ME 492 | Modeling a Burn Wire Circuit
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Gerald Recktenwald
gerry@pdx.edu

1 Design Concept

The burn wire is part of the release mechanism for a helical antenna attached to a CubeSat that will be deployed from a launch vehicle in low earth orbit. The antenna is designed so that it can be compressed axially, like a spring, which allows the antenna to be confined in a small space on one end of the CubeSat. The launch vehicle transports the CubeSat to its orbital position and deploys the CubeSat by ejecting it into space. After deployment, the CubeSat initiates a process to release the constraint on the compressed antenna, allowing the antenna to unfurl into a position suitable for signal transmission.

The current conceptual design for the release mechanism is to confine the antenna with nylon monofilament. A piece of fine gage metal wire is stretched across a region of the monofilament. The wire is connected to an electrical circuit controlled by a microcontroller on the CubeSate. At the appropriate time, a power is supplied to the circuit containing the burn wire, causing it to heat up, and melt through the monofilament, thereby releasing the antenna.

Figure 1 shows a simplified representation of the burn wire. At this point in the design process, the geometric configuration of the burn wire and monofilament are not yet specified. The goal of the current analysis is to put bounds on the electrical current, voltage and power for the circuit that controls the burn wire.

2 Thermal Models

A simple thermal model of the burn wire is used to estimate the electrical current, voltage and power required by the burn wire. The purpose of the model is to guide design decisions. Given that deployment of the antenna is crucial to the success of the mission, thorough testing of the burn wire and the entire antenna deployment system will be necessary.

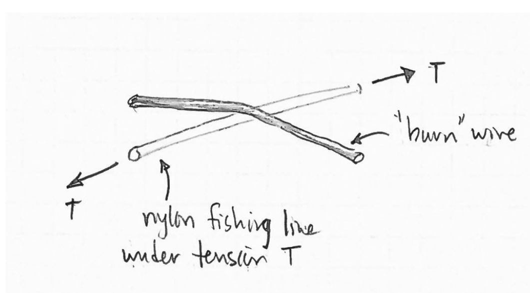

Figure 1: Burn wire lying on top of a nylon monofilament. The T in the sketch is the tension force in the monofilament.

2.1 Conservation of Energy for the Burn Wire

The energy equation for the metal wire is

$$mc\frac{dT}{dt} = P - Q \tag{1}$$

where m is the mass of the wire, c is the specific heat of the wire material, T is the temperature of the wire, which is assumed to be spatially uniform, t is time, P is the power input from electric resistance heating, and Q is the heat loss to the ambient. We neglect Q, which gives an optimistic design. The power input is

$$P = I^2 R = \frac{V^2}{R} \tag{2}$$

where I is the current flowing through the wire, R is the electrical resistance of the wire, and V is the voltage across the ends of the wire.

The wire resistance is determined by the geometry and electrical properties of the wire material according to

$$R = \frac{\rho_e L}{A_c} \tag{3}$$

where ρ_e is the electrical resistivity of the wire material, L is the length of the wire over which V is applied, and $A_c = (\pi/4)d_w^2$ is the cross-sectional area of the wire with diameter d_w.

Notice that if P is constant and $Q = 0$, the wire temperature increases linearly with time. For convenience, define the heating rate as

$$H = \frac{T_f - T_i}{\Delta t}. \tag{4}$$

In the conceptual design calculations, H can be specified by estimating the initial and final temperatures and the time it takes the wire to heat from T_i to T_f in a time interval Δt. In this model T_i is the temperature of the wire in its stored state in the launch vehicle. The value of T_f must be sufficient to melt the monofilament.

Substituting Equation (4) for the time derivative in Equation (1), setting $Q = 0$ and rearranging slightly gives

$$H = \frac{P}{mc}. \tag{5}$$

Equation (5) is used to estimate the voltage, current and power requirements for different combinations of wire diameter and length.

2.2 Electric Resistance Heating of the Wire

Voltage: Using $P = V^2/R$ in Equation (5) allows a simple estimate of the required voltage to be obtained.

$$H = \frac{P}{mc} = \frac{V^2}{R\rho_m c A_c L} = \frac{V^2}{\dfrac{\rho_e L}{A_c}\rho_m c A_c L} = \frac{V^2}{\rho_e \rho_m c L^2} \tag{6}$$

Solving the preceding equation for V gives

$$V = L\sqrt{Hc\rho_m\rho_e}. \tag{7}$$

Current: Analogous to the voltage estimate, substituting $P = I^2 R$ into Equation (5) allows the current through the burn wire to be estimated.

$$H = \frac{P}{mc} = \frac{I^2 R}{\rho_m A_c L} = \frac{I^2 \frac{\rho_e L}{A_c}}{\rho_m c A_c L} = \frac{I^2 \rho_e}{\rho_m c A_c^2} = \frac{16}{\pi^2} \frac{I^2 \rho_e}{\rho_m c d_w^4} \tag{8}$$

Solving the preceding equation for I gives

$$I = \frac{\pi}{4} d_w^2 \sqrt{\frac{\rho_m}{\rho_e} H c} \tag{9}$$

Power: Combining Equation (7) and Equation (9) gives a formula for power consumption as a function of wire diameter and length.

$$P = VI \;=\; L\sqrt{H c \rho_m \rho_e}\; \frac{\pi}{4} d_w^2 \sqrt{\frac{\rho_m}{\rho_e} H c} \;=\; \frac{\pi}{4} d_w^2 L H c \rho_m \tag{10}$$

2.3 Estimation of Heating Rate

The CubeSat will be deployed from a launch vehicle in low earth orbit. The melting point of nylon is in the range $190 \leq T \leq 350$°C. Table 1 gives a range of heating rates assuming that the wire starts at $T_i = -150$°C, which is an estimate of the night time temperature of satellite in low earth orbit.

3 Sample Calculations

Use the properties

$$1.0 \times 10^{-6} \leq \rho_e \leq 1.5 \times 10^{-6}\ \Omega \cdot \mathrm{m}, \qquad \rho_m = 840\, \frac{\mathrm{kg}}{\mathrm{m}^3}, \qquad c = 450\, \frac{\mathrm{J}}{\mathrm{kg\,K}}$$

Table 1: Range of heating rates

Heating rate

melt time	10	s
Ti	-150	°C
Tmelt (low)	200	°C
Tmelt (high)	300	°C
Heating rate (low)	35	°C/s
Heating rate (high)	45	°C/s

Heating rate values -- table values are H (C/s)

	Time (s)		
Tmelt	10	1	0.1
180	33	330	3300
200	35	350	3500
250	40	400	4000
300	45	450	4500
350	50	500	5000

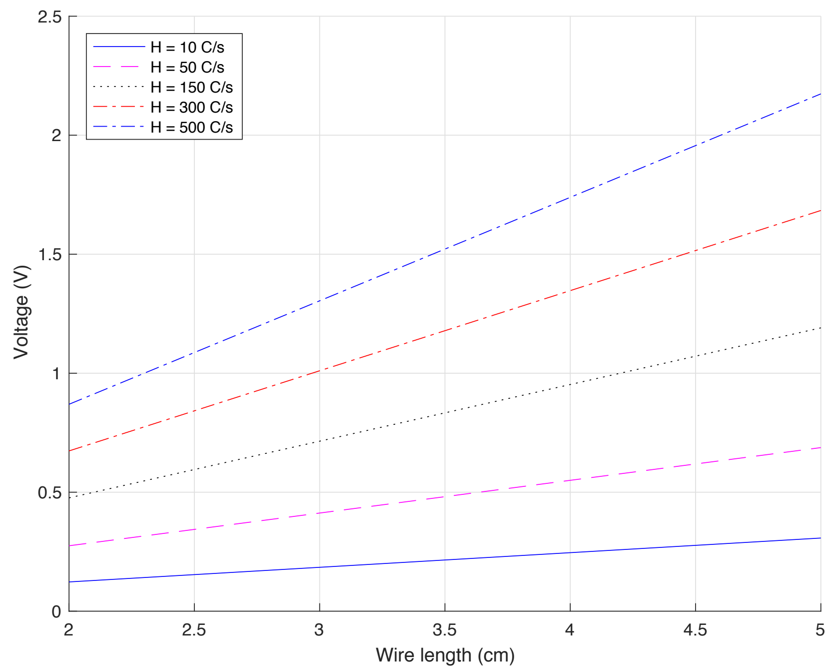

Figure 2: Voltage as a function of wire length.

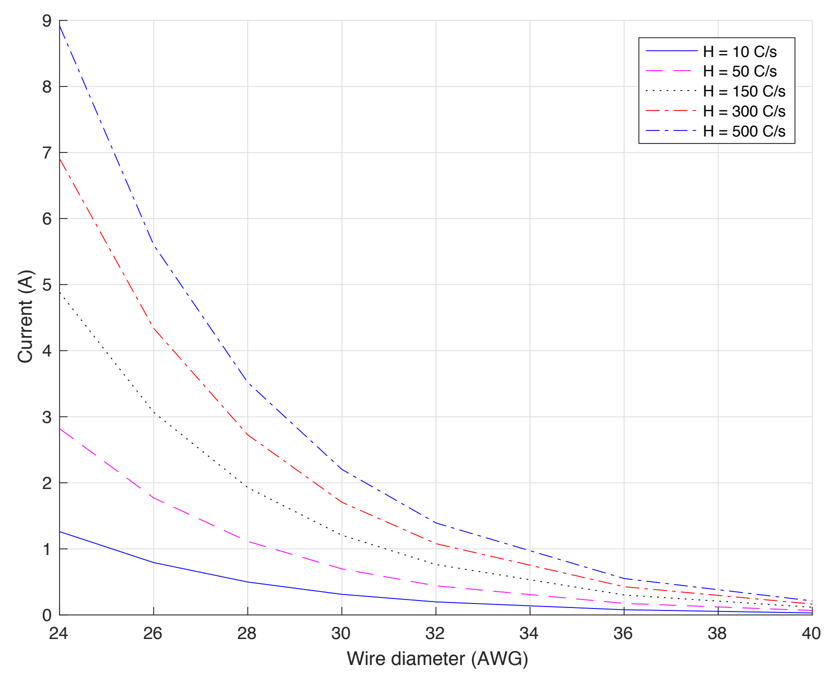

Figure 3: Current as a function of wire diameter.

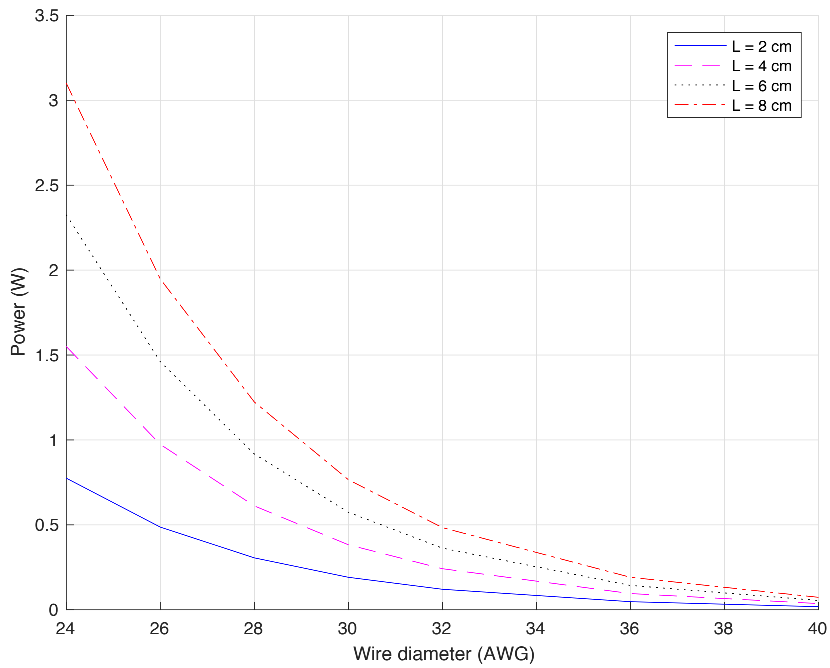

Figure 4: Power consumption as a function of wire length and diameter at $H = 50\,^{\circ}\mathrm{C/s}$.