

Further, the amount of energy added (J) is the rate of addition (W) multiplied by time (t).

$$J = W \cdot t = I_{bw}^2 \cdot R_{bw} \cdot t \quad (6)$$

Following the thinking of the leaky bucket analogy, if the rate of adding energy to the bridgewire is too low (i.e., the rate of adding water to the bucket is too low), the pyrogen layer directly against the bridgewire will heat-up a little, but it will never become hot enough to ignite (i.e., the bucket will never get full) no matter how long the electrical energy is supplied. Although not strictly correct, for the purposes of this discussion the resistance of the bridgewire will be considered to remain constant during the heating process of this particular electric match. With this assumption, referring to equation 5, only the current determines the rate of energy being added to that electric match, and if that current is too low, the electric match will fail to ignite no matter how long the current is applied. The maximum electric current that fails to be capable of igniting the pyrogen even after some specified (long) time, may be called the *no-fire current* for that electric match under a specific set of conditions.

As the amount of electric current passing through the bridgewire is increased beyond the no-fire current level, there will come a time when the electric match will ignite providing one is willing to wait long enough. (In the leaky bucket analogy, this corresponds to the minimum rate of adding water that will eventually cause the bucket to fill completely.) This minimum electric current, that will eventually cause the ignition of an electric match, may be called the *all-fire current* for that electric match under a specific set of conditions.

The least amount of energy needed to ignite the electric match occurs when that energy is supplied very quickly (i.e., when the water is poured very quickly into the leaky bucket so that almost none has a chance to leak out). Using equation 6 above, this *minimum firing energy* can be calculated for a specific electric match.

Some of the principles discussed above are illustrated in Figure 3, which is a graph of firing time as a function of applied current for a generic electric match. Note that the curve takes the approximate shape of a hyperbola. At low currents, the firing time is effectively infinite (i.e., the electric match never ignites). As higher currents are applied, some electric matches fire but on average it takes a relatively long time. As still higher currents are applied, the average time to fire becomes less. However, as the applied current continues to be increased, while the firing times still decrease, the amount of decrease becomes smaller and smaller. Finally, when the applied current becomes very large, there comes a point where the firing time has become essentially constant, because the time for thermal energy to 'leak' away before the device fires has become negligible.

No-Fire Current

In Figure 3, the left and lower edge of the shaded band is an estimate of the no-fire current for this particular electric match, under the test conditions used. However, just specifying the no-fire current of an electric match does not fully define its firing characteristics. To be fully definitive, one also needs to consider both the time during which the current is applied and the thermal environment of the electric match. For example, even applying a minimal test current will cause the match composition to begin to heat up. If that electric current is maintained long enough, and if the heat being produced is allowed to accumulate because the electric match is extremely well insulated, eventually the pyrogen could reach its ignition temperature. (Note that when information about time and thermal environment is not specifically provided, a time of application of 5 to 10 seconds and a thermal environment of free air at 20 °C are typically meant to be implied.)

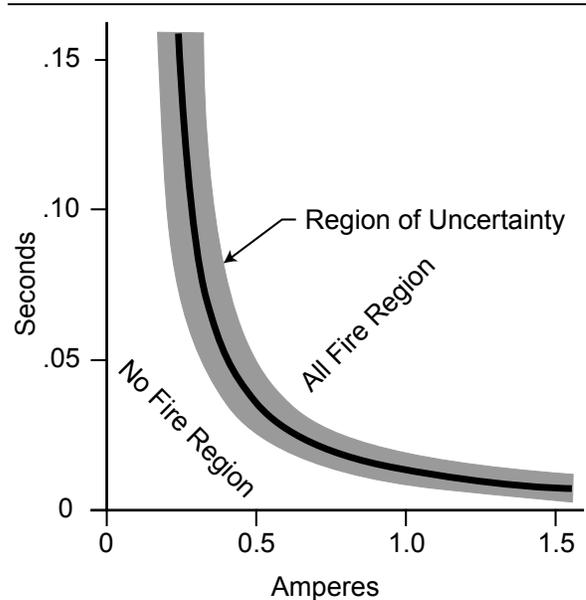


Figure 3. Firing time as a function of applied current for one type of electric match.

Because it cannot be absolutely assured that no electric match of a given type would ever ignite if a current equal to its no-fire current were applied, the maximum continuity test current is generally required not to exceed 20% of the no-fire current stated by the electric match manufacturer. (Note that some manufacturers may not specify the no-fire current for their electric matches. However, in all cases strict adherence to a manufacturer's maximum test current is required.)

All-Fire Current

In Figure 3, the right and upper edge of the shaded area is an estimate of the all-fire current for this particular electric match, under the test conditions used. As with the no-fire current, the same cautions apply to interpreting the meaning of this all-fire current. Changes in test conditions and variations in the performance of an individual electric match can significantly alter the all-fire current value. For example, the type of electrostatic discharges commonly produced by individuals as they work, may produce electric currents many times greater than the all-fire current. Yet very few, if any, standard electric matches will fire from such an electrostatic discharge pulse passing through the bridgewire. This is because the duration of the current pulse

is very short, typically less than a few microseconds in duration, and so has little total energy.

Because it cannot be absolutely assured that all electric matches of a given type will always ignite if a current equal to their all-fire current were applied, the recommended individual electric match firing current is typically about 40% above the all-fire current stated by the manufacturer, and the recommended series firing current is typically about double the all-fire current. (Note that this corresponds to supplying electric power at a rate that is two and four times that at the all-fire current, respectively, see equation 5.)

Additional Considerations

The shaded area in Figure 3, between the no-fire and all-fire currents, is a region of uncertainty, wherein it cannot be absolutely assured whether or not any individual electric match, of the type being considered, will ignite.

For the purposes of this discussion, a *good* electric match will be defined as one for which the thermal contact between the bridgewire and the pyrogen is completely effective, and a *bad* electric match will be one for which the thermal contact is imperfect or incomplete. Within the context of these definitions, note that a good electric match will require a greater firing energy to function than will a bad device. This is because, at normal firing current levels, the good device will transfer more heat away from the critical interface between the pyrogen and bridgewire, before that pyrogen heats up sufficiently to ignite. Whereas, in the bad device, the voids, cracks, decoupling, etc. serve to impede the heat flow away from the interface. As a result, that portion of the pyrogen still well coupled to the bridgewire will reach its ignition temperature sooner, thus requiring less total energy to function the electric match.

Following the good/bad terminology of the previous paragraph, consider an *extremely bad* electric match, one in which there has been a total decoupling of the pyrogen from the bridgewire. This can, and often does, happen because of applying a somewhat too low (or an intermittent) firing current. In that case, the pyrogen in contact with the bridgewire is raised more slowly than intended toward its ignition temperature, and the pyrogen may decompose with-

out actually igniting. As a result of gas produced in this process, a tiny gap can form between the pyrogen and the bridgewire, thus thermally isolating the bulk of the pyrogen from the heat of the bridgewire. In some cases when this occurs the decoupling may be so severe that the bridgewire may become sufficiently far out of contact with the bridgewire, that the bridgewire may actually heat to its melting temperature and burn out (*fuse*) without transferring sufficient heat to ignite the pyrogen. Nicks in the bridgewire, poor welds, solder voids, and switch chatter are frequent causes of such malfunctions. Nicks in the bridgewire, poor welds and solder voids also have the potential for reducing the electric current flowing in the firing circuit because of significantly greater electric match resistance. So called switch chatter can be the result of a physical bouncing of the switch contacts upon closure or because of dirt or oxidation on the surfaces of the switch contacts, either of which has the potential to reduce the intended firing current.

The term “volts to fire” is meaningless unless details of the complete firing system are specified, including all of the wiring and connectors. This is because the resistance of all the firing lead wiring, the connection resistances and the internal resistance of the battery (if used) all affect the voltage required to produce the required firing current through the bridgewire. However, it might be appropriate to speak of “volts to fire” for a bare electric match head, or some other well specified condition.

The term “firing energy” is only meaningful if the rate of delivering that energy (i.e., power) is also specified. Using equation 6, a continuity test current of only 0.02 ampere through a 2 ohm bridgewire for about 20 minutes is found to deliver 1 joule of energy to the bridgewire and pyrogen. By comparison, most electric matches are considered to require a firing energy of approximately 0.02 joule (0.5 ampere through 2 ohms for 0.05 second).

Conclusion

While electric matches are simple devices, like so many other simple devices, they require the user to have some basic knowledge to truly understand and properly use them. It is hoped

that this article has provided a reasonable amount of that information.

Possibly Useful Definitions

To make these definitions more user friendly, there is necessarily some redundancy of the information. Those definitions in quotes are taken from the *CRC Handbook of Chemistry and Physics*, 62nd edition, 1981.

adiabatic: “A body is said to undergo an adiabatic change when its condition is altered without gain, or loss, of heat.” In the case presented in this article, this does not include the heat generated within the bridgewire by the passage of electric current.

ampere: The unit of electric current, for which the abbreviation A may be used, and the symbol *I* is commonly used in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

bridgewire: A small diameter, relatively high resistance, conductor in an electric match. Commonly, bridgewires have a diameter of approximately 0.025 mm and are made of the alloy Nichrome.

calorie: A unit of heat energy, which has fallen into disfavor, is commonly abbreviated cal, and which is equivalent to 4.18 joules (J) (the currently more favored unit).

current (electric): “The rate of transfer of electricity....” The unit of electric current is an ampere, for which the abbreviation A may be used, and the symbol *I* is commonly used as current in equations.

electric detonator: An electrically actuated device producing a detonation that is used to initiate another detonating explosive. These devices are not usually used with pyrotechnic devices. An electric detonator may contain an electric match.

electric match: A small electrically activated device producing a small ignition pulse (flame) used to ignite pyrotechnic devices. (Note: A “**squib**” is **not** an electric match, but a device having a greater energy output, which may be designed and used for propulsion, actuation, or ignition. While it may contain an electric match,

the terms should not be confused or interchanged.)

electric potential: (Also potential difference and related to electromotive force or voltage). The unit of electric potential is the volt, for which the abbreviation V may be used, and the symbol *E* is commonly used as potential difference in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

energy: “The capability of doing work.” In this article, the symbol for energy is *J*, and the unit of energy may be joules (J) or calories (cal).

heat: “Energy transferred by a thermal process.”

heat capacity: “The quantity of heat required to increase the temperature of a system or substance by one degree of temperature. It is usually expressed in calories per degree centigrade or joules per degree Celsius.” (See specific heat capacity.)

joule: A unit of energy, including thermal energy, abbreviated as J. A joule is equal to one watt second, and equals 0.24 calorie.

ohm: The unit of electric resistance is the ohm, for which the abbreviation Ω (Greek capital letter omega) is commonly used, and the symbol *R* is commonly used in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

Ohm’s law: Expresses the direct relationship between current (*I*), potential difference (*E*), and resistance (*R*) in an electric circuit. A common form of Ohm’s law is expressed by the equation,

$$I = \frac{E}{R}$$

power: Is the time rate of energy transfer or production. A common unit of power is the watt, which is commonly abbreviated as W, defined as one joule per second, and the symbol *W* may be used for power in equations. In an electric circuit, the amount of power produced is equal to the product of current (*I*) through the circuit and potential difference (*E*) across the circuit,

$$W = I \cdot E, \text{ or } W = \frac{J}{t}$$

pyrogen: An energetic mixture of chemicals used to produce heat, flame, or similar.

resistance: "...is a property of conductors depending on their dimensions, material and temperature which determines the current produced by a given difference of potential." The unit of resistance is the ohm, which is commonly abbreviated as Ω (Greek capital letter omega), and the symbol R is commonly used in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

specific heat capacity: Heat capacity per gram (g) of material, commonly using the units of joules per gram-degree Celsius ($J / g\text{-}^\circ\text{C}$), and the symbol C is commonly used in equations.

squib: (Also electric squib) A device containing an electric match plus a pyrotechnic base charge, generally contained in a small metal tube.

temperature: "Temperature may be defined as the condition of a body which determines the transfer of heat to or from other bodies." Note: The units of temperature may be degrees Fahrenheit ($^\circ\text{F}$), degrees Celsius ($^\circ\text{C}$) or Kelvin (K)

(by custom, when using K the word degree is not used). Modern technical usage tends toward using either $^\circ\text{C}$ or K. The temperature scales may be converted as follows:

$$^\circ\text{F} = 32 + \left(\frac{9}{5}\right) ^\circ\text{C}$$

$$^\circ\text{C} = \left(\frac{5}{9}\right) (^\circ\text{F} - 32)$$

$$\text{K} = ^\circ\text{C} + 273.15$$

time: Time is usually expressed in seconds, for which the abbreviation s may be used, and the symbol t is commonly used as time in equations.

volt: "The unit of electric potential difference...", for which the abbreviation V may be used, and the symbol E is commonly used for voltage in equations.

watt: The unit of electric power, which is commonly abbreviated as W, and corresponds to the production or consumption of energy at the rate of one joule per second.