The Dahlquist Resistor Igniter

Bob Dahlquist © 1998

WARNING! Anyone intending to make use of this technology should first be familiar with standard safety precautions for electricity, rocketry, and pyrotechnic materials. Neither the author, Aerocon Systems, Tripoli Central California, the Webmaster, nor the Reaction Research Society will be responsible for any accidents or damages, as the use of this technology by the reader is beyond their control. If you do not agree, you are advised to stop reading now.

Note: Bob Dahlquist died a couple of years ago of unexpected health complications. He leaves this white paper behind as part of his legacy to the rocketry community.
–Aerocon Systems, Editor, 2008

The following variables will be used in the calculations:

R_i = Initial resistance of the resistor (ohms)
R_h = Resistance of resistor when hot*
R_c = Sum of all circuit resistances except resistor
R_t = Total circuit resistance including resistor*
P_t = Total power dissipated in Rt (watts)*
P_r = Power rating of resistor (watts)
P = Power dissipated in resistor (watts)*
E = Open-circuit EMF (voltage) of power source
I = Current flowing in the circuit (amps)*

(Instantaneous values)*

Note: R_c includes the internal resistance of the battery or other power source; the contact resistance of all the connectors, terminals, relay or switch contacts, battery clips, and igniter clips in the firing circuit; and the resistance of the battery cables, firing leads, and igniter leads.

1 Introduction

The use of carbon resistors as ignition initiators has been developed by the author over the past three years. Additional testing and experimentation on pyrotechnic coatings was done by Niels Anderson and Stan Currey. The resistor initiator has now been quantified and perfected to the point that it is ready for practical use.

The resistor initiator is useful for most pyrotechnic and rocketry purposes. Some examples are:

- Ignition of quickmatch
- Firing cannons and mortars
- Ignition of black powder charges and primes
- Ignition of less sensitive pyrotechnic compositions
- Ignition of rocket motors

The resistor igniter has proven to be 100% reliable when used according to the correct procedure in a system designed for the application. When various applications are contemplated, if the system is designed for the most difficult application, then it will usually work with the same reliability in the less difficult applications.

Note that the reliability under the above conditions was not 99% or 99.9%, but 100%. There were zero premature ignitions and zero ignition failures. Under other conditions, this level of reliability has not been achieved.

The main advantages of the resistor initiator, in addition to reliability, are:

- The ability to convert substantial quantities of electrical energy into heat within a very small space, due to the concentration of high resistance into a small area.
- The ability to transfer substantial quantities of energy over long distances with high efficiency, due to the high resistance of the resistor initiator.

With appropriate ignition system design, 25 Joules can easily be transferred from a compact, hand-held firing box to a pair of resistor initiators half a mile away. A single resistor initiator can be fired two miles away, using #18 AWG zip cord firing leads. No relay box is required.

The ability to easily and conveniently supply so much energy by electrical means alone allows a relatively insensitive first fire composition to be used. (The resistor igniter will produce fire even without any pyrotechnic coating, thus in many applications it can be used without any first fire composition; it can ignite the booster compound directly.)

The first fire composition (if used) can be chosen such that its no-fire energy, in Joules, is higher than the electrostatic spark energy available from a human body charged to 30,000 volts; while the same compound's all-fire energy is lower than the energy provided by the resistor initiator. In this way, an igniter can be produced which can not be ignited accidentally by electrostatic discharge from a human body, yet will ignite without fail when intentionally fired. Such an igniter will also be insensitive to other sources of extraneous energy, such as induced currents from nearby radar or radio transmitting antennas.

The high energy density provided by the resistor initiator eliminates the need to use any of the highly sensitive primer compositions (unless, of course, you are making detonators; and for that, a bridgewire is preferred anyway).

The resistor releases heat energy over a longer period of time than electric matches, which (consistent with their original application) only produce a very brief flash. This allows ample time for heat to transfer from the resistor to the booster compound, making ignition more reliable.

The availability of resistors manufactured to close tolerances adds to the reliability and repeatability of the resistor igniter for any given application.

However, there is no such thing as a standard resistance for all resistor initiators; the proper resistance depends upon the application and system in which it is to be used. The optimum value can vary from 1 to 1,000 ohms. Equations for predicting the optimum resistance for use in two different classes of firing systems (constant-voltage and capacitor discharge) were developed by the author.

The author has also developed several different electrical firing systems for use with resistor igniters (in addition to systems for use with other types of igniters).

2 The Resistor Initiator

The heart of the resistor igniter is a quarter-watt, carbon film 5% tolerance resistor. Its value in ohms is chosen such that it will draw enough current to produce a 200x to 400x overload in the resistor. For a quarter-watt resistor, this means that when the firing button is pushed, 50 to 100 watts will be dissipated in the resistor. This overload pyrolyzes the resistor's coating and converts it to flame in a fraction of a second.

The rate of heat release at 50 Watts dissipation is 12 (gram)calories per second. The surface area of the carbon film in a n-Watt resistor is roughly 5 mm^2 or 0.05 cm^2. The heat flux per unit area, or thermal energy density, is then

$$q'' = \frac{12\ \text{cal/sec}}{0.05\ \text{cm}^2} = 240\ \text{cal/cm}^2 - \text{sec}. \qquad (1)$$

This is roughly 8 times the heat flux required to ignite HTPB propellant directly, if the resistor is cast into the propellant. But to have a short ignition delay overall, a faster burning pyrotechnic compound is needed as a booster when igniting rocket motors.

Experiments by the author showed that the energy required to pyrolyze the resistor and produce flames amounted to about 14 Joules. The time delay between application of the firing current and the appearance of flame varied inversely with the average power dissipation, approximately as follows:

$$t \text{ (sec.)} = \frac{14 \text{ Watt} - \text{sec}}{P_{avg} \text{ (Watts)}} \tag{2}$$

When the resistors were immersed in black powder or coated with a pyrogen composition, the time delay for ignition was substantially less. In Stan Currey's experiments using a sensitive pyrogen compound, some brands of resistors ignited the coating with as little as 3 or 4 Joules. However, ignition was not reliable at such a low energy. Reliable ignition of the sensitive coating was achieved at about 7 Joules per resistor.

Carbon composition resistors were also tested by the author, and had much longer ignition delays. This is because the carbon, where the heat is released, is covered by a thick layer of insulating material, which has appreciable thermal mass and thermal resistance (see Figure 1)[1]. Considerable energy is consumed in pyrolyzing this thick coating; so that Equation (2) is not valid for carbon composition resistors unless a much larger value for the energy is used.

Carbon composition resistors often broke in half without producing any flame. Carbon film resistors, on the other hand, have a ceramic substrate which normally holds the resistor together during and after firing. Often the carbon film resistor can be fired twice.

Flameproof and metal film resistors were tested also, but held true to their name; producing no flame at all, even at extreme overloads.

The resistance of the carbon film resistor was found to decrease during firing, to about half of its initial value. With the application of sufficient firing energy, the resistance then increased to several thousand ohms or more. For this reason, average power is used in Equation (2).

When computing power dissipation, all the other resistances in the circuit must be taken into account. This includes the internal resistance of the battery or other power source, the resistance of the wires, and the contact resistances of all the switch and relay contacts, wire connections, and igniter clips.

As long as a DC power source is used (such as a battery or a capacitor), inductance and capacitance can be assumed to be insignificant for the purpose of this calculation.

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[1] No figures have been developed for this document as of last update.

At any given instant, the current flowing in the firing circuit will be equal to the open-circuit voltage of the power source, divided by the total of the resistances mentioned above.

$$I = \frac{E}{R_t} \tag{3}$$

The instantaneous power dissipation will then be equal to the square of the current, multiplied by the actual resistance of the igniter resistor at that moment.

$$P = I^2 R_i \tag{4}$$

Integrating the instantaneous power over the elapsed time gives the energy (in Watt-seconds or Joules) dissipated in the resistor. Dividing the energy by the elapsed time gives the average power in Watts. The open-circuit voltage may be essentially constant (as when a battery system is used) or may vary from a high value to near zero during firing (as when a capacitor discharge system is used).

AC from an inverter or generator may also be used, with appropriate precautions. The author has not tested the use of AC with resistor igniters, but if 50 or 60 Hz is used, the equations for constant voltage DC given below should produce a resistance value that will be close enough for practical purposes. RMS values of voltage and current must be used.

When using AC, it is best not to connect the firing circuit to the same power source used by other important items such as computers and solenoid valves.

3 Constant Voltage Firing Systems

To achieve the most reliable ignition and shortest delay when using carbon resistor igniters with a constant voltage source, the other resistances in the firing circuit should not add up to more than half of the igniter resistor's initial value. Then when the igniter's resistance decreases during firing, the sum of all the other resistances in the circuit will not exceed the resistance of the igniter.

When the igniter resistance is equal to the sum of all the other resistances in a constant-voltage circuit, the power dissipation in the igniter will be at a maximum.[2]

In a well-designed system, the resistor undergoes a thermal runaway during firing. As the resistor initially conducts electricity and begins to heat up, its resistance decreases due to carbon's negative temperature coefficient. This causes more current to flow, which

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[2] To clarify: By constant-voltage circuit, the author means a circuit in which the open-circuit voltage of the power source is constant, not the voltage across the load, or igniter resistor.

generates more heat, which causes the resistance to decrease further, which causes more current to flow, and so on.

When the resistor gets hot enough, pyrolysis converts some of the insulation to additional carbon in parallel with the original carbon film, further decreasing the resistance. This causes more current to flow, generating more heat, and so on.

If the other resistances in the circuit add up to more than the igniter resistance, this thermal runaway will be inhibited as the other resistances will control the current.

In addition, the energy transfer from the source to the resistor will no longer be at its maximum, as the other resistances in the circuit dissipate more power than the igniter. This will increase the ignition delay.

In choosing what value of resistor to use, the criteria are:

- The resistor must draw enough current so that it dissipates at least 200 times its power rating initially.
- The value of the igniter resistor, in ohms, must be at least twice the total of all other resistances in the firing circuit.
- For shorter ignition delay, the resistor should dissipate 400 times its power rating when it is hot (assume its hot resistance is half the initial resistance).
- You must use a standard value of resistance unless you are making your own resistors or ordering custom made resistors. Standard values are shown in Table (1).

3.1 Design Calculations

The maximum circuit resistance for a given circuit voltage is calculated as follows:

For a given value of R_c, maximum power transfer from the power source to the resistor will occur when $R_h = R_c$. Then $R_t = R_h + R_c = 2R_h$. As these resistances are in series, the power dissipated in each will be proportional to the resistance. Thus, half of the total power will be dissipated in R_h and half will be dissipated in R_c.

Under these conditions, the total circuit power P_t required is twice the power required to pyrolyze the resistor:

$$P_t = 2(400P_r) = 800P_r \tag{5}$$

as P_r is 1/4 watt, P_t required is 800/4, or 200 watts.

Now we can calculate the total resistance:

$$R_t = \frac{E^2}{P_t} = \frac{E^2}{200} \tag{6}$$

1.0	1.5	2.2	3.3	4.7	6.8
1.1	1.6	2.4	3.6	5.1	7.5
1.2	1.8	2.7	3.9	5.6	8.2
1.3	2.0	3.0	4.3	6.2	9.1

Table 1: Standard 5% Resistor Values (Ohms). If higher values are necessary, multiply any of the above by 10, 10^2, or 10^3.

Since R_c is half of R_t,

$$R_c = \frac{R_t}{2} = \frac{E^2}{400} \tag{7}$$

$$R_h = R_c = \frac{E^2}{400} \tag{8}$$

For less ignition delay, if possible, make your R_c half of the maximum allowable value:

$$R_c = \frac{E^2}{800} \tag{9}$$

The approximate initial resistance of the igniter resistor is twice our assumed hot resistance:

$$Ri = 2Rh = E^2/200 \tag{10}$$

This value must be rounded off to a standard value (see Table (1)). It should always be rounded off to a higher value unless it is very close to a lower one. Now calculate a value of current that will cause $400P_r$ to be dissipated in the new value of R_h (which is half the new, standard value of R_i):

$$I = \left(\frac{P}{R_h}\right)^{0.5} = \left(\frac{400P_r}{R_h}\right)^{0.5} = \left(\frac{100}{R_h}\right)^{0.5} \tag{11}$$

and with Ohm's Law, we can calculate a value of total resistance such that the desired current will flow:

$$R_t = \frac{E}{I} \tag{12}$$

The new value of R_c is then found by subtracting the new value of R_h from the new value of R_t:

$$R_c = R_t - R_h \tag{13}$$

This is the new maximum value for R_c; if possible, make your actual circuit R_c no more than half of this maximum value, for less ignition delay. Check the initial power dissipation in the resistor; it should be at least $200P_r$. Begin with the new R_t:

$$R_t = R_i + R_c \tag{14}$$

The initial current, based on the new R_t is:

$$I = \frac{E}{R_t} \tag{15}$$

and the initial power dissipation in the resistor is:

$$P = I^2 R \tag{16}$$

Since P_r is 1/4 watt, we want the initial value of P to be at least 50 watts. If it is not, re-check your calculations or have someone else check them for you.

3.2 Example 1

The power source for this example is a 12.6 volt lead-acid battery.

$$R_h = \frac{E^2}{400} = \frac{158.76}{400} = 0.3969 \text{ ohms}$$

$$R_i = 2R_h = 0.7938 \text{ ohms}$$

The nearest standard value is 1.0 ohms. Therefore the new R_i will be 1.0 ohms and the new R_h will be 0.5 ohms. Using Equation (11), the required firing current is now:

$$I = \left(\frac{100}{0.5}\right)^{0.5} = 200^{0.5}$$

The square root of 200 is 14.14; therefore I = 14.14 amps. The new total resistance to allow this current to flow is:

$$R_t = \frac{E}{I} \tag{17}$$

or 12.6/14.14 = 0.891 ohms. The new maximum R_c is found by subtracting the new R_h from the new R_t:

$$R_c = R_t - R_h \tag{18}$$

for a value of 0.891 -0.5 = 0.391 ohms. For less ignition delay, use about half that value for R_c, or about 0.2 ohms if possible. Checking the initial power dissipation in the entire system, using the resistance value of 1.391 ohms calculated with Equation (14),

$$I = 12.6/1.391 = 9.06 \text{ amps}$$

from Equation (15), and thus

$$P = (9.06)^2 \times 1.0 = 82.06 \text{ watts}$$

by Equation (16). Re-checking with R_c = 0.2 ohms:

$$R_t = 1.0 + 0.2 = 1.2 \text{ ohms}$$

$$I = \frac{12.6}{1.2} = 10.5 \text{ amps}$$

$$P = 10.5^2 \times 1.0 = 110.25 \text{ watts}$$

3.3 Example 2

The power source for this example is a 28-volt lithium-manganese dioxide battery.

$$R_h = \frac{28^2}{400} = \frac{784}{400} = 1.96 \text{ ohms}$$

$$R_i = 2R_h = 3.92 \text{ ohms}$$

The nearest standard value is 3.9 ohms. The new R_i will be 3.9 ohms and R_h will be 1.95 ohms. The firing current required is

$$I = \left(\frac{100}{1.95}\right)^{0.5} = 51.28^{0.5} = 7.16 \text{ amps}$$

The total resistance for this current to flow is:

$$R = \frac{28}{7.16} = 3.91 \text{ ohms}$$

The maximum circuit resistance outside the igniter is:

$$R_c = 3.91 - 1.95 = 1.96 \text{ ohms}$$

For less ignition delay, use $R_c = 1$ ohm, if possible. Remember that R_c includes the battery's internal resistance; therefore its internal resistance must be substantially less than 1.96 ohms, and less than 1 ohm if possible.

This time, let us assume that the battery internal resistance is 2/3 of an ohm and that the remainder of R_c is also 2/3 ohm. R_c is then 1.33 ohm. Now the total initial resistance is:

$$R_t = R_i + R_c = 3.9 + 1.33 = 5.23 \text{ ohms}$$

The initial firing current is:

$$I = \frac{E}{R_t} = \frac{28}{5.23} = 5.354 \text{ amps}$$

The initial power dissipation is:

$$P = I^2 R_i = (5.354)^2 \times 3.9 = 112 \text{ watts}$$

The total resistance when the resistor is hot is:

$$R_t = R_h + R_c = 1.95 + 1.33 = 3.28 \text{ ohms}$$

The predicted firing current becomes:

$$I = \frac{E}{R_t} = \frac{28}{3.28} = 8.54 \text{ amps}$$

The predicted power dissipation in the hot resistor is:

$$P = I^2 R_h = (8.54)^2 \times 1.95 = 142 \text{ watts.}$$

These power values indicate that the igniter resistance, or the circuit resistance, or both, could safely be increased slightly. It would be preferable to increase the igniter resistance slightly rather than the circuit resistance, to leave some margin for any unplanned increase in battery internal resistance. You are invited to try this for yourself; change R_i to 4.3 ohms and calculate the power dissipations, then increase the battery internal resistance 50% and re-calculate. To learn more, increase R_i to 4.7 ohms and repeat the same calculations with the original battery internal resistance and with it increased 50%.

The final resistor value to use should be determined by test-firing the brand of resistors you intend to use, in a range of values bracketing the calculated optimum value.

Don't make the mistake of ordering 1,000 resistors without first ordering 10 and testing them to make sure they will work in this application.

4 Capacitor Discharge Firing Systems

For launching big, powerful rockets safely, one needs a safe and reliable igniter. When you push the button, you don't want the rocket to just sit there while you wonder whether or not you have a hang fire. Nor do you want it to ignite accidentally due to a discharge of static electricity. An accidental ignition can instantly incinerate anyone standing near a really big rocket.

Igniters that require a lot of electrical energy to fire are safer. Nichrome wire, Thermalite wire-wrap, Firestar and resistor igniters are four examples. When such igniters are used in low-voltage systems, heavy batteries and heavy wires are normally required, to deliver enough energy to the igniter to assure rapid and reliable ignition.

High energy can be provided with less weight, lighter wire and greater portability by using a high voltage capacitor-discharge system. A large-value capacitor stores energy during the arming sequence, releasing it in a fraction of a second when the launch button is pushed.

The energy stored in a capacitor is proportional to the square of the voltage. Thus, at 350 volts, a 600 microfarad capacitor smaller than a salt shaker can store more energy than a bulky 300,000 microfarad capacitor bank at 12.6 volts.

But, there is a catch. At the high voltages that make capacitors efficient for storing energy, most igniters aren't efficient in utilizing the energy. To use the energy efficiently, the igniter must be designed for high voltage; it must have high resistance. And to produce reliable ignition, the resistance must be concentrated in a small space, not spread out.

The resistor igniter is very easy to make with high resistance. In addition, it may be unique in its ability to concentrate a high resistance within a very small volume; ensuring that the conversion of electrical energy to heat occurs within a very small volume as well. This produces a very high heat flux per unit area.

The high resistance of the resistor igniter causes the stored energy in the capacitor to be released in a smooth and controlled manner rather than creating a shock wave or micro-explosion.

In addition, the high resistance of the igniter ensures that most of the stored energy will be transferred to the resistor rather than being dissipated in the resistance of the wires. This allows the igniter to be built with a high no-fire energy, greatly reducing the chances of accidental ignition.

Igniters made from 1/4 watt carbon film resistors require more than 10 joules to fire. A human body carrying a static charge of 30,000 volts has only about 0.045 joule of stored electrical energy. Thus an accidental electrostatic discharge from a human body has less than 1/200 of the energy needed to fire an uncoated resistor igniter.

Because the resistor igniter uses so much electrical energy, it produces a good flame without needing any sensitive pyrotechnic compound. The energy in the flame comes from the firing current alone.

Yet, the resistor igniter will work at a distance of 2 miles, and a pair of resistor igniters will work at a distance of 2,000 feet, when used with an appropriate capacitor discharge firing system.

A relatively insensitive pyrotechnic compound can be used as a booster. For greatest safety, the booster compound should be electrically non-conductive, and have low sensitivity to electrostatic discharge.

4.1 Design Calculations

First, the voltage must not exceed the dielectric strength (peak voltage rating) of the wire you are going to use. If you use a ballast resistor in the firing box, the capacitor voltage can be allowed to exceed the voltage rating of the wire by 5% to 15%, depending on how much the resistor drops the voltage.

Second, the voltage must not exceed the voltage rating of available capacitors.

Having chosen your voltage, calculate the required energy for the number of igniters you intend to fire on one circuit. You need at least 12 and no more than about 20 joules per igniter, delivered to the igniters (when using 1/4-watt resistors). Very simply,

$$U = 14N \tag{19}$$

where U is the energy in joules to be delivered to each igniter, and N is the number of igniters to be fired.

Now you must multiply by a reasonable factor to allow for energy lost in the wires and in the ballast resistor. Modifying Equation (19) with this factor returns

$$U = 1.2(14N) \tag{20}$$

or

$$U = 17N \tag{21}$$

Now calculate the required capacitance. The energy stored in a capacitor is:

$$U = \frac{1}{2}V^2C \tag{22}$$

where U is stored energy in joules, V is capacitor voltage, and C is capacitance in Farads[3].

Solving Equation (22) for C gives

$$C = \frac{2U}{V^2} \tag{23}$$

With a capacitor-discharge system, the negative temperature coefficient of the carbon resistor causes the igniter resistance to decrease as the capacitor voltage is decreasing, which maintains the current flow more or less constant while the first 3/4 of the energy is discharged. Therefore we need only use the initial value of resistance (R_i) in the calculations (unlike the resistor igniter for use at constant voltage).

Each resistor should be overloaded by a factor of 400; thus

$$R_i = \frac{E^2}{400P_r} \tag{24}$$

or

$$R_i = \frac{E^2}{100} \tag{25}$$

for 1/4 watt resistors, where R_i is the initial igniter resistance in ohms, P_r is the power rating of the resistor in watts, and E is the initial voltage applied to the resistor.

The voltage applied to the resistor igniters will be somewhat less than the capacitor voltage due to the ballast resistor and the resistance of the wires. Divide the capacitor voltage by

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[3] Not microfarads. One million microfarads = one Farad.

1.2 for a first approximation, assuming you will be connecting all the igniters in parallel. The load resistance, R_L, will be:

$$R_L = \frac{R_i}{N} \tag{26}$$

where R_i is the resistance of a single igniter in ohms, and N is the number of igniters connected in parallel. The total resistance should not be more than about 1.2 times the load resistance. Therefore, the sum of the ballast resistance and wire resistance should equal 10% to 20% of the load resistance. The minimum ballast resistance is determined by the current rating of your firing contacts. This resistance serves to limit the line current if an arc develops. The type of arc most likely to occur results from the resistor opening while there is still considerable energy remaining in the capacitor. The minimum ballast resistance for protecting the contacts against this kind of arc is based on the assumption that half of the energy has already been discharged, and that the EMF across the arc is 40 volts. Therefore the minimum sum of ballast and wire resistance is:

$$R_b + R_w = \frac{E}{I} \tag{27}$$

where $E = \left(\frac{V}{1.414}\right) - 40$, V = capacitor voltage at full charge, E = voltage drop across the wire and ballast, and I = current rating of the contacts.

The resistance of 1,000 ft. of #18 zip cord is 13 ohms; the resistance of 1/2 mile is 34.4 ohms. The resistance of other gauges of wire can be found in standard electrician's tables; the little blue book, Pocket Ref, by Thomas J. Glover, contains such a table.

When calculating the ballast resistance you need, base your calculation on the shortest firing leads you will ever use. Then check to make sure that the sum of ballast and wire resistance does not exceed about 20% of the load resistance with the longest firing leads you intend to use. If it does, you have two choices. Use heavier contacts, or always use a certain minimum length of firing leads, with less ballast.

For the ballast, you can use several 10-ohm 10-watt wire-wound resistors in series. For balanced circuits (neither lead grounded), half of the resistance should be connected in series with each lead.

Most switch and relay contacts are not designed to interrupt more than 30 volts when used with DC; higher voltages can strike an arc. Therefore you must take care not to open the contacts while the capacitor is still discharging. Keep the contacts closed until the capacitor has discharged to 30 volts or less.