

# ADIABATIC FUSING OF ALUMINUM & POLY RUNNERS

[Fuse Calculations.MCD]

**PURPOSE:** 1. Calculate the energy margin for blowing an Al fuse by discharging a 100uF cap.  
2. Calculate time and energy for blowing poly fuses.

## SILICON, ALUMINUM, GOLD, COPPER & SOLDER MATERIAL CONSTANTS

THERMAL CONDUCTIVITIES:

$$\begin{aligned} \text{cond\_silicon} &:= 1.45 \cdot \frac{\text{watt}}{\text{cm}} & \text{cond\_solder} &:= 0.60 \cdot \frac{\text{watt}}{\text{cm}} & \text{cond\_copper} &:= 3.96 \cdot \frac{\text{watt}}{\text{cm}} \\ \text{cond\_si\_500C} &:= 0.41 \cdot \text{watt} \cdot \text{cm}^{-1} & \text{cond\_au} &:= 3.15 \cdot \text{watt} \cdot \text{cm}^{-1} \end{aligned}$$

HEAT CAPACITY, cp, THERMAL DIFFUSIVITY, K, MASS DENSITY, ρm:

$$\begin{aligned} \text{cp\_cu} &:= 3.37 \cdot \text{watt} \cdot \text{sec} \cdot \text{cm}^{-3} & \text{cp\_solder} &:= 3.68 \cdot \text{watt} \cdot \text{sec} \cdot \text{cm}^{-3} \\ \text{cp\_si} &:= 1.75 \cdot \text{watt} \cdot \text{sec} \cdot \text{cm}^{-3} & \text{Ksi} &:= 0.87 \cdot \text{cm}^2 \cdot \text{sec}^{-1} \\ \text{cp\_al} &:= 0.637 \cdot \text{cal} \cdot \text{cm}^{-3} & \rho\text{m\_si} &:= 2.33 \cdot \text{g} \cdot \text{cm}^{-3} \\ \text{cp\_au} &:= 0.606 \cdot \text{cal} \cdot \text{cm}^{-3} & \rho\text{m\_au} &:= 19.3 \cdot \text{g} \cdot \text{cm}^{-3} \end{aligned}$$

HEAT OF FUSION, Hf, HEAT CAPACITY, Hc, Melt Temp, Tmelt, RESISTIVITY @0C/Tmelt, ρo/ρmelt:

Ambient Temp, Ta:	Ta := 25		ρo_SnPb := 16·μohm·cm
Hf_al := 248.5· $\frac{\text{cal}}{\text{cm}^3}$	Hc_al := cp_al	Tmelt_al := 660	ρo_al := 2.42·μohm·cm
		Tmelt_au := 1066	ρ240_al := 5.1·μohm·cm
		Tmelt_si := 2057	ρo_au := 2.35·μohm·cm
Hf_au := 306.9· $\frac{\text{cal}}{\text{cm}^3}$	Hc_au := cp_au	Rise to Melting Temp, ΔT	ρo_poly := 2000·μohm·cm
		ΔTm_al := Tmelt_al - Ta	
Hf_si := 337· $\frac{\text{cal}}{\text{g}}$ ·ρm_si	Hc_si := cp_si	ΔTm_si := Tmelt_si - Ta	ΔTm_au := Tmelt_au - Ta
		Tvap_si := 2355	ΔTv_si := Tvap_si - Tmelt_si

$$\rho_{al} = 2.42, 2.65, 3.50, 4.62, 5.81, 7.05, 8.36, 9.77, 10.95, 24.2 \mu\Omega\text{-cm @ } 0, 20, 100, 200, 600, 660, 660 \text{ (Liquid)}$$

$$\rho_{au} = 2.35, 2.97, 3.83, 6.62, 12.52 \mu\Omega\text{-cm @ } 0, 100, 200, 500, 1000\text{C}$$

$$\beta, \text{ TempCoefficient of Resistance, TCR: } \beta_{au} := 0.0035 \quad \beta_{al} := 0.00475 \quad \beta_{poly} := 0.00087$$

Resistivity Averaged Over Fuse Energy for constant current. (Smaller for charging cap):

$$\rho_{avf}(\rho_{melt}, \rho_o, X_f) := \left[ \frac{\rho_{melt}}{2} \cdot (1 + 3 \cdot X_f) - \frac{\rho_o}{2} \cdot (1 + X_f) \right] \cdot \mu\text{ohm} \cdot \text{cm}$$

Xf is the fraction of total energy expended to fuse metal once Tmelt is reached. Values given below.

$$\rho_{avf\_al} := \rho_{avf}(11, 2.42, 0.422) \quad \rho_{avf\_al} = 10.742 \mu\text{ohm} \cdot \text{cm} \quad \rho_{melt\_al} := 24.2 \cdot \mu\text{ohm} \cdot \text{cm}$$

$$\rho_{avf\_au} := \rho_{avf}(12, 2.35, 0.35) \quad \rho_{avf\_au} = 10.714 \mu\text{ohm} \cdot \text{cm}$$

Electrical Overstress FA Analysis in Microcircuits, pg 131

$$\rho_{melt\_au} := 13.7 \cdot \mu\text{ohm} \cdot \text{cm}$$

$$\rho_{melt\_al} := 11.1 \cdot \mu\text{ohm} \cdot \text{cm}$$

**ADIABATIC THERMAL MODEL FOR FUSION (MELTING):**

Consider a conductor during a time period short enough (<10us) that none of the I<sup>2</sup>R heat into the wire can escape. In a unit length of conductor, the joule heating power density is Pd = ρ\*(1+β\*T)J<sup>2</sup>, where β is the TCR of the conductor and J is the current density. If a conductor fuses within a time, τf, then the energy dissipated is Pd\*τf. The amount of heat energy density required for fusion is Qf = δTm x heat capacity/cm<sup>3</sup> + heat of fusion/cm<sup>3</sup>. Then the time to fusion, τf = Qf/Pd. If we group the material constants together we get τf = Km/J<sup>2</sup>. Km represents the minimum amount of energy to melt. Now experimental data shows that the time required to adiabatically open an aluminum runner is twice the melt time. Therefore the material constant to open, Ko = 2\* Km.

$$K_{o\_al} := \frac{2 \cdot (\delta T_{m\_al} \cdot cp\_al + Hf\_al)}{\rho_{240\_al}} \quad K_{o\_si} := \frac{2 \cdot (\delta T_{m\_si} \cdot cp\_si + Hf\_si)}{\rho_{o\_poly} \cdot (1 + 0.5 \cdot \beta_{poly} \cdot \delta T_m)} \quad K_{o\_au} := \frac{2 \cdot (\delta T_{m\_au} \cdot cp\_au + Hf\_au)}{\rho_{avf\_au}}$$

$$K_{o\_al} = 1.072 \times 10^9 \left( \frac{\text{amp}}{\text{cm}^2} \right)^2 \cdot \text{sec} \quad K_{o\_si} = 3.633 \times 10^6 \left( \frac{\text{amp}}{\text{cm}^2} \right)^2 \cdot \text{sec} \quad K_{o\_au} = 7.329 \times 10^8 \left( \frac{\text{amp}}{\text{cm}^2} \right)^2 \cdot \text{sec}$$

$$K_{v\_si} := \frac{2 \cdot (\delta T_{m\_si} \cdot cp\_si + Hf\_si + \delta T_{v\_si} \cdot cp\_si)}{\rho_{o\_poly} \cdot (1 + 0.5 \cdot \beta_{poly} \cdot \delta T_{m\_si})}$$

**Fraction of Energy Needed for Heat of Fusion, Xf**

$$\frac{Hf\_al}{\delta T_{m\_al} \cdot cp\_al + Hf\_al} = 0.381 \quad \frac{Hf\_si}{\delta T_{m\_si} \cdot cp\_si + Hf\_si} = 0.48 \quad \frac{Hf\_au}{\delta T_{m\_au} \cdot cp\_au + Hf\_au} = 0.327$$

**DETERMINE THE MARGIN IN SERIES RESISTANCE, Rs, TO FUSE A PID ALUMINUM TRIM FUSE:**

Define Re2f as the ratio of the energy that goes into joule heating the wire to the energy required to fuse the wire. Re2f = (J<sup>2</sup>/Ko) \* τf = 1. To extend this to the case where the current varies with time, replace the time product with a time integral. Apply 7V to 100uF CAP through Series Resistance, Rs. Four (Initial: 150milliΩ Max, End of life: 250milliΩ Ma) relays. T2500B Triac: 1.1V@6A (0.6V plus 100 milliOhm incremental). Unknown ESR.

**ALUMINUM FUSE**

**FOR A POLY FUSE (wp,thp). FIND FUSE TIME, tfp:**

Cvres := 100·μF    Vdtriac := 0.6·volt    Resr := 0.1·Ω    wp := 1.2·μm    th\_p := 0.35·μm    len := 18·0.286·μm  
 Rtriac := 0.1·ohm    R2probes := 0.2·Ω  
 th := 3.3·μm    w := 0.315·mil    L := 1·mil    t<sub>fp</sub> := K<sub>v\_si</sub> ·  $\left( \frac{0.07 \cdot \text{amp}}{w \cdot th \cdot n} \right)^{-2}$     t<sub>fp</sub> = 1.407 × 10<sup>-8</sup> sec  
 R<sub>fuse</sub> :=  $\frac{L}{th \cdot w} \cdot \rho_{melt\_al}$     R<sub>fuse</sub> = 0.107 ohm    PD := 15·0.08·watt · (wp·th\_p·len)<sup>-1</sup>    PD = 5.55 × 10<sup>11</sup>  $\frac{\text{watt}}{\text{cm}^3}$   
 R<sub>ckt</sub>(Rs) := R<sub>triac</sub> + 4·R<sub>initial\_relay</sub> + Resr + R<sub>fuse</sub> + R<sub>2probes</sub> + Rs·Ω    R<sub>s</sub> := 0 0 0 5    Current during discharge I<sub>c</sub>(Rs,t):  
 R<sub>ckt</sub>(0) = 1.107 ohm

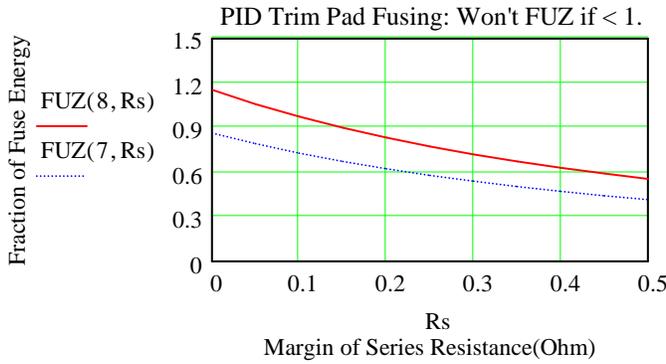
Check: Experimental Fuse data: I<sub>peak</sub> = 6A

$$I_{peak}(V_{bat}) := \frac{V_{bat} \cdot \text{volt} - V_{dtriac}}{R_{ckt}(0)} \quad I_c(V_{bat}, R_s, t) := \frac{V_{bat} \cdot \text{volt} - V_{dtriac}}{R_{ckt}(R_s)} \cdot \left( e^{-\frac{t \cdot \text{ms}}{R_{ckt}(R_s) \cdot C_{vres}}} \right)$$

I<sub>peak</sub>(7) = 5.783 amp

Define FUZ as the Ratio of the applied energy to the energy required to melt ALUMINUM quickly (10us) i.e. fuse open, not puddle. Express this Ratio as a function of added series resistance and Vbat to find the resistance margin.

$$FUZ(V_{bat}, R_s) := \int_0^{0.004} \frac{0.5}{K_{o\_al}} \cdot \left( \frac{I_c(V_{bat}, R_s, t)}{th \cdot w} \right)^2 \cdot \text{ms} \cdot dt \quad E_f(V, R_s) := \int_0^{0.004} \rho_{avf\_al} \cdot \frac{L}{th \cdot w} \cdot (I_c(V, R_s, t))^2 \cdot \text{ms} \cdot dt$$



$$E_f(22, 0) = 149.086 \mu\text{J} \quad I_{\text{peak}}(7) = 5.783 \text{ amp}$$

$$E_c := \frac{1}{2} \cdot C_{\text{vres}} \cdot (7 \cdot \text{volt})^2 \quad E_c = 2.45 \text{ mJ}$$

$$\frac{E_f(7, 0.1)}{E_c} = 4.592 \times 10^{-7} \cdot \hat{C}_{\text{vres}} \cdot R_{\text{ckt}}(0) = 0.111 \text{ ms}$$

$$t_f := K_{o\_al} \cdot \left( \frac{I_{\text{peak}}(6)}{w \cdot th} \right)^{-2} \quad t_f = 3.14 \times 10^{-6} \text{ sec}$$

$$2 \cdot [(\delta T_{m\_al\_cp\_al} + H_{f\_al}) \cdot w \cdot th \cdot 21 \cdot \mu\text{m}] = 3.032 \mu\text{J}$$

$$2 \cdot [(\delta T_{m\_si\_cp\_si} + H_{f\_si}) \cdot w_p \cdot th_p \cdot 21 \cdot \mu\text{m}] = 0.121 \mu\text{J}$$

**CONCLUSION: 7V or less is not a marginal charge voltage** for end of life fusing conditions **Rs = 0.4 Ohm**.

**DETERMINE THE MARGIN IN SERIES RESISTANCE, Rs, TO FUSE A MLR ALUMINUM-2 TRIM FUSE:**

<u>AL FUSE:</u>	<u>PID</u>	<u>AMPS</u>	<u>SPS/MLR01</u>	<u>ASPS/MLR02</u>
Geometry	8 x 25u	12 x 36u	18 x 73 UDR	6 x 61 UDR
Aspect Ratio	3.1	3	4	10
Thickness	Metal 1&2: 3.3um		Metal 2: 2 um	Metal 2: 2 um
	Single Bump Resistance ~ 0.020 Ohm			

Define  $Re2f$  as the ratio of the energy that goes into joule heating the wire to the energy required to fuse the wire.  $Re2f = (J^2/Ko) \cdot t_f = 1$ . To extend this to the case where the current varies with time, replace the time product with a time integral. Apply 3V to 10uF CAP through Series Resistance,  $R_s$ . Four (Initial: 150milli $\Omega$  Max, End of life: 250milli $\Omega$  Max) Clare DSS41A12B relays. T2500B Triac: 1.1V@6A (0.6V plus 100 milliOhm incremental). Unknown Cap ESR.

### MLR ALUMINUM FUSE

$$C_{\text{vres}_M} := 10 \cdot \mu\text{F} \quad th_M := 2 \cdot \mu\text{m} \quad w_M := 6 \cdot \text{UDR} \quad L_M := 65 \cdot \text{UDR} \quad R_{\text{bump}} := \frac{25 \cdot \mu\text{m}}{\pi \cdot (1 \cdot \text{mil})^2} \cdot \rho_{o\_SnPb}$$

$$R_{\text{fuse}_M} := \frac{L_M}{th_M \cdot w_M} \cdot \rho_{\text{melt\_al}} \quad R_{\text{fuse}_M} = 0.601 \text{ ohm}$$

$$R_{\text{bump}} = 1.974 \times 10^{-3} \text{ ohm}$$

$$R_{\text{bump}} := 20 \cdot 10^{-3} \cdot \text{ohm}$$

$$R_{\text{ckt}_M}(R_s) := R_{\text{triac}} + 4 \cdot R_{\text{initial\_relay}} + R_{\text{esr}} + R_{\text{fuse}_M} + R_{2\text{probes}} + R_s \cdot \Omega$$

Current during discharge  $I_{c_M}(R_s, t)$ :

$$R_{\text{ckt}_M}(0) = 1.601 \text{ ohm}$$

$$I_{\text{peak}_M}(V_{\text{bat}}) := \frac{V_{\text{bat}} \cdot \text{volt} - V_{\text{dtriac}}}{R_{\text{ckt}_M}(0)}$$

$$I_{c_M}(V_{\text{bat}}, R_s, t) := \frac{V_{\text{bat}} \cdot \text{volt} - V_{\text{dtriac}}}{R_{\text{ckt}_M}(R_s)} \cdot \left( e^{-\frac{t \cdot \text{ms}}{R_{\text{ckt}_M}(R_s) \cdot C_{\text{vres}_M}}} \right)$$

$$I_{\text{peak}_M}(3) = 1.499 \text{ amp}$$

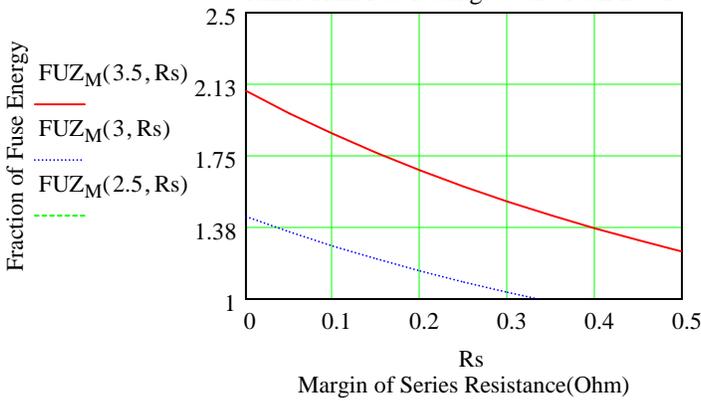
Define FUZ as the Ratio of the applied energy to the energy required to melt ALUMINUM quickly (10us) i.e. fuse open, not puddle. Express this Ratio as a function of added series resistance and  $V_{\text{bat}}$  to find the resistance margin.

$$FUZ_M(V_{\text{bat}}, R_s) := \int_0^{0.002} \frac{0.5}{K_{o\_al}} \cdot \left( \frac{I_{c_M}(V_{\text{bat}}, R_s, t)}{th_M \cdot w_M} \right)^2 \cdot \text{ms} \cdot dt$$

$$R_s := 0, 0.05 \dots 0.6$$

$$E_{f_M}(V, R_s) := \int_0^{0.002} \rho_{\text{avf\_al}} \cdot \frac{L_M}{th_M \cdot w_M} \cdot (I_{c_M}(V, R_s, t))^2 \cdot \text{ms} \cdot dt$$

MLR Trim Pad Fusing: Won't FUZ if < 1.



$$q(3, 0) = 2.313 \mu\text{J} \quad I_{\text{peak}_M(3)} = 1.499 \text{ amp}$$

$$v_M := \frac{1}{2} \cdot C_{\text{vres}_M} \cdot (3 \cdot \text{volt})^2 \quad E_{c_M} = 0.045 \text{ mJ}$$

$$\frac{v_M(3, 0.1)}{E_{c_M}} = 0.046 \quad C_{\text{vres}_M} \cdot R_{\text{ckt}_M(0)} = 0.016 \text{ ms}$$

$$t_M := K_{o\_al} \cdot \left( \frac{I_{\text{peak}_M(3)}}{w_M \cdot th_M} \right)^{-2} \quad t_{f_M} = 6.185 \times 10^{-7} \text{ sec}$$

**CONCLUSION: The minimum charge voltage for fusing is 2.5V.**

200	12
250	.05
300	.015
350	.005
400	0.0023
500	0.001
600	0.0003
700	0.00028
800	0.00025
900	0.0002

$$a1 := 10000 \cdot \frac{\text{mA}^2}{\text{sec}^{0.5}} \quad a3 := K_{o\_si} \cdot (w_p \cdot th_p)^2$$

$$a2 := (10 \cdot \text{mA})^2 \quad I(t) := \sqrt{a1 \cdot t^{0.5} + a2 + \frac{a3}{t}}$$

$$t_{\text{min}} := 10^{-6} \quad t_{\text{max}} := 1 \quad n := 100 \quad r := \ln\left(\frac{t_{\text{max}}}{t_{\text{min}}}\right)$$

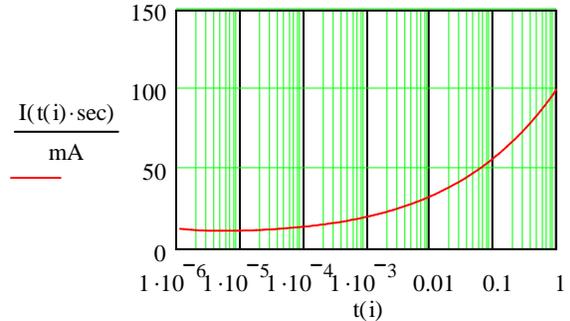
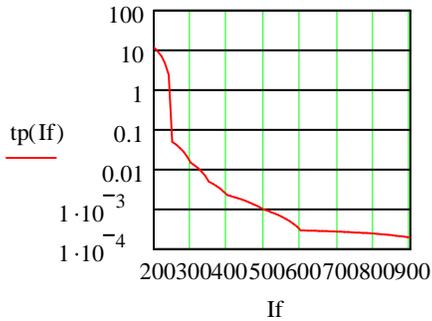
$$t(i) := t_{\text{min}} \cdot e^{i \cdot \frac{r}{n}} \quad i := 1..n$$

i := 0..9

If := 200, 210.. 900

vs := cspline(tp2<0>, tp2<1>)

tp(If) := linterp(tp2<0>, tp2<1>, If)     i := 1..n



FIND THE MINIMUM TIME NEEDED TO FUSE A 2 MIL GOLD WIRE,  $\tau_f$ , FOR CONSTANT 8A:

CASE 1:  $\tau_f$  for constant 8A:  $I := 8 \cdot \text{amp}$  radius of wire, rw:  
 $\text{rw} := 1 \cdot \text{mil}$

$$J := \frac{I}{\pi \cdot \text{rw}^2} \quad J = 3.947 \times 10^5 \frac{\text{amp}}{\text{cm}^2} \quad \tau_f := \frac{K_{o\_au}}{J^2} \quad \tau_f = 4.704 \text{ msec}$$

Expand on this simple case. Define  $Re2f$  as the ratio of charge energy that goes into joule heating the wire to the energy required to fuse the wire. For constant 8 amps after 2.2ms this is unity, i.e.  $Re2f = (J^2/K_o) \cdot \tau_f = 1$ . To extend this to the case where the current varies with time, replace the time product with a time integral.

This gives:  $Re2f := \int_0^{2.2} \frac{1}{K_{o\_au}} \cdot \left( \frac{8 \cdot \text{amp}}{\pi \cdot \text{rw}^2} \right)^2 \cdot \text{ms} \, dt \quad Re2f = 0.468$

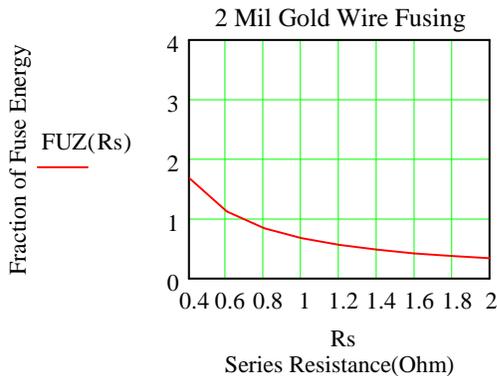
**$Re2f = 1$ , i.e. sufficient energy to fuse.**

CASE 2: Apply 15V to 1800uF CAP through 1.5/ 2  $\Omega$  Series Resistance,  $R_s$ : Current during charge  $I_c(R_s, t)$ :

$$V_{bat} := 15 \cdot \text{volt} \quad C_{vres} := 1800 \cdot \mu\text{F} \quad I_c(R_s, t) := \frac{V_{bat}}{R_s \cdot \Omega} \cdot \left( e^{-\frac{t \cdot \text{msec}}{R_s \cdot \Omega \cdot C_{vres}}} \right)$$

What is the ratio of charge energy to energy required to fuse wire when the cap is fully charged (1000ms). Use this definition to define the fuse function: FUZ, for a range of series resistance.

$$FUZ(R_s) := \int_0^{1000} \frac{1}{K_{o\_au}} \cdot \left( \frac{I_c(R_s, t)}{\pi \cdot \text{rw}^2} \right)^2 \cdot \text{msec} \, dt \quad R_s := 0.4, 0.6..2$$



**CONCLUSION: A minimum series resistance of 1.5  $\Omega$  is required for sufficient energy to fuse a 2 mil gold wire.**

**FUSE TIME PREDICTIONS FROM EMPIRICAL ENCAPSULATED WIRE FUSE DATA :**  
 FIT DATA TO FIND PRODUCT OF FUSE TIME(ms) AND CURRENT<sup>2</sup> FOR GOLD WIRES IN EPOXY:

(PRODUCT VALID FOR $t < 20$ MS.)	PRODUCT/ $K_{o\_au}$
2.0 MIL 86 MIL BOND SPACING: $t \cdot I^{2.47} = 751$	(0.634)
2.5 MIL 75 MIL BOND SPACING: $t \cdot I^{2.7} = 3733$	(0.663)
2.5 MIL 111 MIL BOND SPACING: $t \cdot I^{2.27} = 1103$	(0.57)
2.5 MIL 175 MIL BOND SPACING: $t \cdot I^{2.07} = 636$	(0.624)

FIND ABOUT A 14% REDUCTION IN FUSE CURRENT AT 1 SEC.

BECAUSE OF ADDITIONAL HEAT LOSSES FROM CONDUCTION TO TERMINALS AND THROUGH EPOXY, EMPIRICAL FUSE TIMES ARE LONGER.

Equation Fitted for time to fuse vs Current from Data for 86 Mil long 2 Mil Au Wire in Epoxy, tlab (msec):

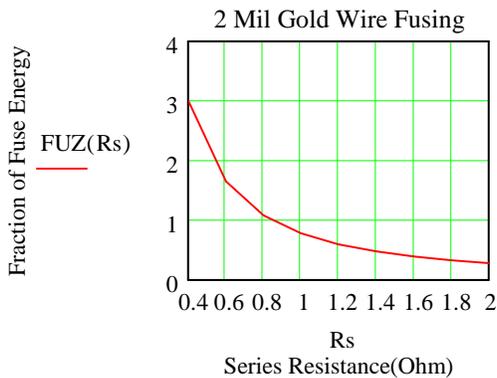
CASE 1: Find time to fuse for constant 8 amps.

$$\tau_{lab}(I) := \frac{751}{I^{2.47}}$$

$$\tau_{lab}(8) = 4.416$$

CASE 2: Will charging a 1800mF capacitor to 15V fuse an encapsulated wire?

$$FUZ(R_s) := \int_0^{1000} \frac{1}{751} \cdot \left( \frac{I_c(R_s, t)}{\text{amp}} \right)^{2.47} dt$$



**CONCLUSION: A minimum series resistance of 0.8 Ω is required for sufficient energy to fuse an encapsulated 2 mil gold wire.**

### FUSE CURRENT VS BOND SPACING (MILS) DATA

Fit lines to data

Data for 2.0 Mil Wire:

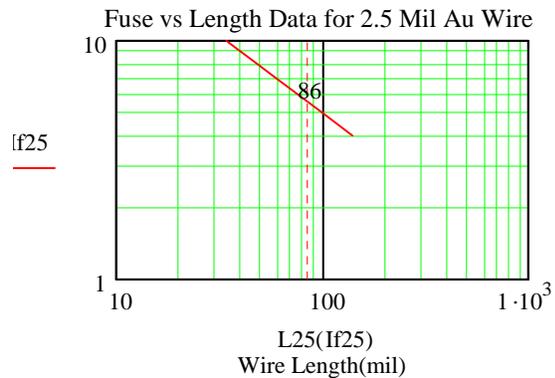
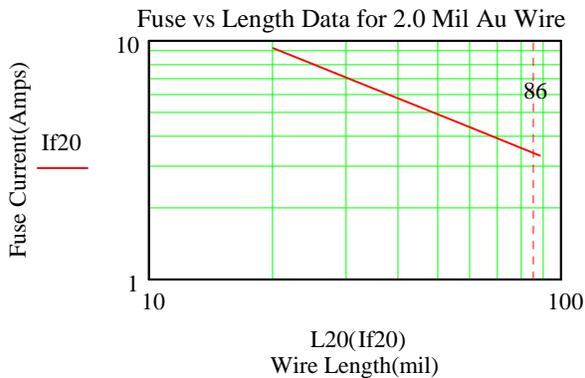
$$L_{20}(I_f) := 496 \cdot I_f^{-1.44}$$

$$I_{f20} := 3.3 \cdot 10$$

Data for 2.5 Mil Wire:

$$L_{25}(I_f) := 1185 \cdot I_f^{-1.54}$$

$$I_{f25} := 4 \cdot 10$$



## DRAIN - SOURCE SHORT RESISTANCE

$$L := 3 \cdot \mu\text{m} \quad t_{\text{al}} := 1 \cdot \mu\text{m}$$

$$R_{\text{short}} := \rho_{\text{al}} \cdot \frac{L}{L \cdot t_{\text{al}}} \quad R_{\text{short}} = 0.024 \Omega$$

$$\text{millihenry} \equiv 10^{-3} \cdot \text{henry}$$

$$\Omega \equiv \text{ohm}$$

$$\text{millisec} \equiv 10^{-3} \cdot \text{sec}$$

$$\text{msec} \equiv \text{millisec}$$

$$\mu\text{ohm} \equiv 0.000001 \cdot \text{ohm}$$

$$\mu\text{F} \equiv 0.000001 \cdot \text{farad}$$

$$\mu\text{m} \equiv 10^{-6} \cdot \text{m}$$

$$\text{nm} \equiv 10^{-9} \cdot \text{m}$$

$$\text{ms} \equiv 10^{-3} \cdot \text{sec}$$

$$\text{mil} \equiv 10^{-3} \cdot \text{in}$$

$$\text{mJ} \equiv 10^{-3} \cdot \text{joule}$$

$$\mu\text{J} \equiv 10^{-6} \cdot \text{joule}$$

$$A \equiv 10^{-8} \cdot \text{cm}$$

$$\text{UDR} \equiv \frac{1.2 \cdot \mu\text{m}}{4}$$