

Problem 8

Fuses

A short length of wire can act as an electrical fuse. Determine how various parameters affect the time taken for the fuse to 'blow'.



Mladen Matev, Bulgaria

Structure

- ❖ General Intro – historical remarks, origin of the problematics fuses (types and functionality), fuse wires and composition
- ❖ Demonstration – video and figures of fuse-burning stages.
- ❖ Stages in more detail: resistance, heat distribution, local resistivity & area
- ❖ Qualitative explanation of the fusing current effects
- ❖ Hints for quantitative model(s)
- ❖ Some introductory experiments – basic and advanced (IYPT)

The sources are quoted on the slides.

Examples – light bulbs and cartridge fuses

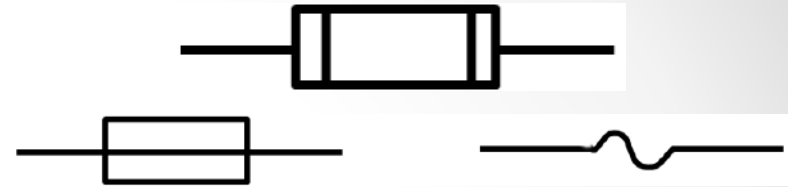


<https://en.wikipedia.org/w/index.php?title=File:Filament.jpg&action=edit>



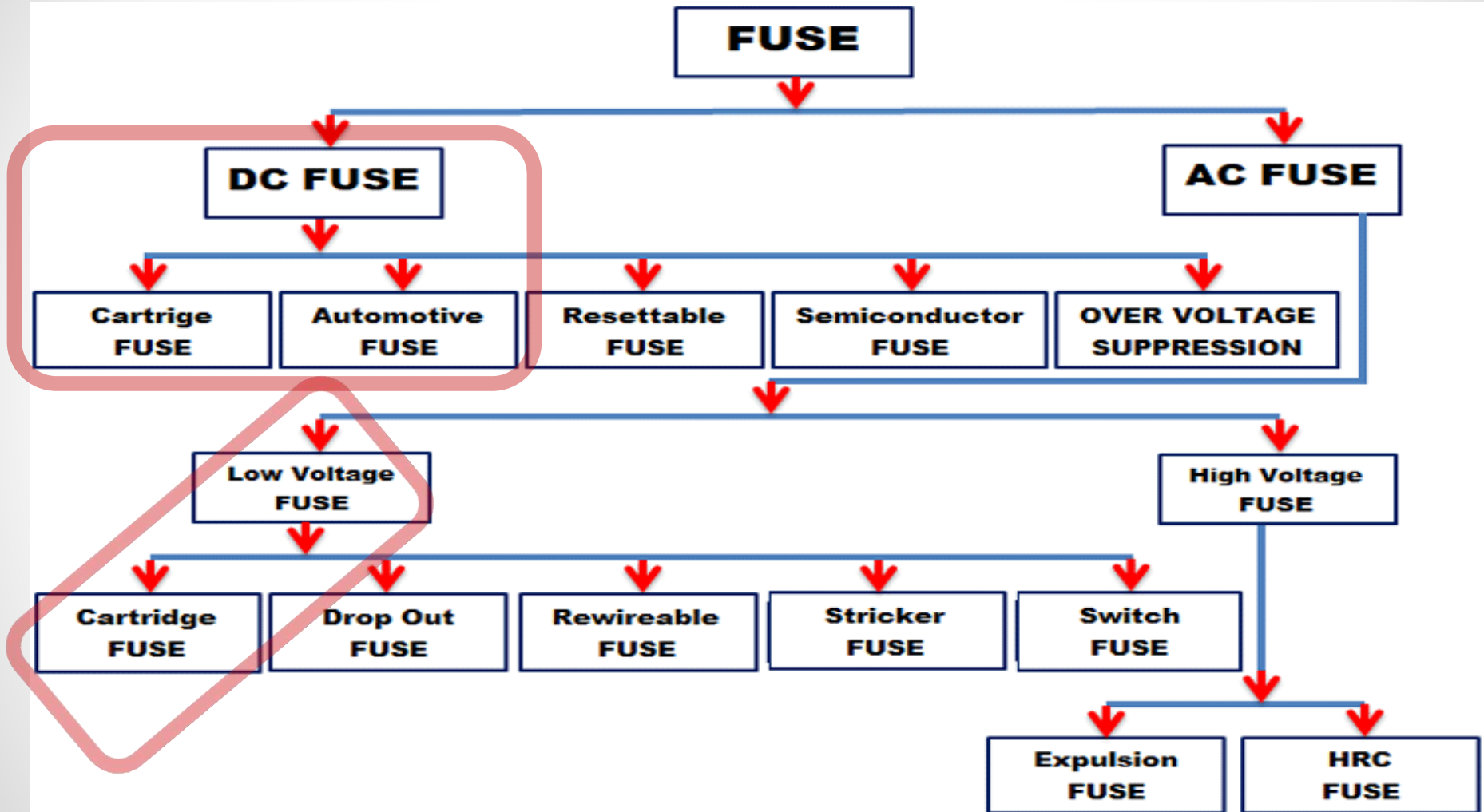
<https://components101.com/articles/different-types-of-fuses-and-their-applications>

Wright, A., and Newbery, P.G., **Electric Fuses**, 3rd Ed., Institution of Electrical Engineers, Stevenage, UK (2004)



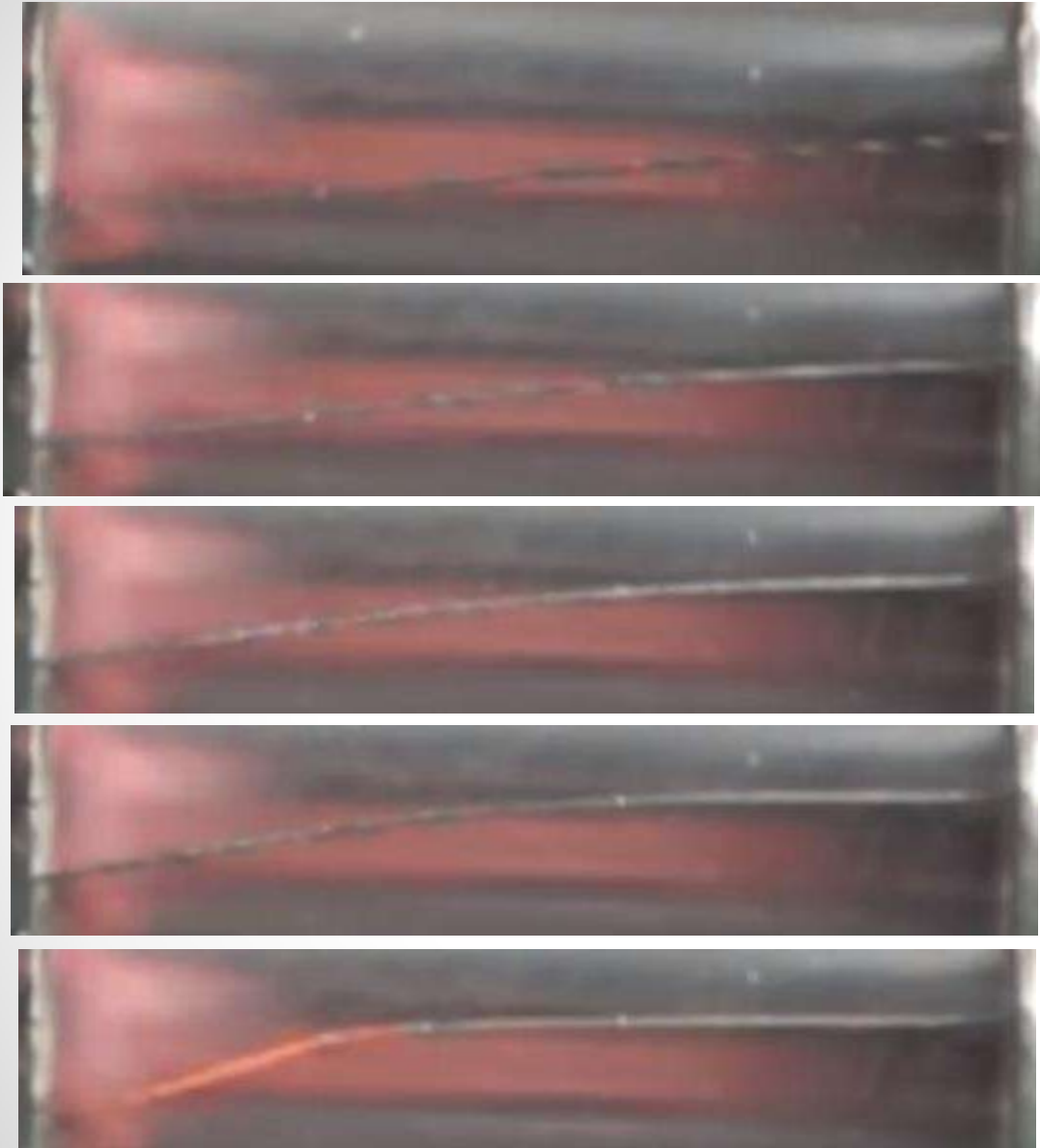
Fuse Types and Function

The Bigger Picture

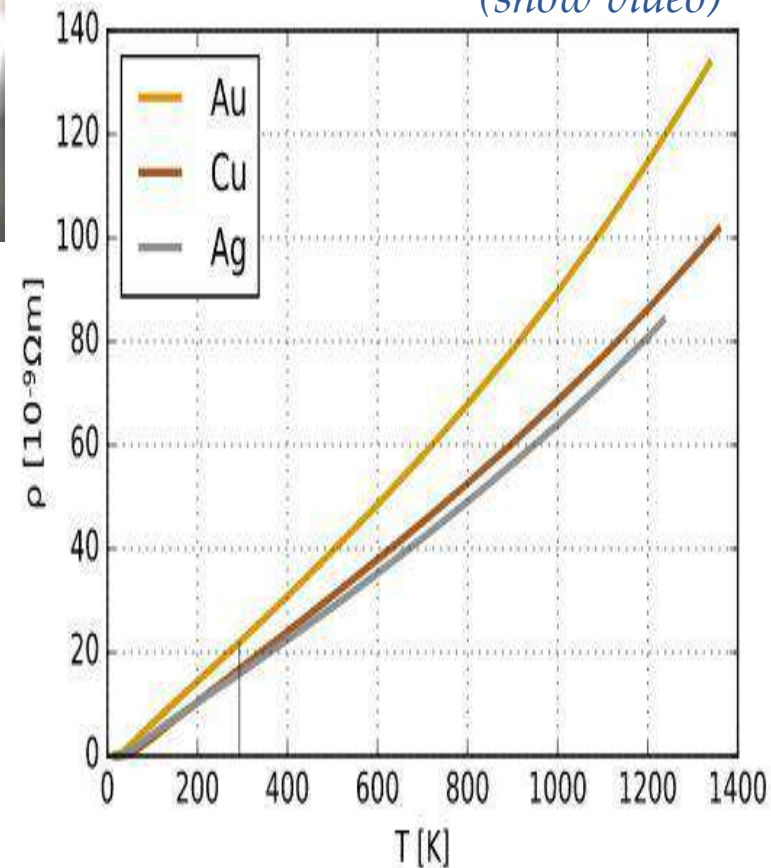


<https://components101.com/articles/different-types-of-fuses-and-their-applications>

The Wire – Initial overheating phase



(show video)



"Electrical resistivity of copper, gold, palladium, and silver". *J.Phys.Chem.Ref. Data* 8 (4): 1147–1298.

[DOI:10.1063/1.555614](https://doi.org/10.1063/1.555614). [ISSN 0047-2689](https://www.issn.org/0047-2689).

By Geek3 - Own work, CC BY-SA 4.0,
<https://commons.wikimedia.org/w/index.php?curid=74783698>

The Fuse Burning Process - Stages (slo-mo video)



The Fuse Burning – Thermal Expansion Effects

$t^{\circ}\text{C}$

550

630

680

740

770

800

850

900

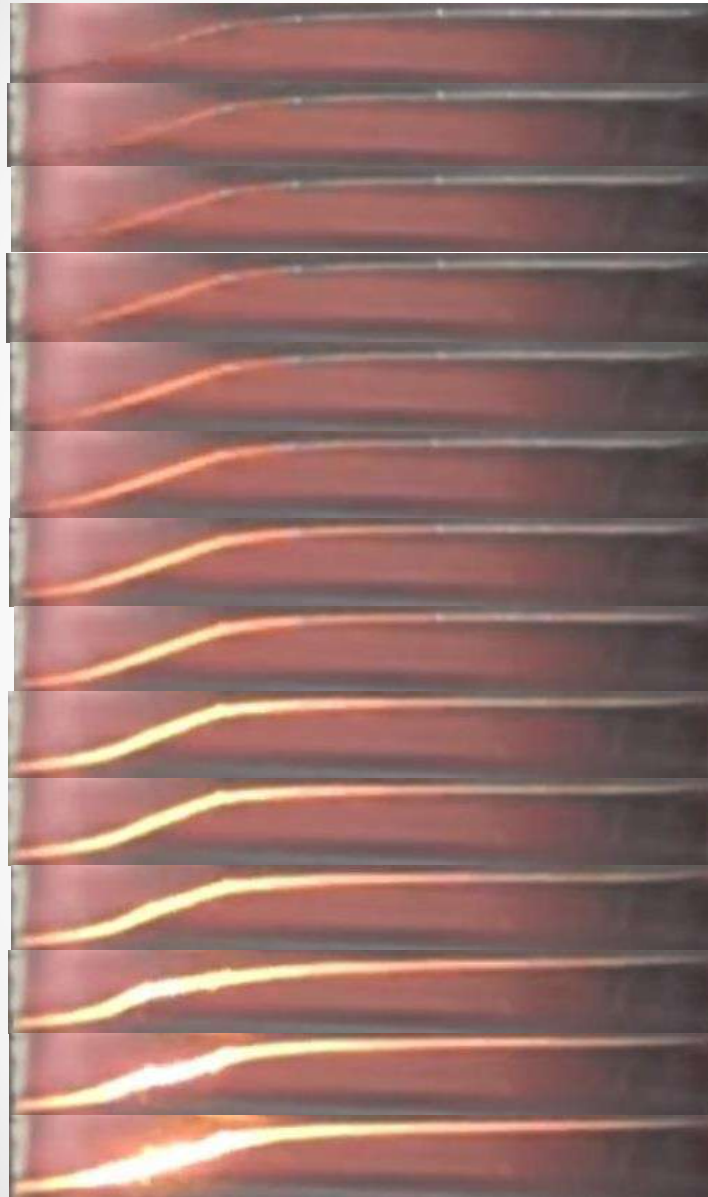
950

1000

1100

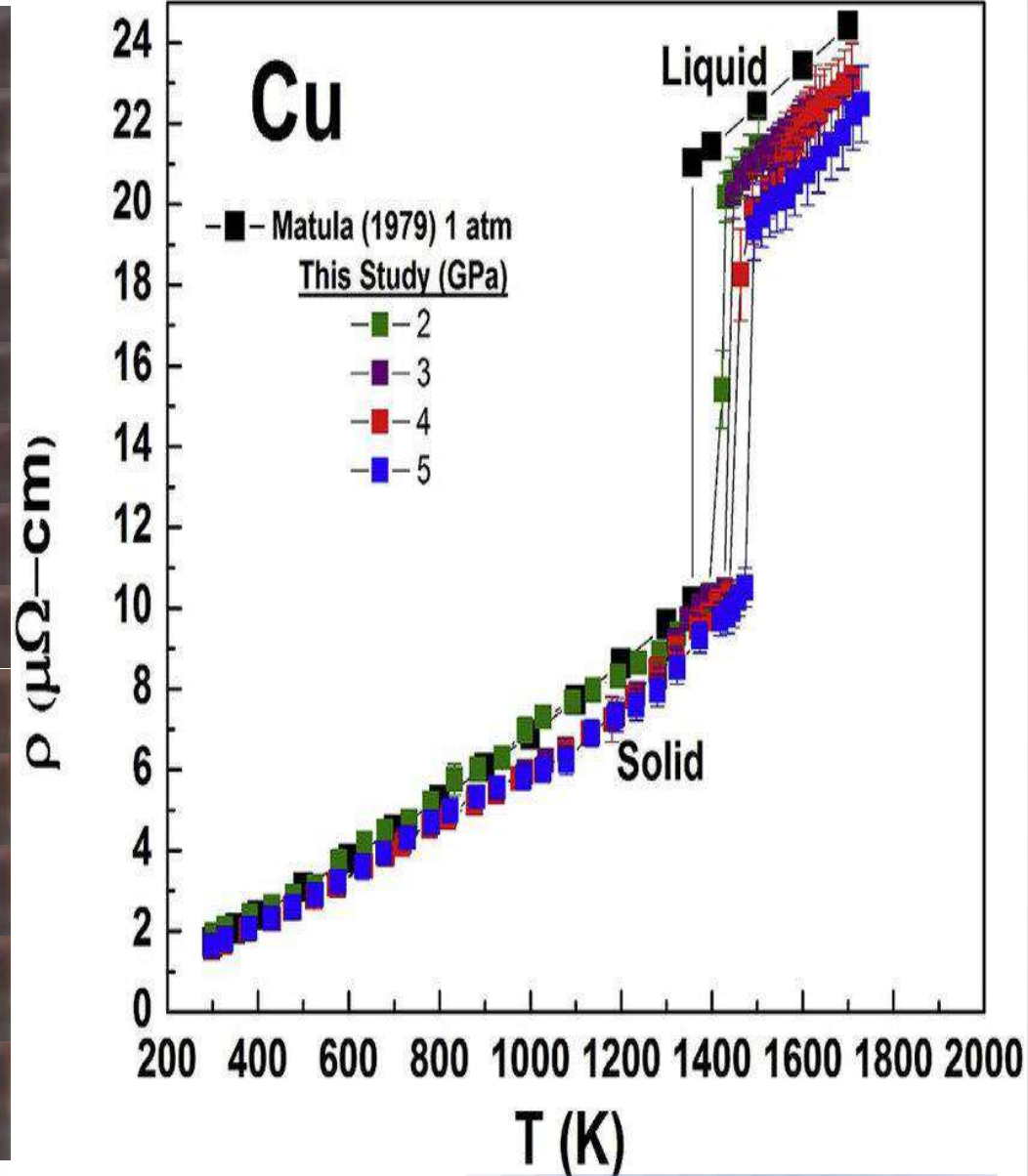
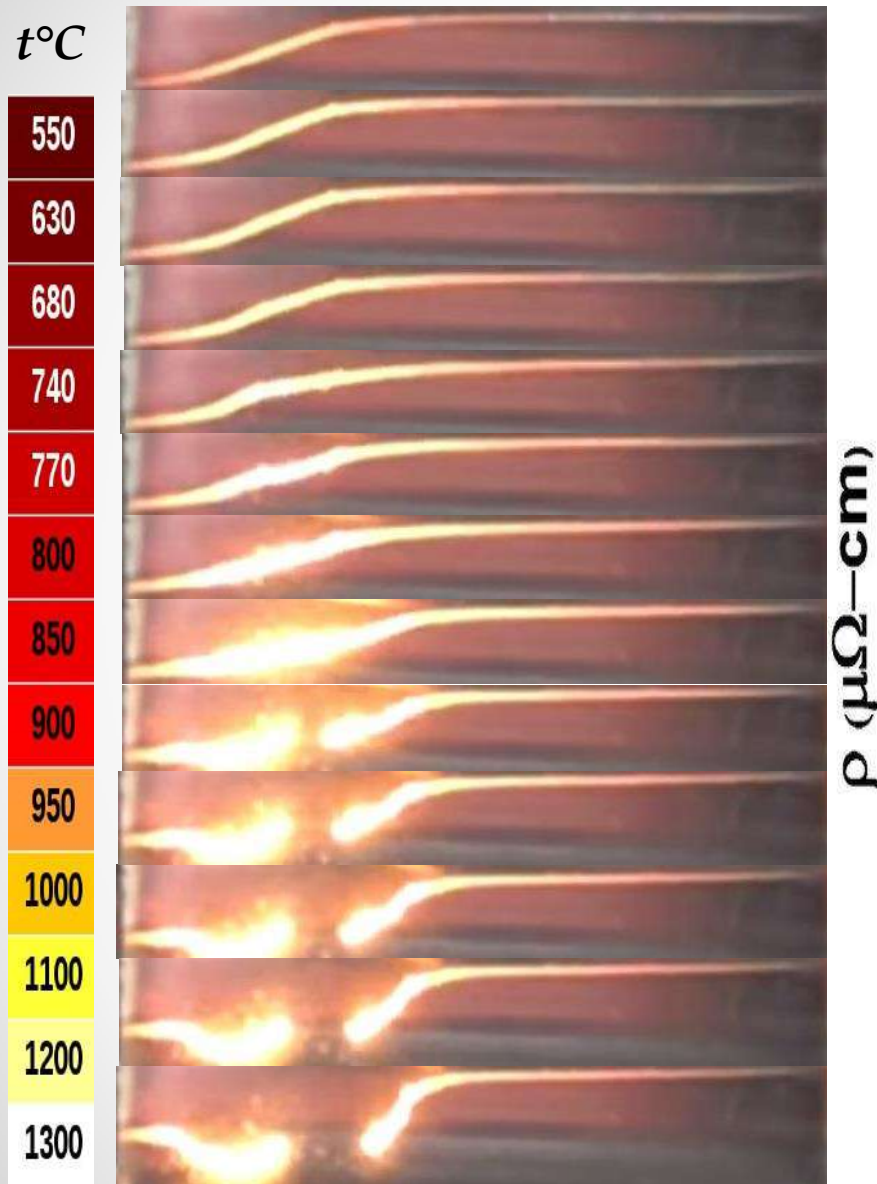
1200

1300



- ❖ The constricted wire expands between unmovable contacts
- ❖ Its length and area increases - swelling
- ❖ May form local bend(s) causing microcracks and lattice defects, thermo-corrosion or oxidation on the surface
- ❖ Narrower regions will form and get more and more overheated
- ❖ Local overheating causes even more intensive surface evaporation
- ❖ Resistivity in metals rapidly rises with temperature
- ❖ Plasticity of the material – softer regions get crushed by the accumulated mechanical tension from the more elastic parts of the wire
- ❖ Partial melting with local liquefaction and surface+inner region evaporation, micro-droplets leaving the surface
- ❖ Thermal microexplosions with rapid loss of material in one or several points
- ❖ Rupture of entire region(s), electric contact disrupted and end-to-end connection lost

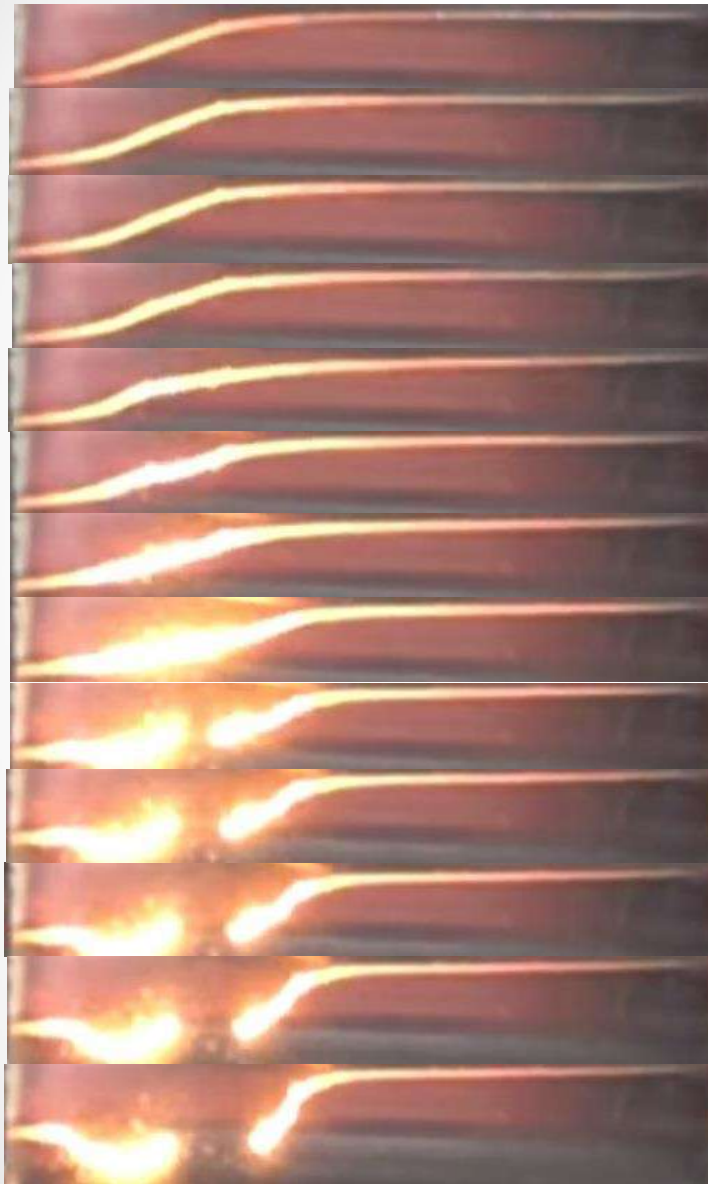
The Melting Phase



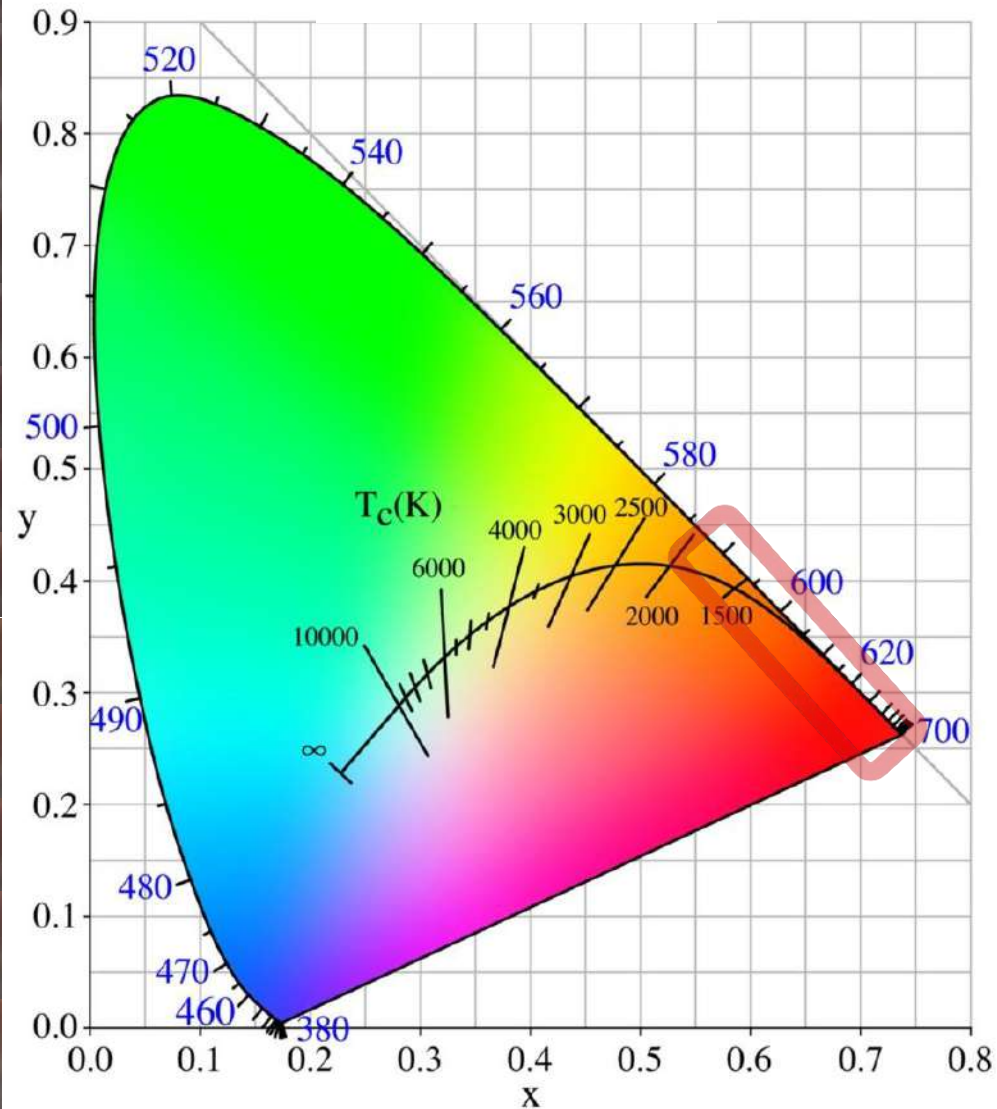
The Melting Phase – Estimating Temperatures

$t^{\circ}\text{C}$

550
630
680
740
770
800
850
900
950
1000
1100
1200
1300



Planckian Locus



Fuse Wire Material - Metals

- ❖ **Good conductors: Cu, Ag, Au**
- ❖ Most **low-voltage (LV)** fuse elements are made of **Cu**.
- ❖ For fast acting fuses & high-voltage (HV) fuses - primarily **Ag**.
(Silver plated copper is also commonly used.)
Pure silver is used for fuses because its electrical resistivity is very specific. Due to it being very low, **very thin wires can be designed with precise control over dimensions** that function perfectly well in high amperage circuits.
Additional advantage of Ag is that it **does not oxidize**, for the same reasons sometimes even gold is preferred.
- ❖ As a rule, fuse elements of **time delay fuses** contain **low melting point materials**, e.g. tin (Sn) or zinc (Zn) and their alloys
- ❖ Formerly used alloys containing lead (Pb) and cadmium (Cd) have widely been eliminated (by EU Directive for elimination of hazardous materials) because of the toxicity of these metals.

Thin Copper Wires - Size and "Ampacity"

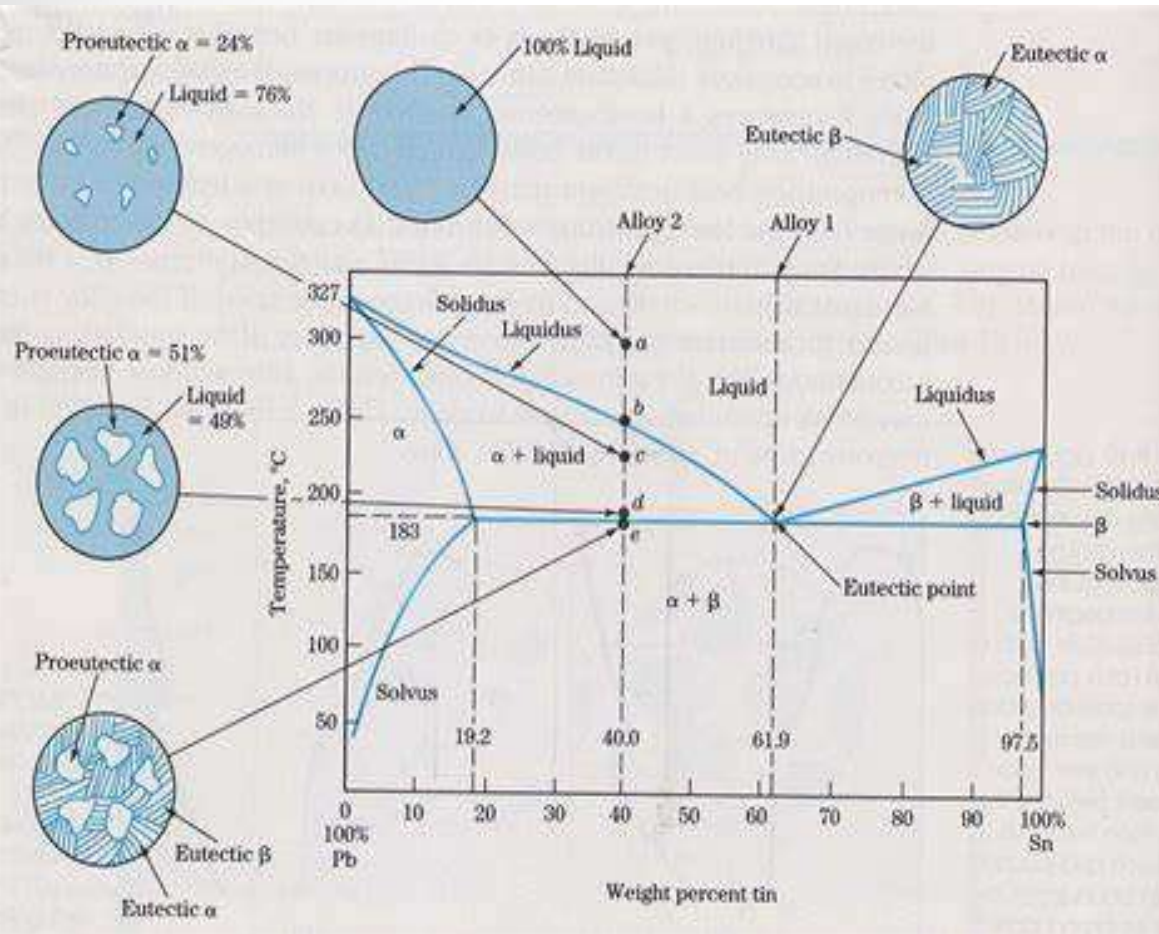
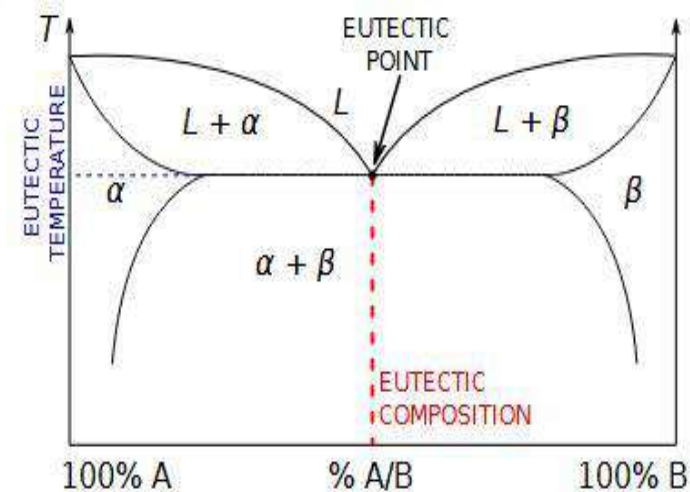
AWG gauge	Conductor Diameter, inches	Conductor Diameter, mm	Conductor cross section mm ²	Resistance Ω / km	Max Current (for chassis wiring)	Maximum Current (for power transmission)	For 1 cm AWG36
28	0.0126	0.32004	0.080	212.872	1.4	0.226	$R=12.5-13.6 \text{ m}\Omega/\text{cm}$ 
29	0.0113	0.28702	0.0647	268.4024	1.2	0.182	
30	0.01	0.254	0.0507	338.496	0.86	0.142	
31	0.0089	0.22606	0.0401	426.728	0.7	0.113	
32	0.008	0.2032	0.0324	538.248	0.53	0.091	
Metric 2.0	0.00787	0.200	0.0314	555.61	0.51	0.088	$IR \sim 2.8 \text{ mV}$ $IR \sim 0.5 \text{ mV}$
33	0.0071	0.18034	0.0255	678.632	0.43	0.072	
Metric 1.8	0.00709	0.180	0.0254	680.55	0.43	0.072	
34	0.0063	0.16002	0.0201	855.752	0.33	0.056	
Metric 1.6	0.0063	0.16002	0.0201	855.752	0.33	0.056	
35	0.0056	0.14224	0.0159	1079.12	0.27	0.044	$IR \sim 0.5 \text{ mV}$
Metric 1.4	0.00551	0.140	0.0154	1114	0.26	0.043	
36	0.005	0.127	0.0127	1360	0.21	0.035	
Metric 1.25	0.00492	0.125	0.0123	1404	0.20	0.034	
37	0.0045	0.1143	0.0103	1715	0.17	0.0289	
Metric 1.12	0.00441	0.112	0.00985	1750	0.163	0.0277	$\text{Metric}=10*d$ $A_{\text{AWG}}/A_{\text{AWG}+3}=2$
38	0.004	0.1016	0.00811	2163	0.13	0.0228	
Metric 1	0.00394	0.1000	0.00785	2198	0.126	0.0225	
39	0.0035	0.0889	0.00621	2728	0.11	0.0175	
40	0.0031	0.07874	0.00487	3440	0.09	0.0137	

Adapted from https://www.powerstream.com/Wire_Size.htm

Other Fuse Wire Material - Alloys

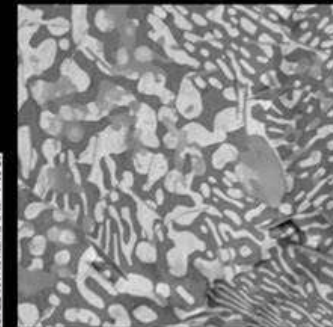
Eutectic ('easy-melting') alloys

https://en.wikipedia.org/wiki/Eutectic_system



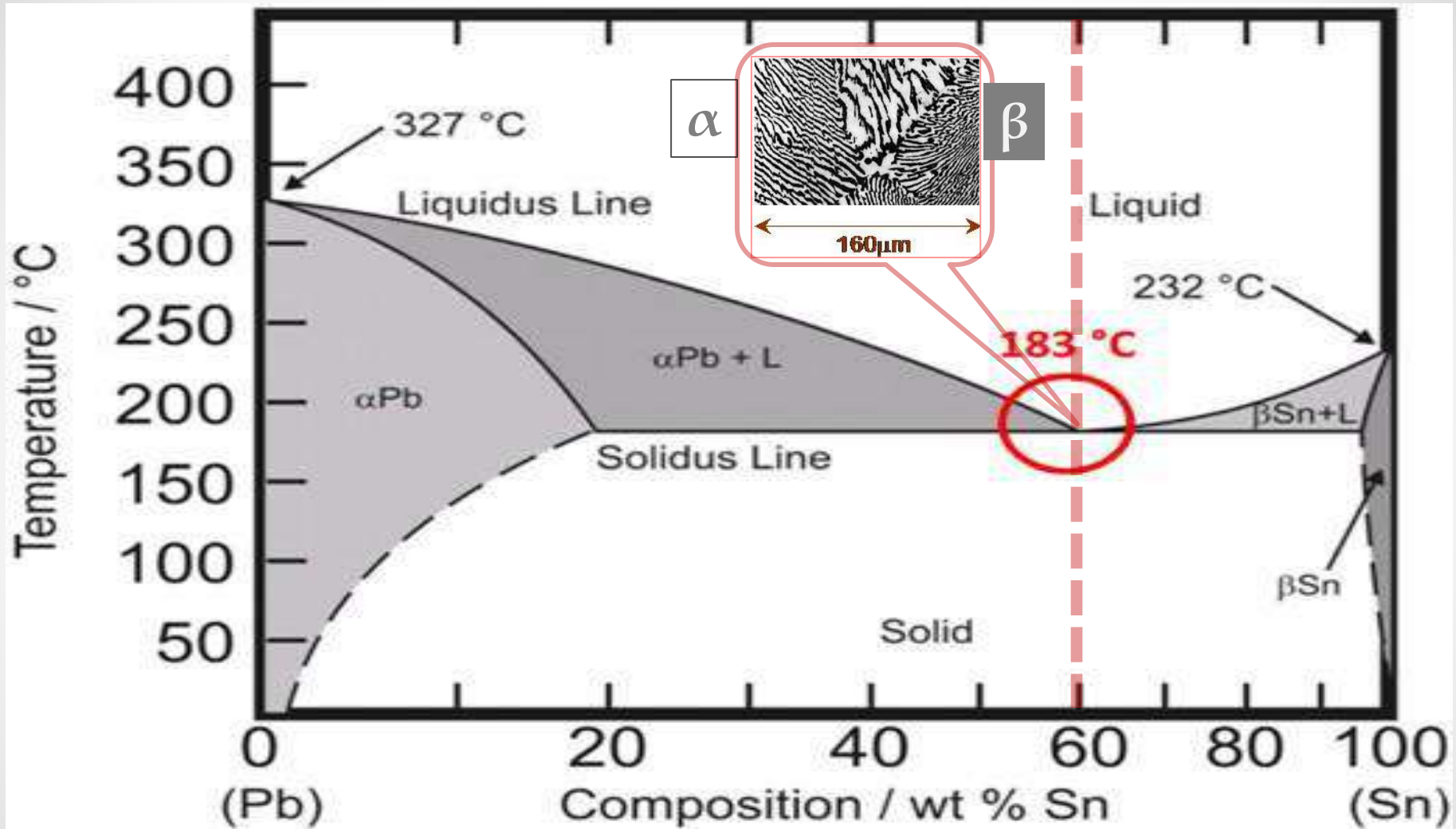
Pb-Sn Microstructures

The dark layers are Pb-rich α phase, the light layers are the Sn-rich β phase.



By Eutektikum_new.svg: *Eutektikum.gif: Dr. Báder Imre derivative work: Michbich (talk) derivative work: Wizard191 (talk) - Eutektikum_new.svg, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=8826869>

The Eutectic 63Sn-37Pb ("60/40") Alloy Used for Soldering

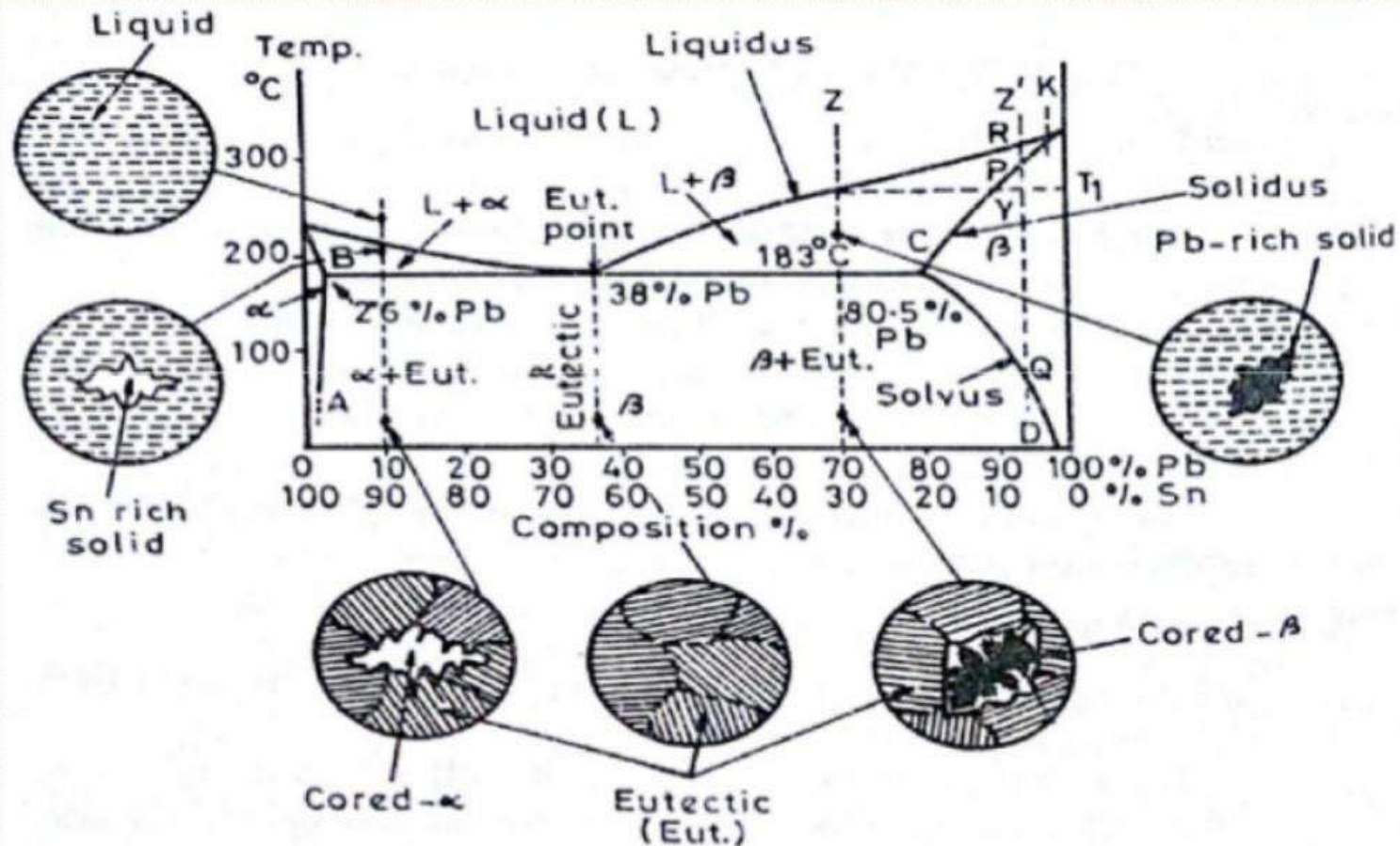


<https://www.indium.com/blog/soldering-101-ii-the-miracle-of-soldering.php>

By Eutektikum_new.svg; *Eutektikum.gif; Dr. Báder Imre derivative work: Michbich (talk) derivative work: Wizard191 (talk) - Eutektikum_new.svg, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=8826869>

Details of the Sn-Pb Alloy "60/40"

2. Two metals completely soluble in the liquid state, but only partly soluble in the solid state



The Tin-lead equilibrium diagram.

Cu PCB Trace (equiv wire) - Temperature vs Current Models

Book: D.G. Brooks and J.Adam, PCB Trace and Via Currents and Temperatures: The Complete Analysis, CreateSpace Independent Publishing Platform (March 4, 2016)
ISBN-13: 978-1530389438, **ISBN-10:** 1530389437

UltraCAD's Wire Gauge Calculator v3

UltraCAD Design, Inc.

Wire Gauge Calculator v3
By UltraCAD Design, Inc.

Units: ☒ English ☐ Metric ☒ Oz ☐ Mils

Wire Gauge:
Enter any two variables and solve for the third

Solve	Wire Gauge (Equivalent)	40.76
Solve	Trace Weight (Thickness) (Oz)	.5
Solve	Trace Width (mils)	10

Trace Resistance:
Enter trace temperature and length. Then solve for the resistance of the trace described above. Enter trace current and solve for its voltage drop

Solve	Trace Temperature (oC)	30
Solve	Trace Length (in.)	9
Solve	Trace Resistance (Ohms)	.9767997
Solve	Current down Trace (Amps)	.150
Solve	Voltage Drop (Volts)	.14651996

Copyright 2010 UltraCAD Design, Inc., Bellevue, WA.

<https://www.ultracad.com/articles/fusingr.pdf>

UltraCAD's Trace Current/Temperature Calculator 1.0

UltraCAD Design, Inc.

UltraCAD's Trace Current/Temperature Calculator
Version 1.0

Copper: ☒ Oz ☐ mils ☐ μm

Width: ☒ mils ☐ mm

Copper Thickness: 1.5 Oz

Trace Width: 150 mils

Current: 9 Amps

Trace CHANGE of Temperature External: 26.8 oC

Internal Temperature

Trace Depth (Rel. 0.0 - 0.5): .3

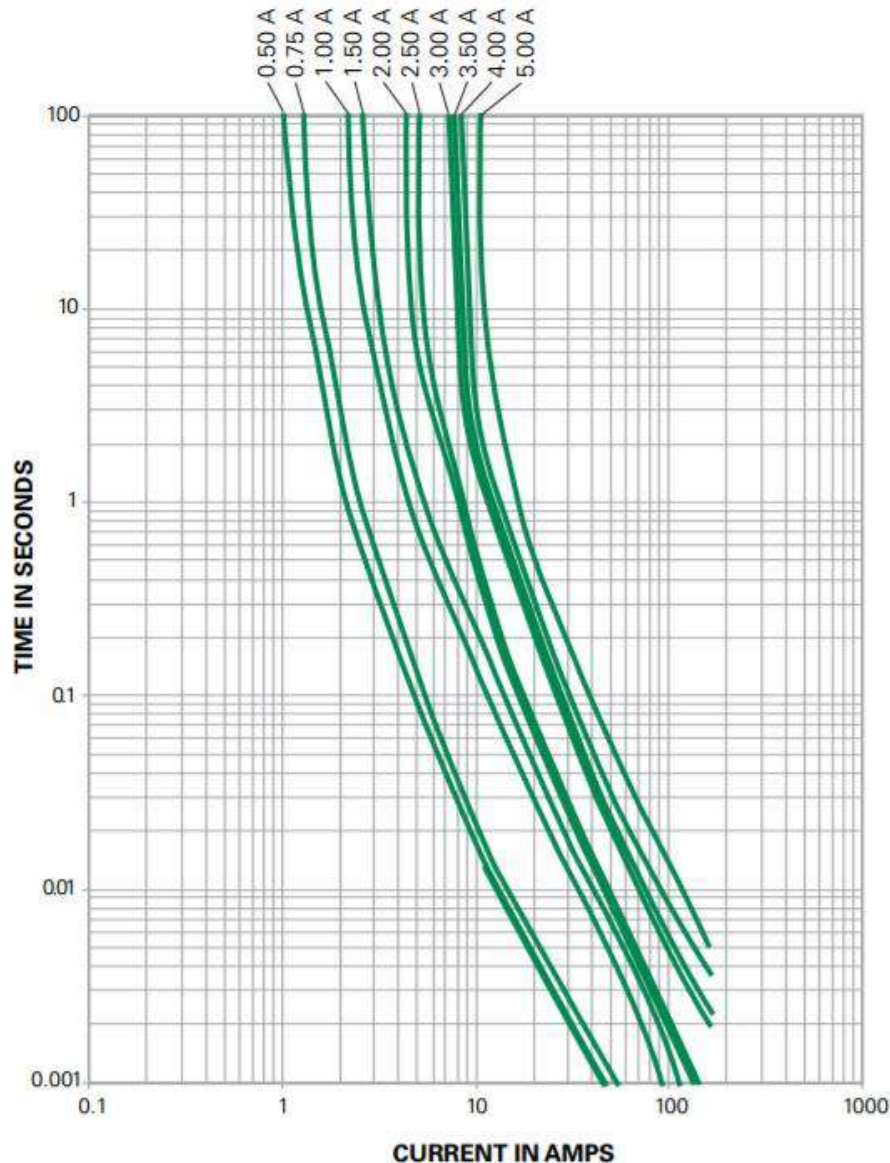
Trace CHANGE of Temperature Internal: 22.9 oC

Licensed to: Doug Brooks
Company: UltraCAD

Copyright 2018 UltraCAD Design, Inc., Issaquah, WA.

https://ultracad.com/ucad_ttemp.htm

Fuse - Timing



(Show <https://www.ultracad.com/articles/fusingr.pdf>
"Fusing Currents in Traces")

Onderdonck's approx for Cu
with $T_{ref}=20^{\circ}\text{C}$, melting at 1083°C

$$t = \left(\frac{1}{33.5} \right) \left[\log_{10} \left(\frac{\Delta T}{234 + T_{ref}} + 1 \right) * \left(\frac{A}{I} \right)^2 \right]$$

$$t = .0346 * (A/I)^2$$

For Fuse Model

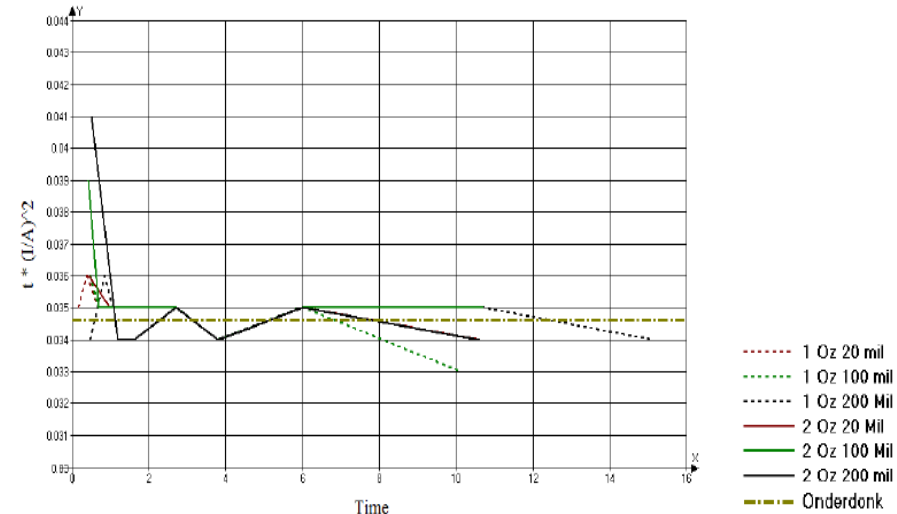


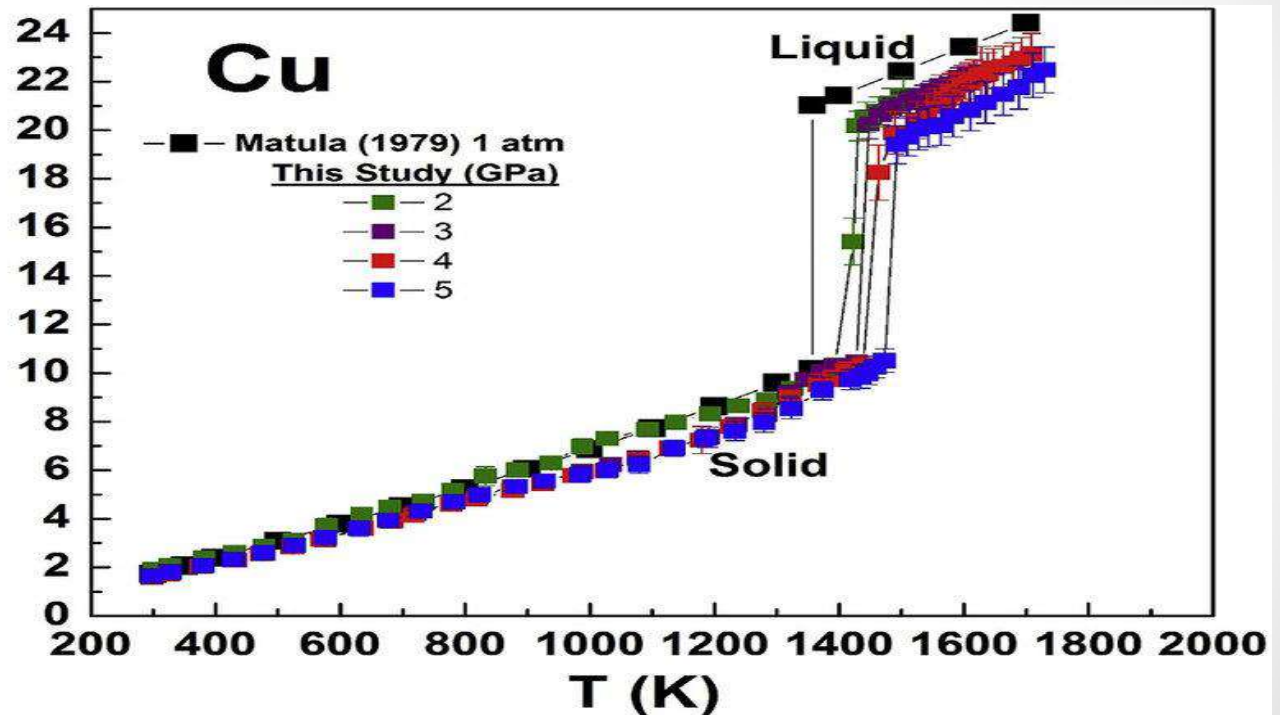
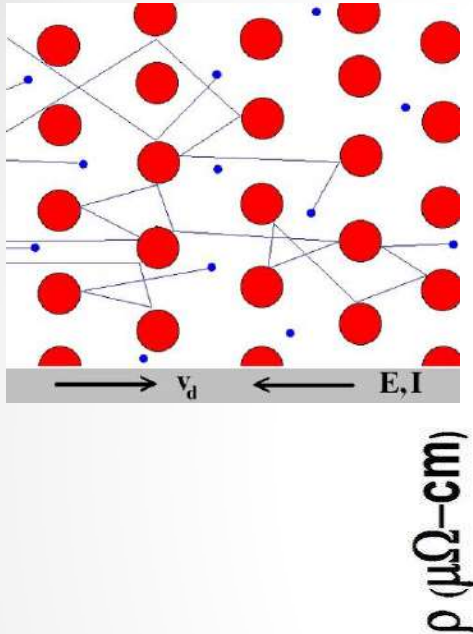
Figure 6

Plot of $t * (I/A)^2$ for the various configuration simulations of the fuse trace.

The Hairy Details - Advanced

❖ Theories of electronic transport in metals+alloys:

“Ohm’s Law” in different forms,
with possible modifications at high temperature



I.C.Ezenwa, R.A.Secco, W.Yong, M.Pozzo, D.Alf, J.Phys.Chem.Solids 110 (Nov 2017), 386-93

https://unlcms.unl.edu/cas/physics/tsymbal/teaching/SSP-927/Section%2008_Electron_Transport.pdf

By Rafaelgarcia - Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=2817438>

Experiment With Alloys: "60-40" - Timing

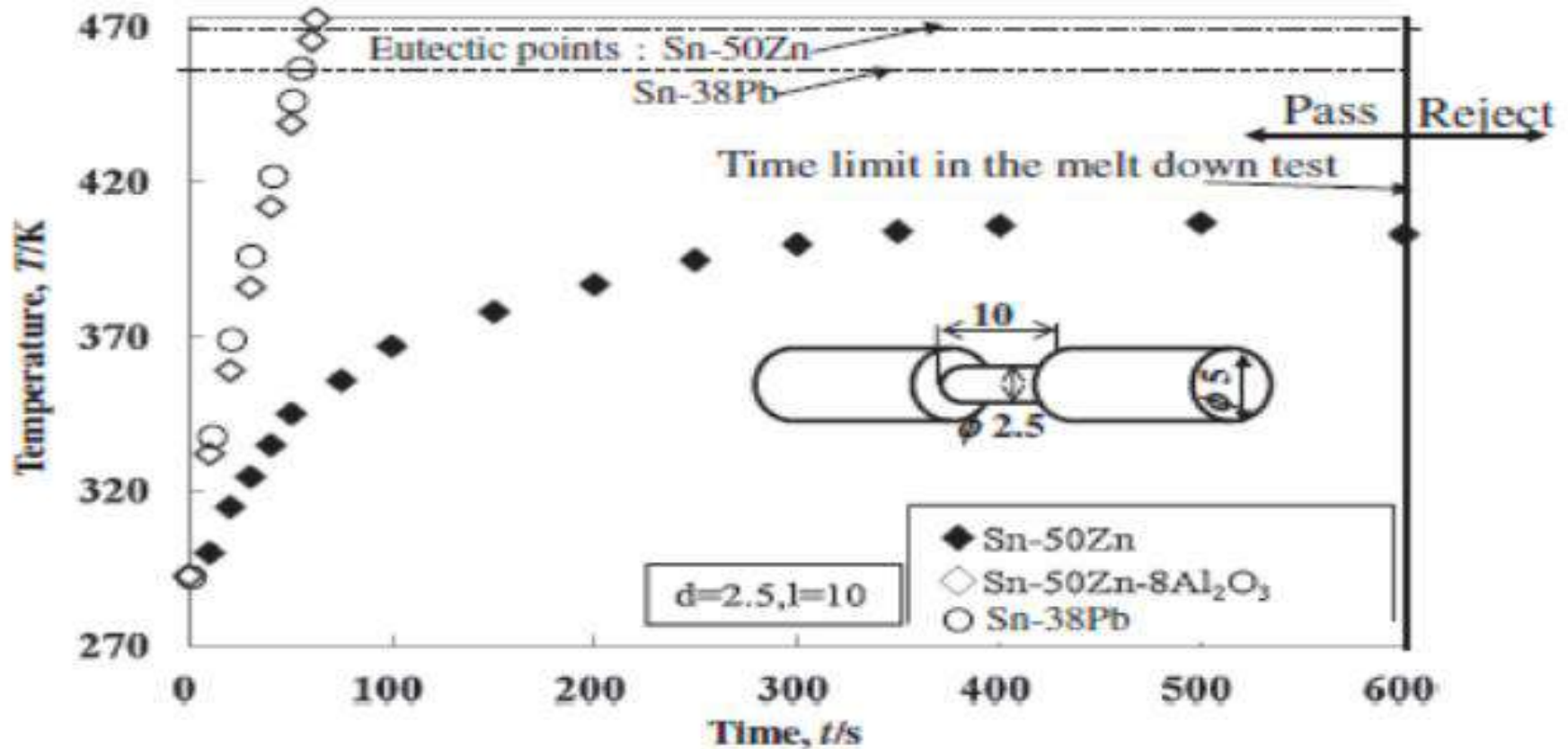


Fig. 9 The relation between the temperature and time obtained from the calculations under the constant current flow of 99 A at the center in fuse elements made of Sn-50Zn with and without 8 vol% Al₂O₃ and Sn-38Pb.
 * d and l represent the diameter and length in their smaller diameter parts.

Alloys – Intermetallic Compounds

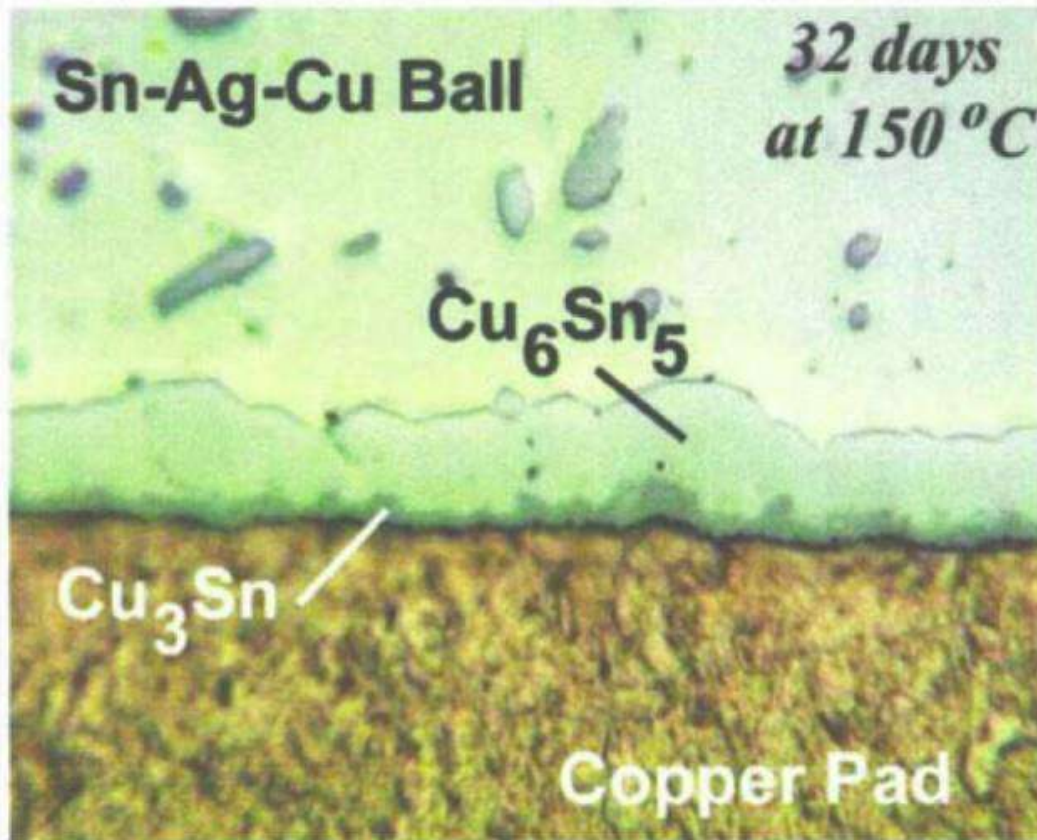
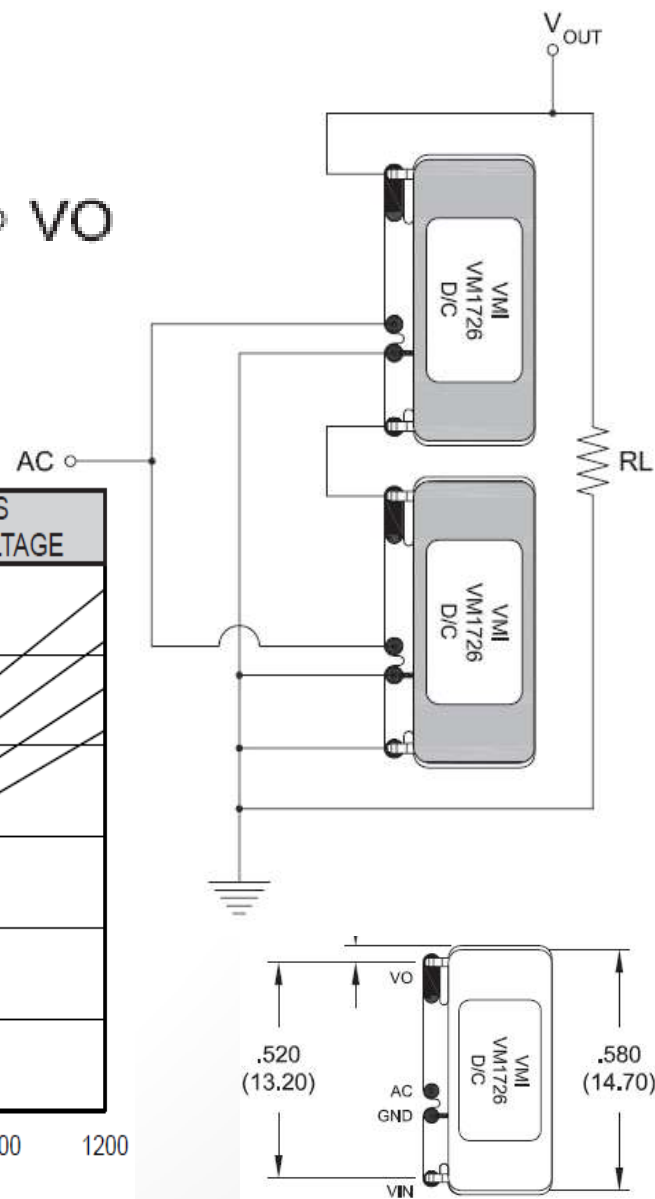
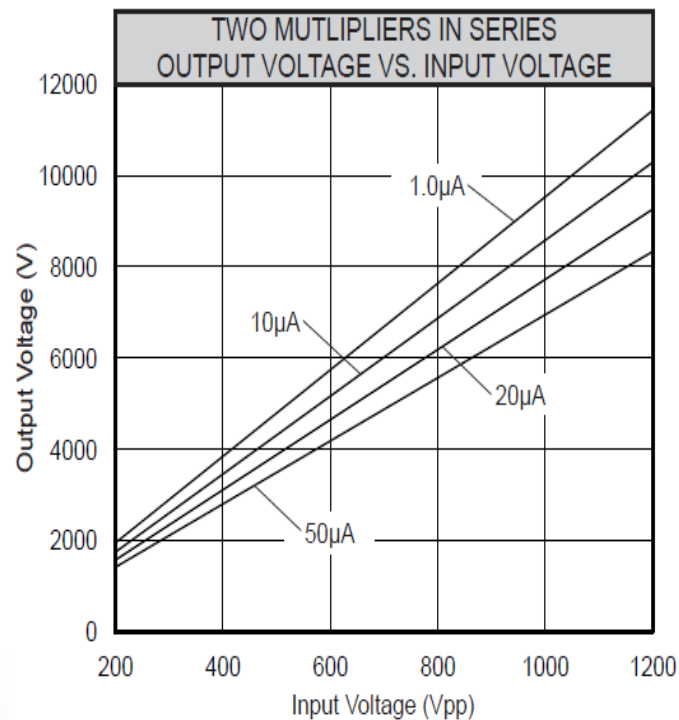
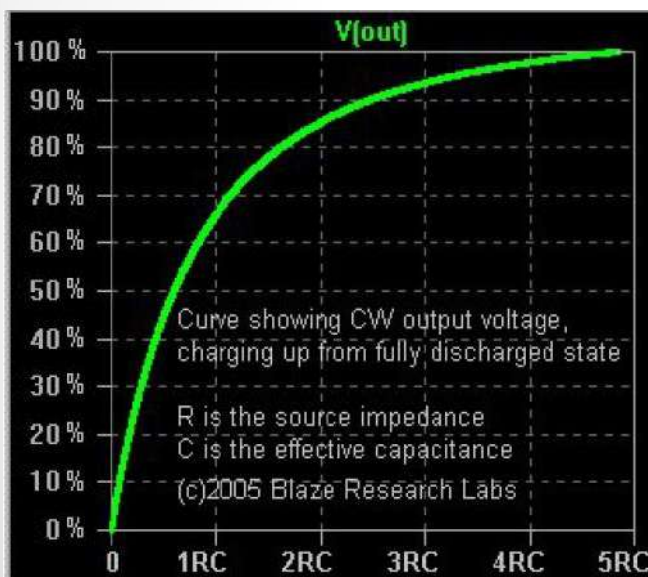
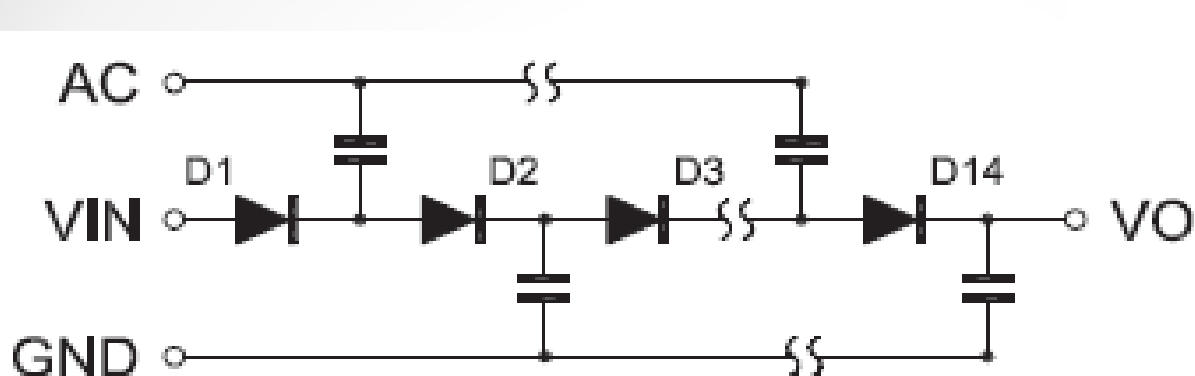


Fig. 2 – Intermetallic compounds at the interface of the copper pad and a Sn-4Ag-0.5Cu ball after 32 days of aging at 150°C.

Experimentation – HV Source



Thank you for your attention!