Co-funded by the Erasmus+ Programme of the European Union

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

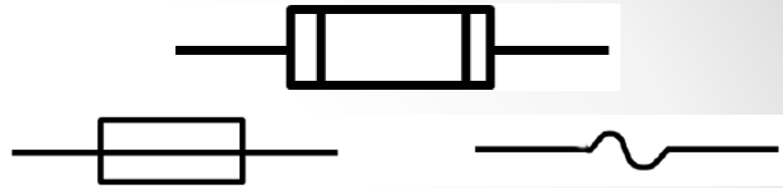
Structure

- ❖ 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

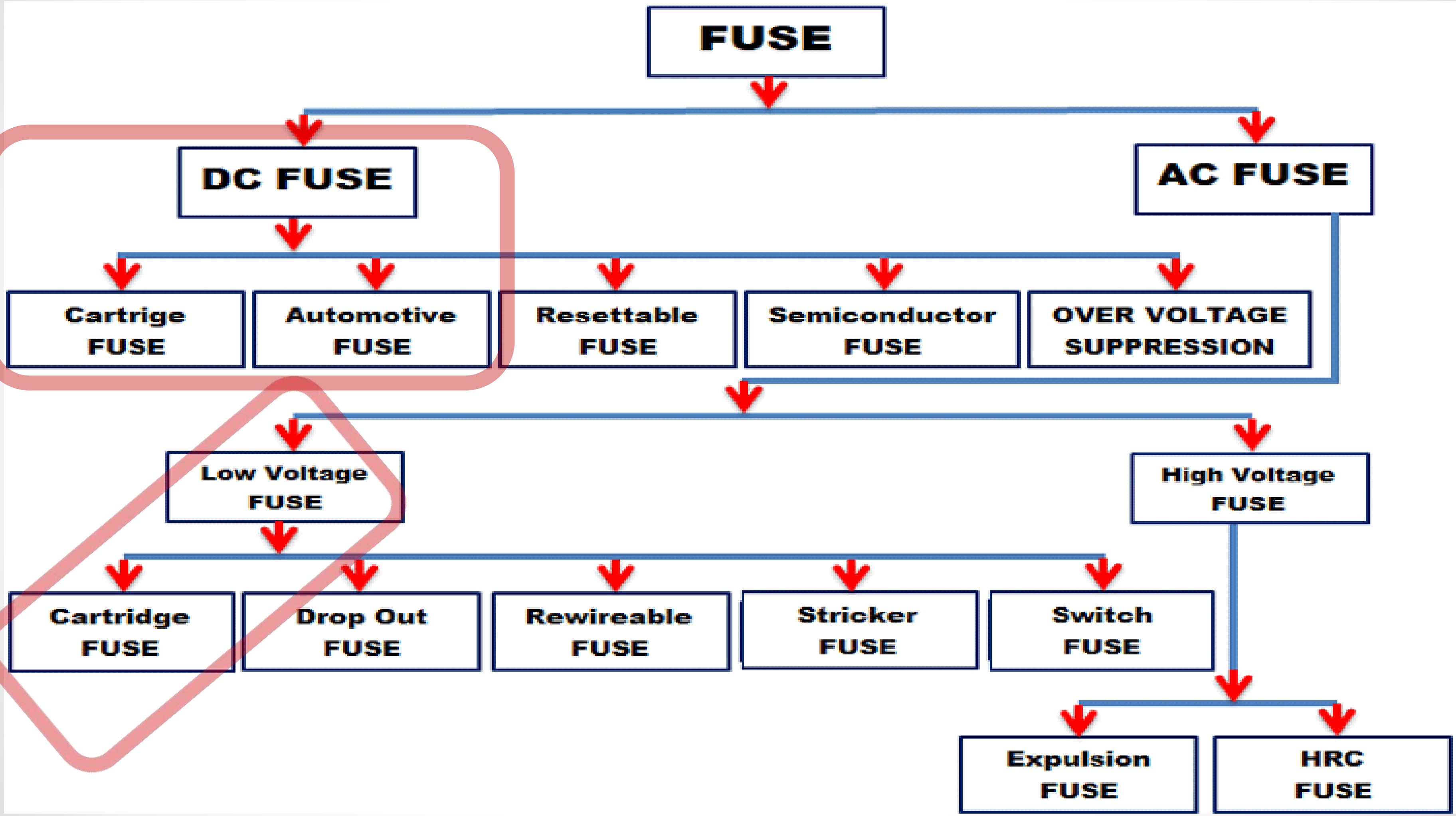


https://components101.com/articles/different-types-of-fuses-and-their-applications

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

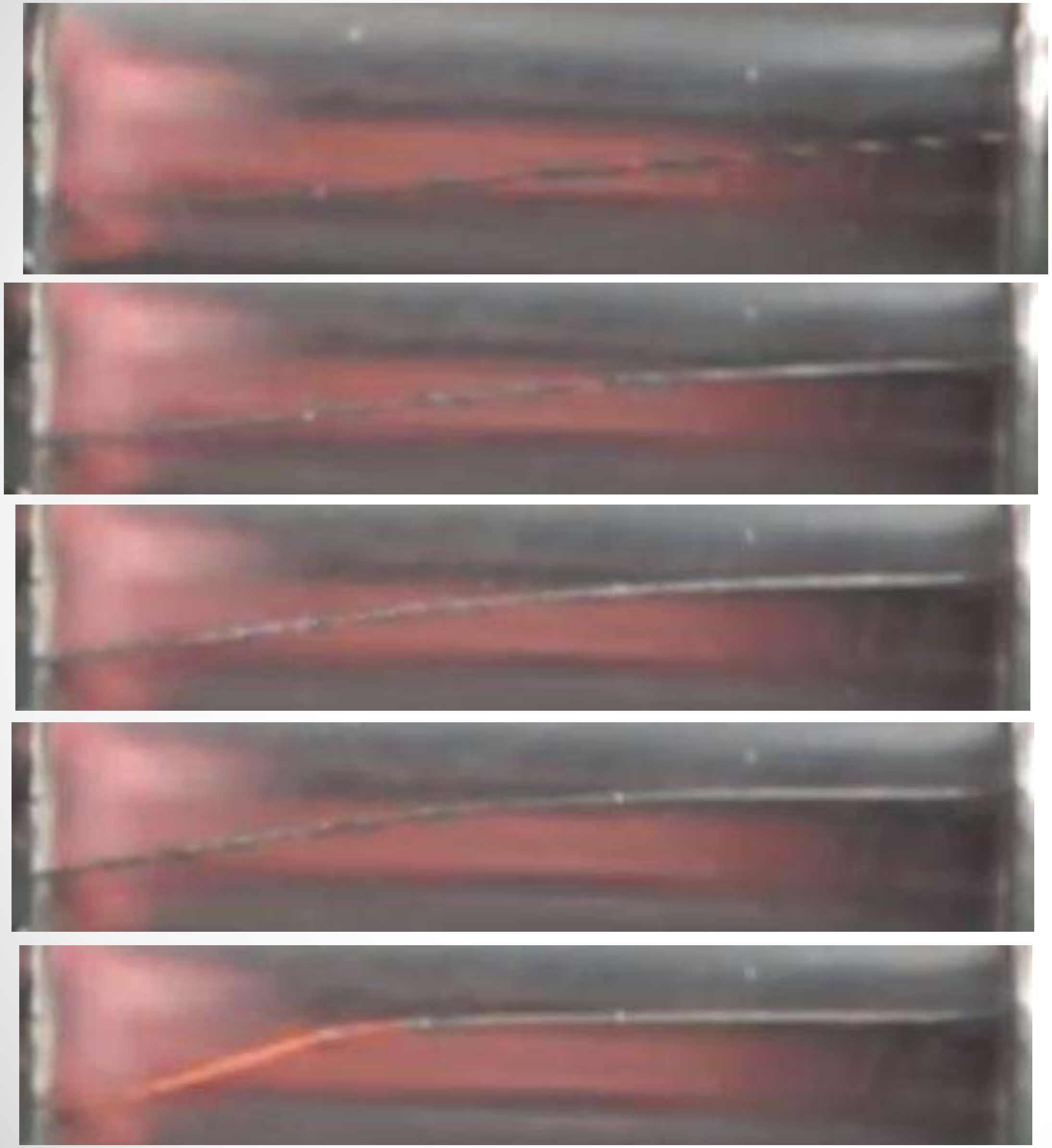
Fuse Types and Function

The Bigger Picture

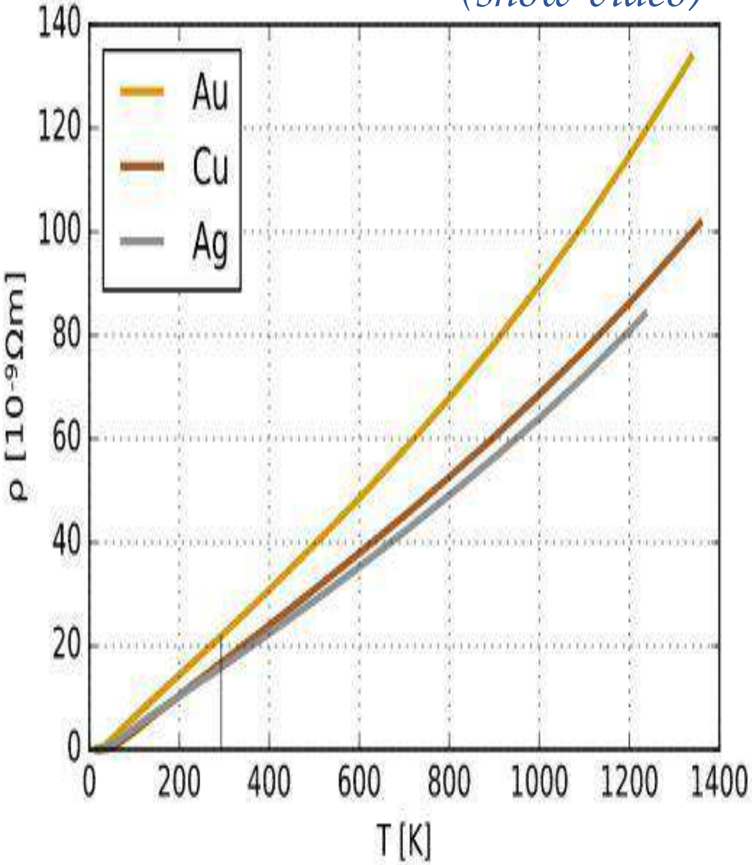


https://components101.com/articles/different-types-of-fuses-and-their-applications

The Wire – Initial overheating phase



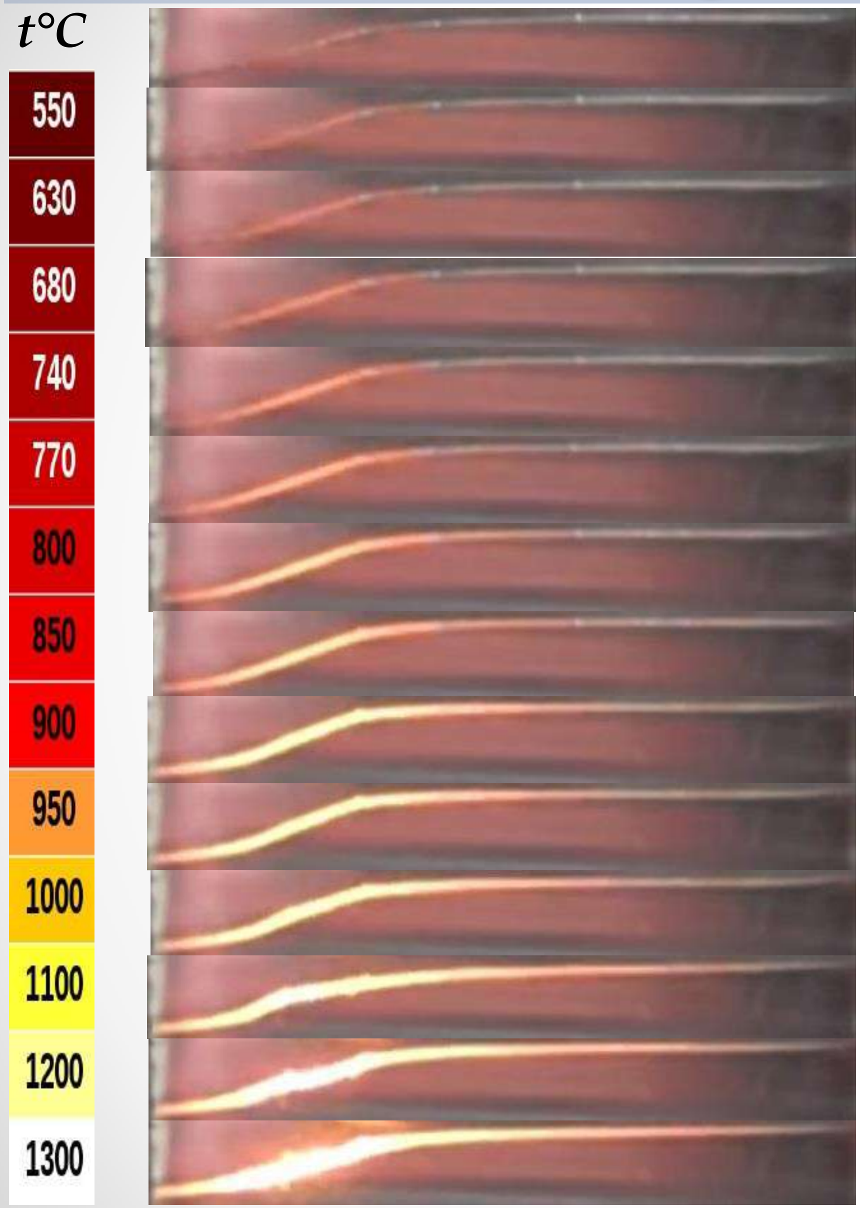
(show video)



"Electrical resistivity of copper, gold, palladium, and silver". *J.Phys.Chem.Ref. Data* 8 (4): 1147–1298. DOI:10.1063/1.555614. ISSN 0047-2689.

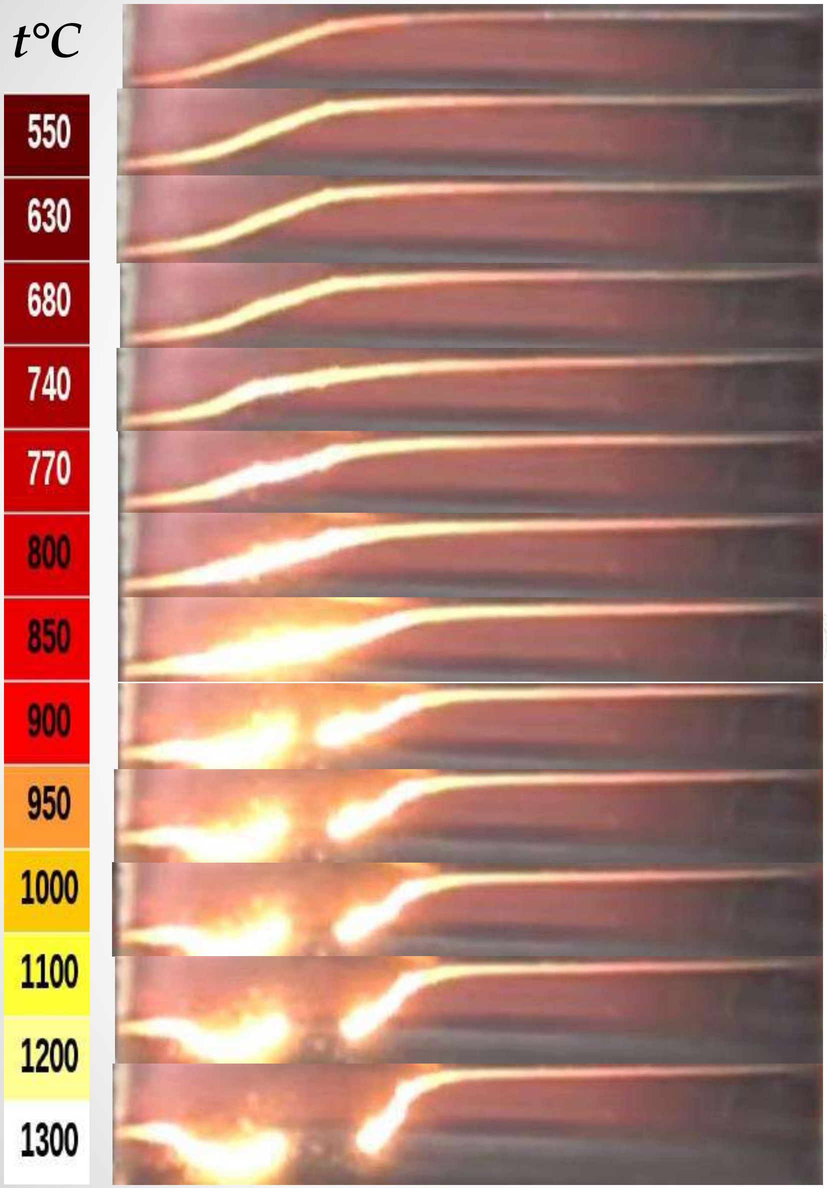
The Fuse Burning Process - Stages (slo-mo video)

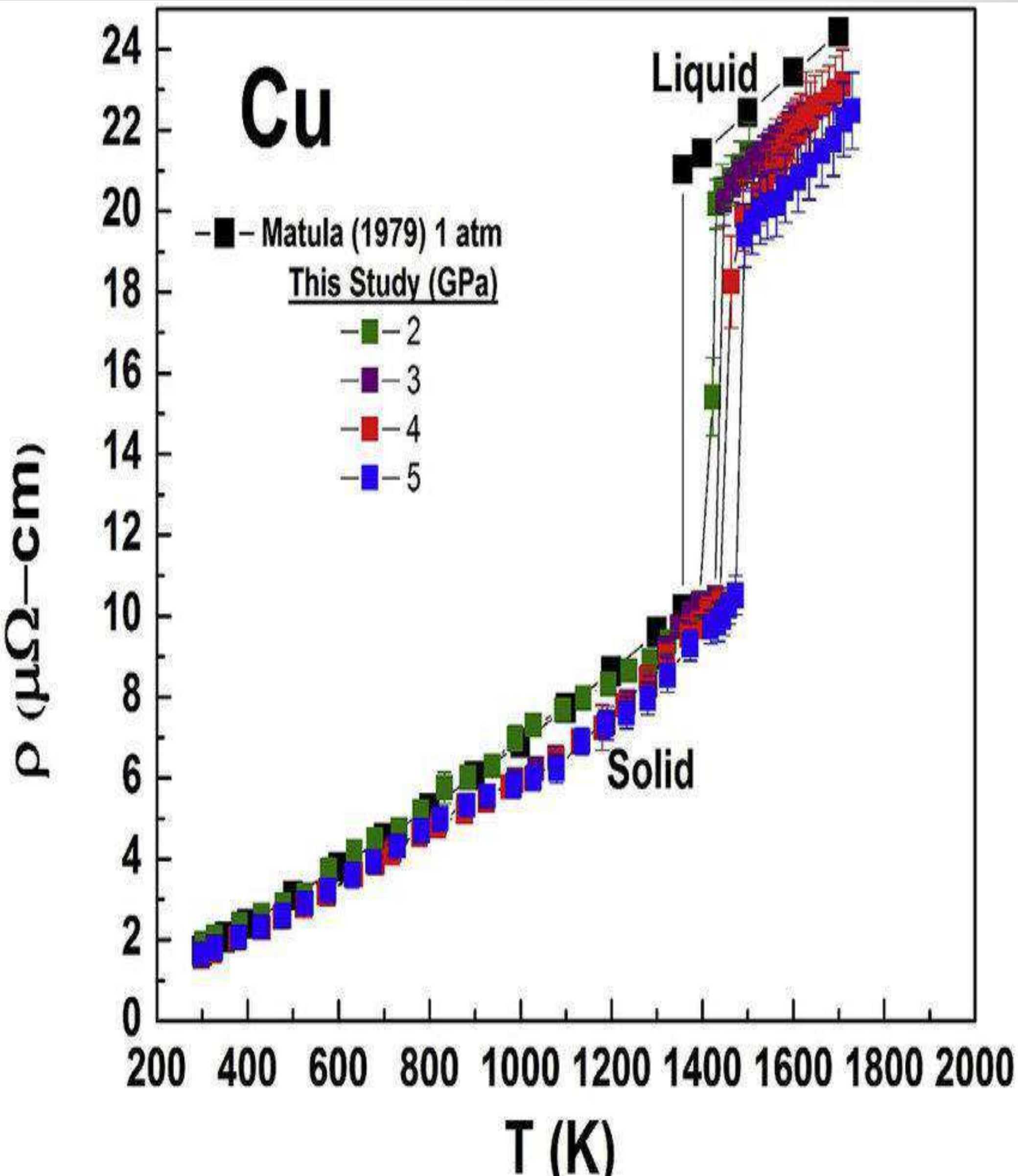
The Fuse Burning – Thermal Expansion Effects



- 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 liquefication 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

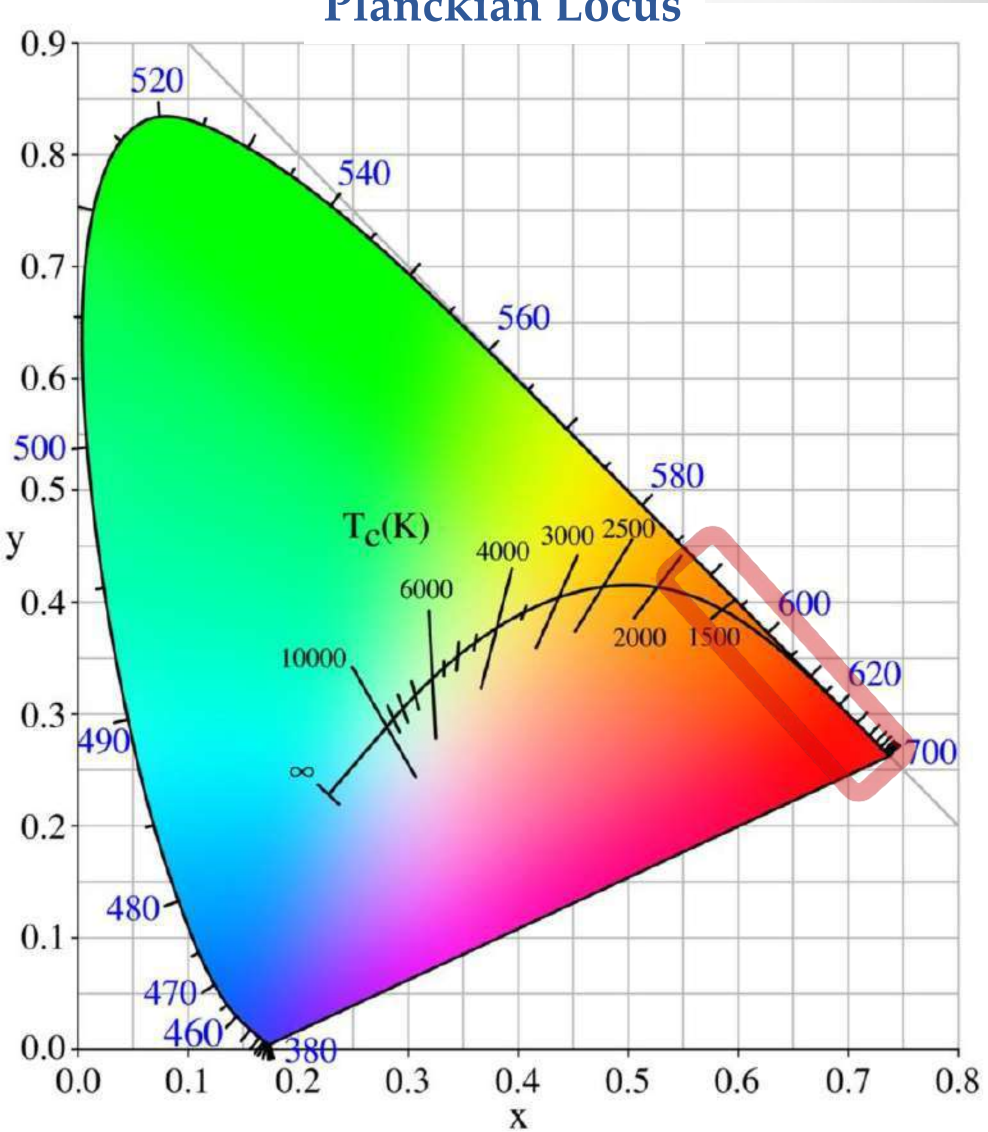




The Melting Phase – Estimating Temperatures

t°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.

  Additonal 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)
28	0.0126	0.32004	0.080	212.872	1.4	0.226
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
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
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
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

For

1 cm AWG36

R=12.5-13.6 mΩ/cm

***IR* ~ 2.8 mV**

***IR* ~ 0.5 mV**

Metric=10*d

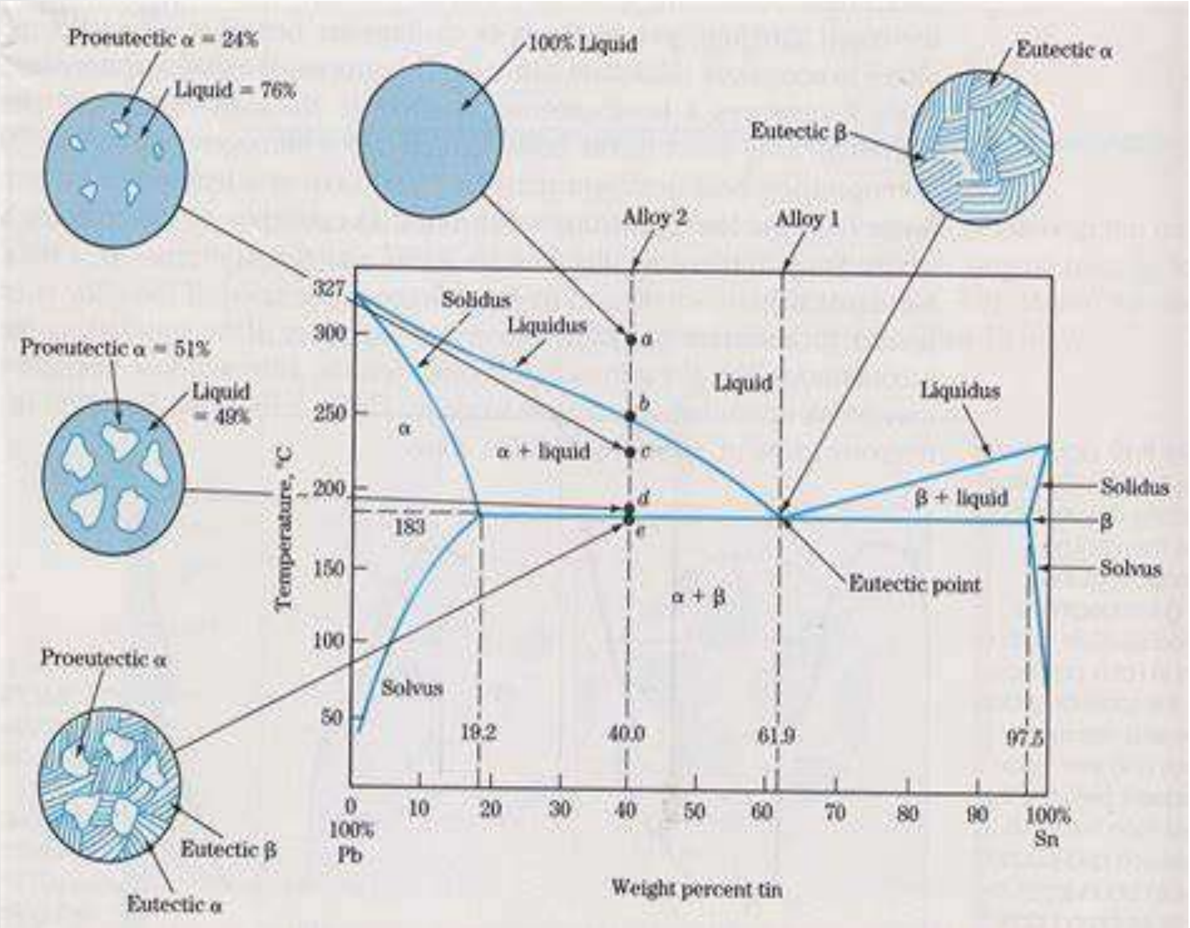
$A_{AWG}/A_{AWG+3}=2$

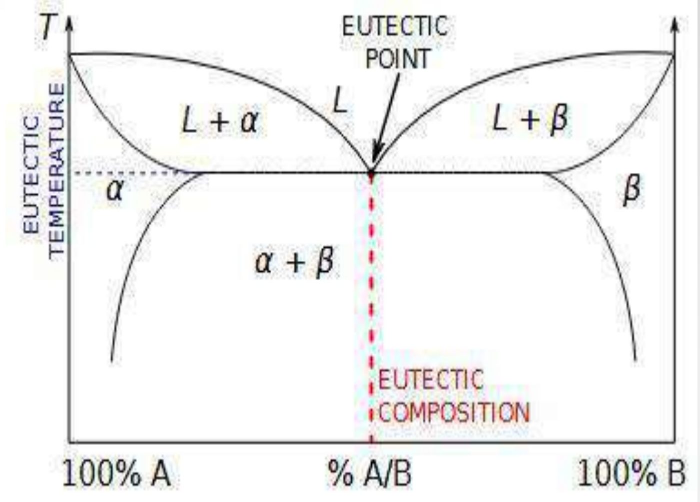
Adapted from https://www.powerstream.com/Wire_Size.htm

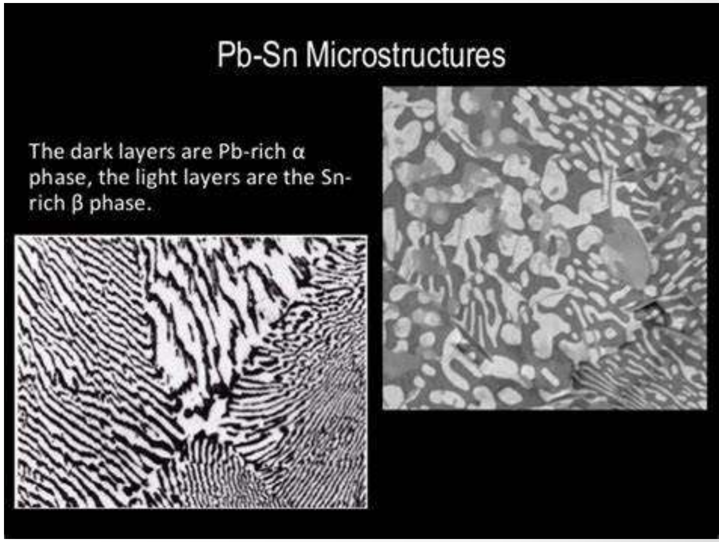
Other Fuse Wire Material - Alloys

Eutectic ('easy-melting') alloys

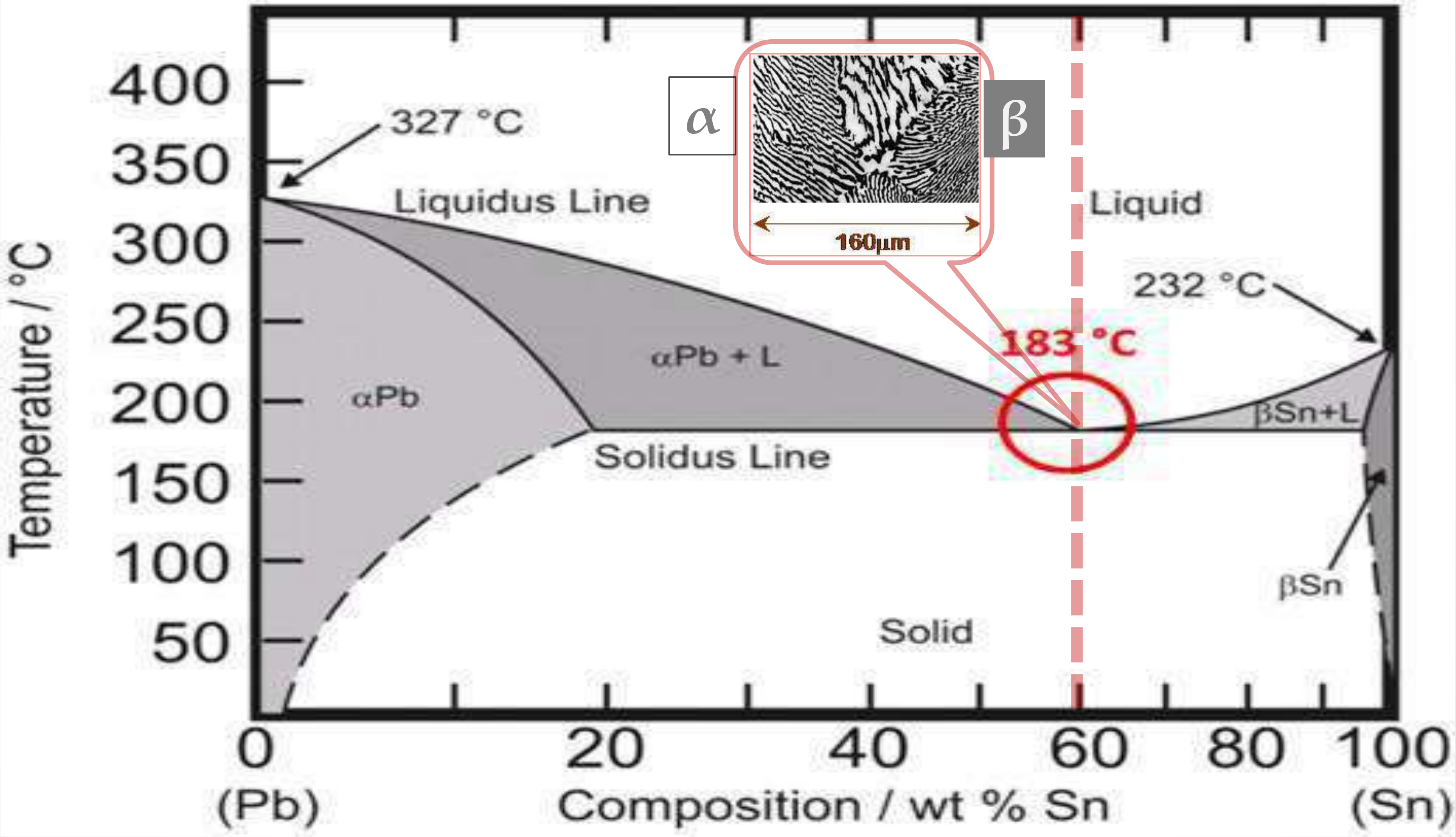
https://en.wikipedia.org/wiki/Eutectic_system







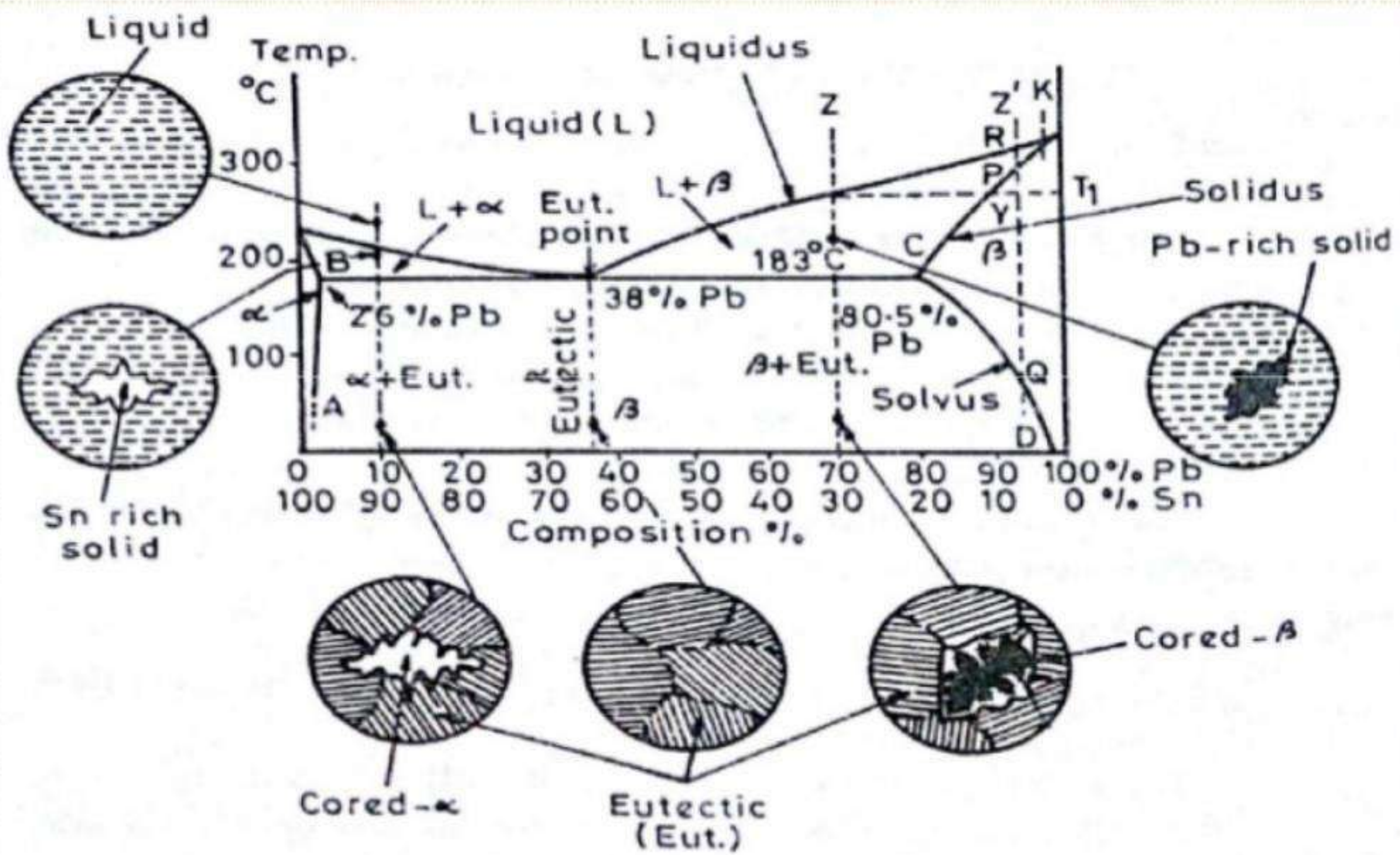
The Eutectic 63Sn-37Pb (“60/40”) Alloy Used for Soldering



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

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

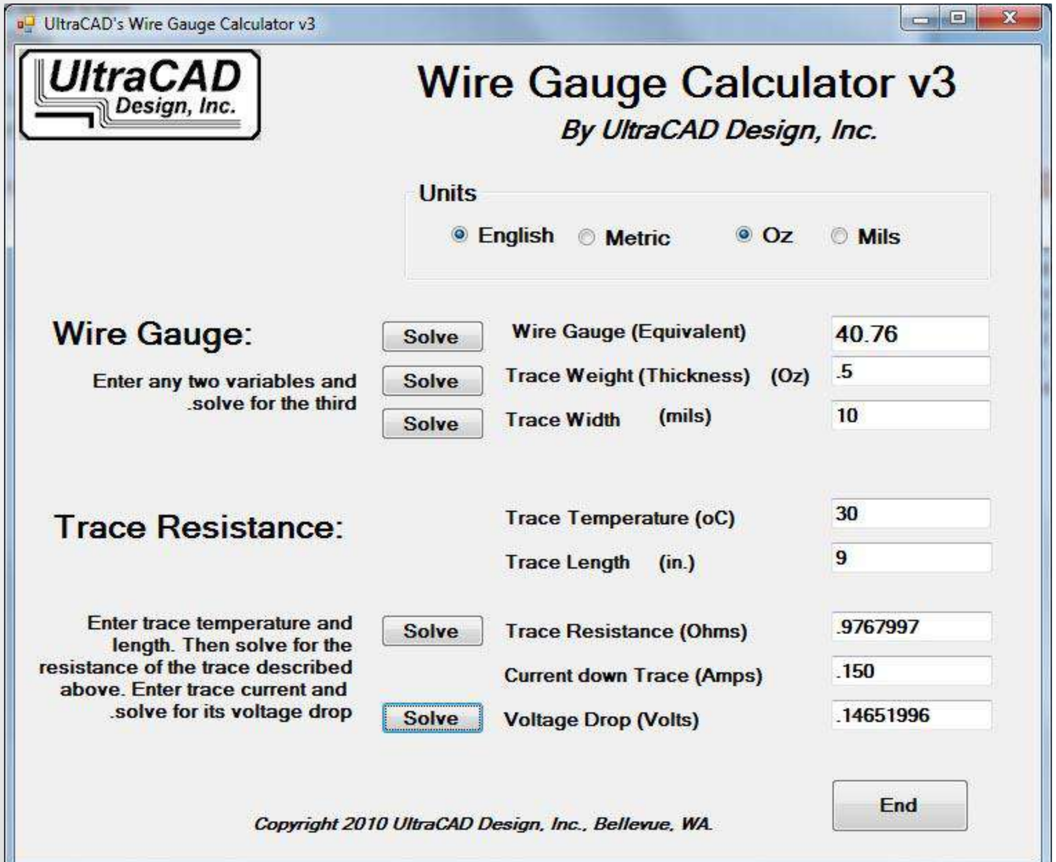


The Tin-lead equilibrium diagram.

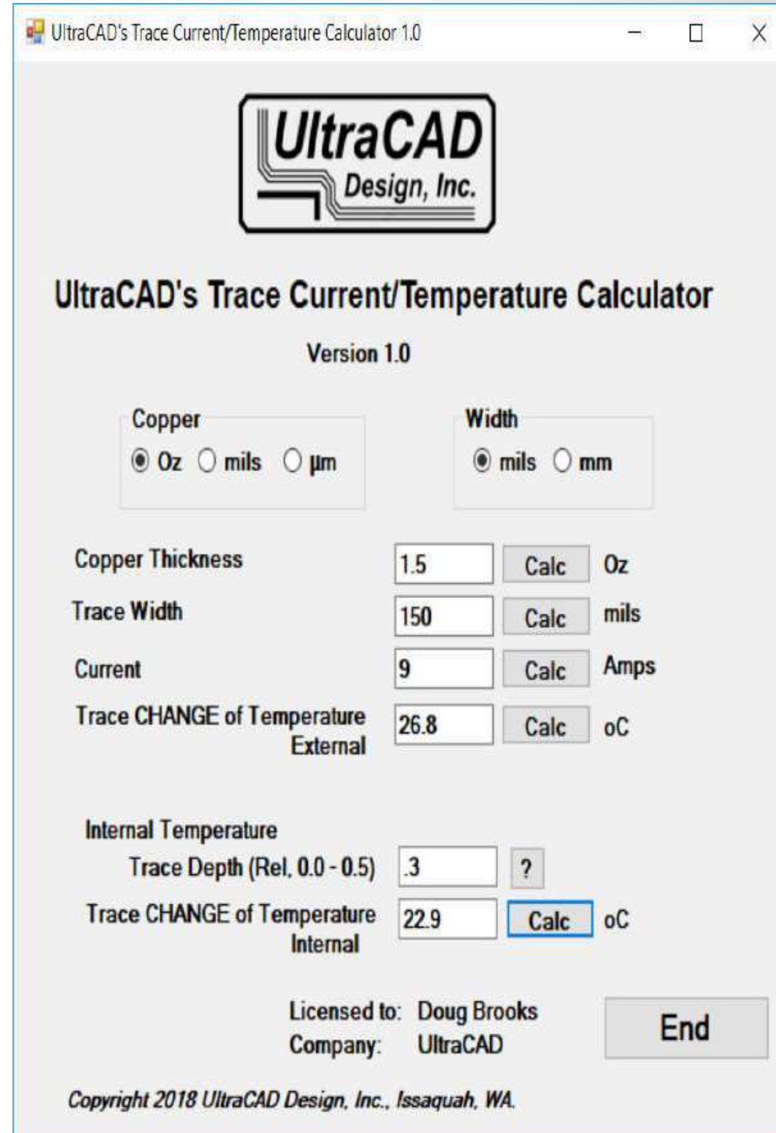
12 Prem Kumar Soni 8/5/2018

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

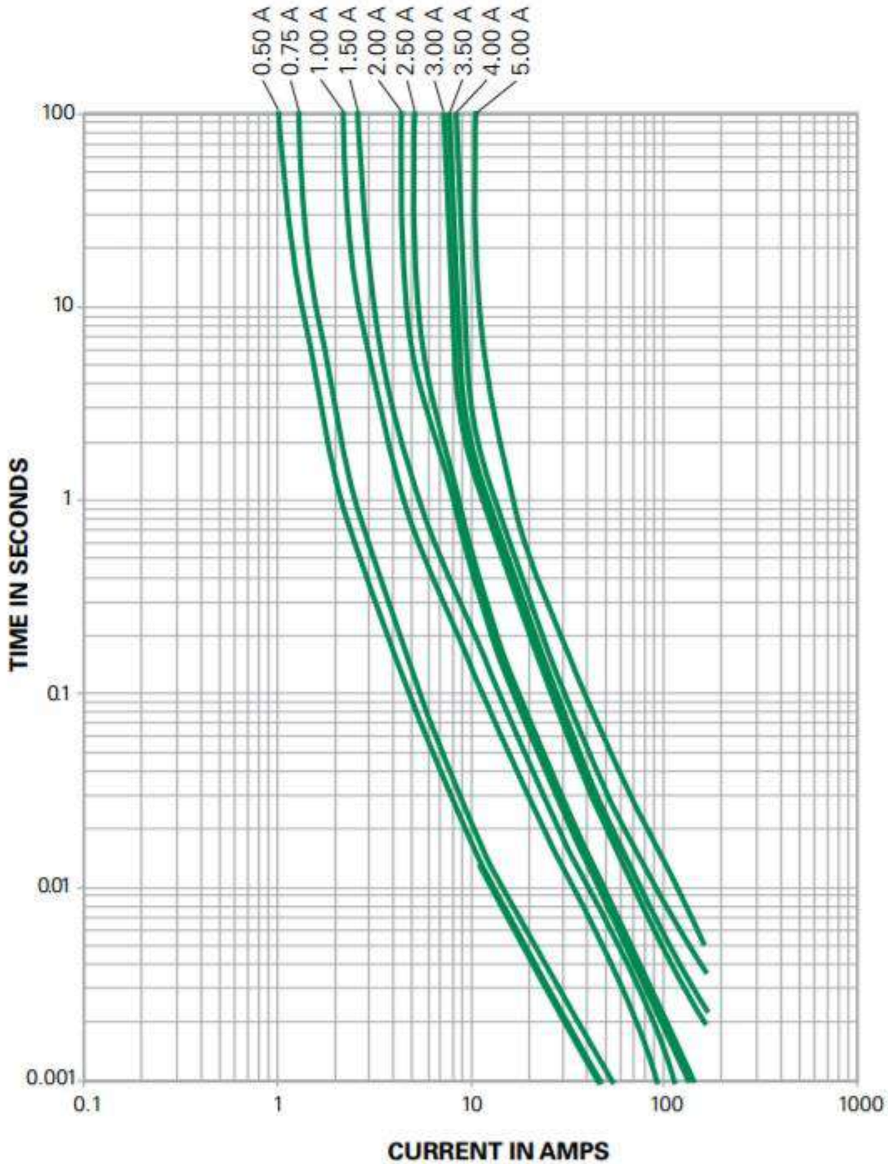


https://www.ultracad.com/articles/fusingr.pdf



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 Tref=20°C, melting at 1083°C

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

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

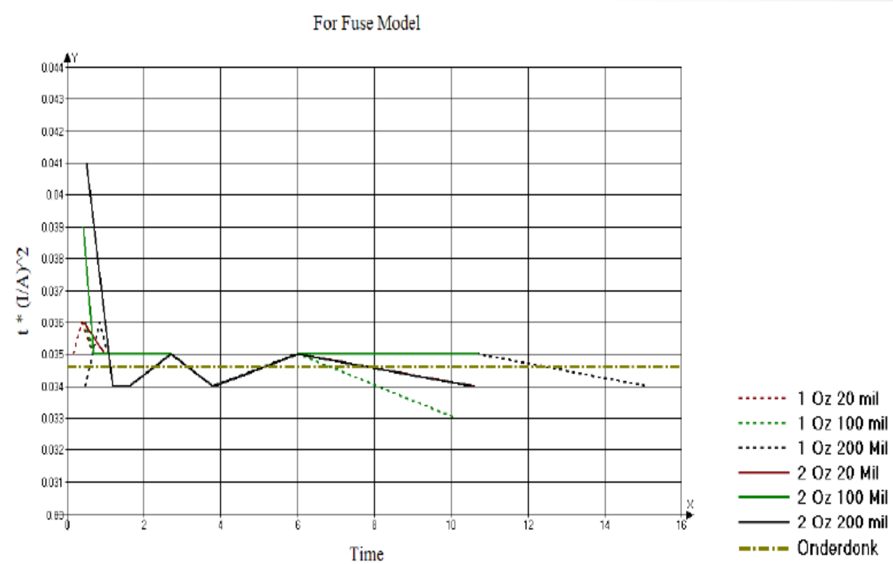


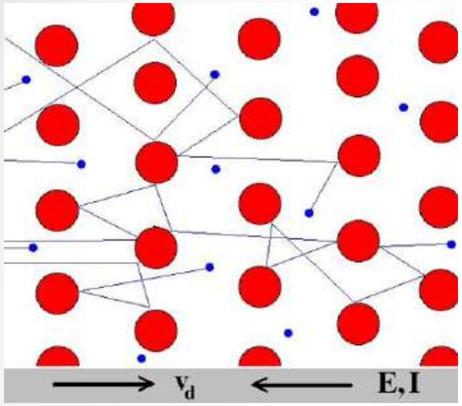
Figure 6
Plot of $t^*(I/A)^2$ for the various configuration simulations of the fuse trace.

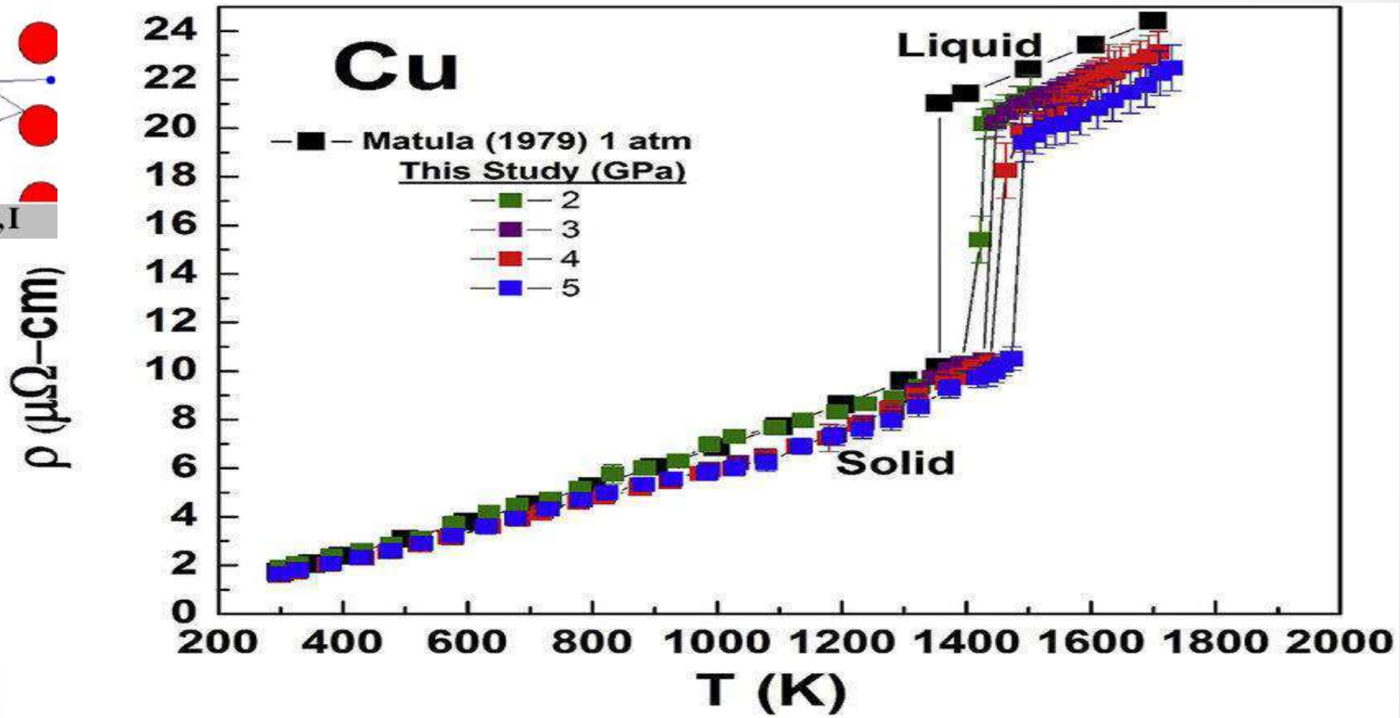
The Hairy Details - Advanced

❖ 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

Experiment With Alloys: “60-40” - Timing

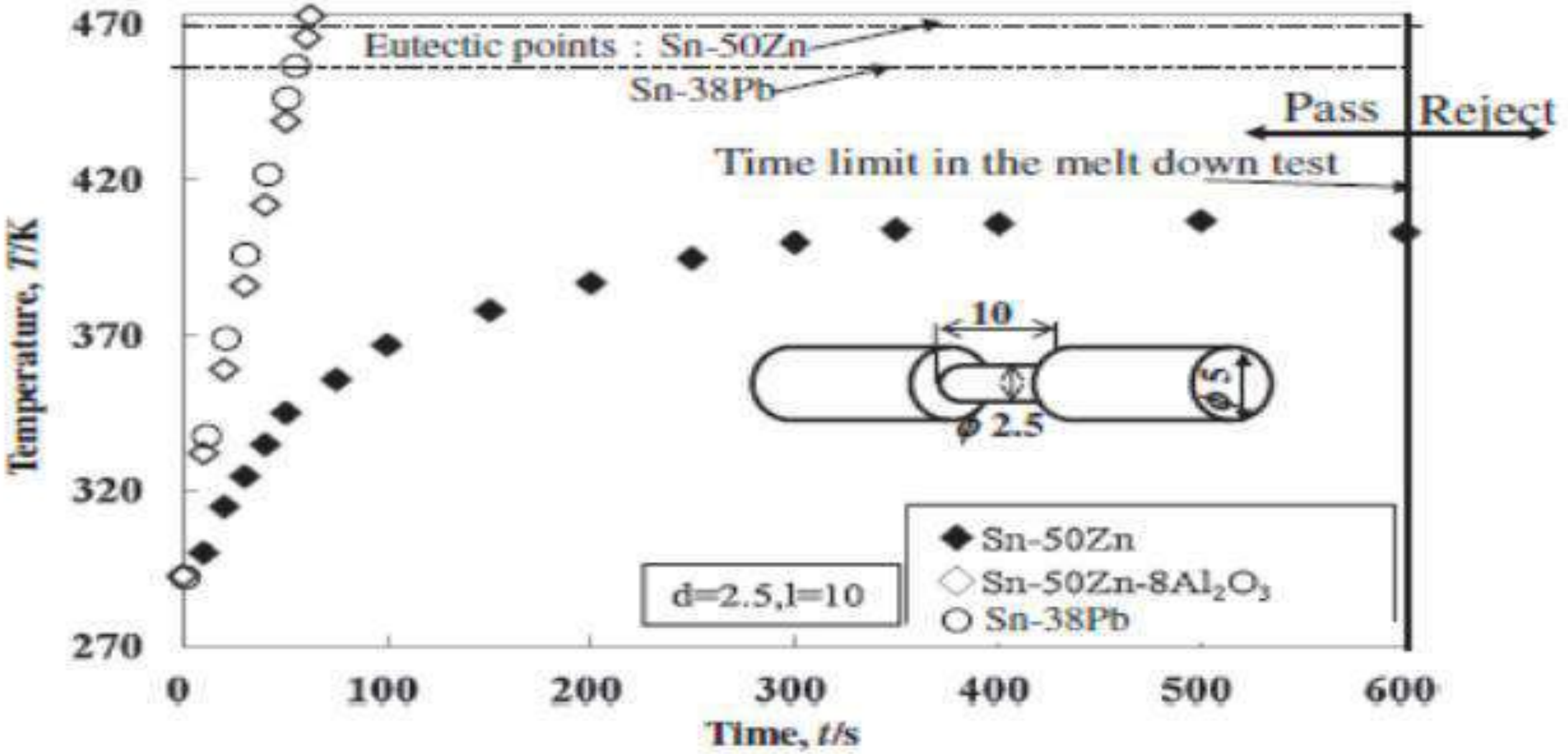


Fig. 9 The relation between the temperature and time obtained from the calculations under the constant current flow of 99 A at the center in fuse elements made of Sn–50Zn with and without 8 vol% Al_2O_3 and Sn–38Pb.
* *d* and *l* represent the diameter and length in their smaller diameter parts.

Alloys – Intermetallic Compounds

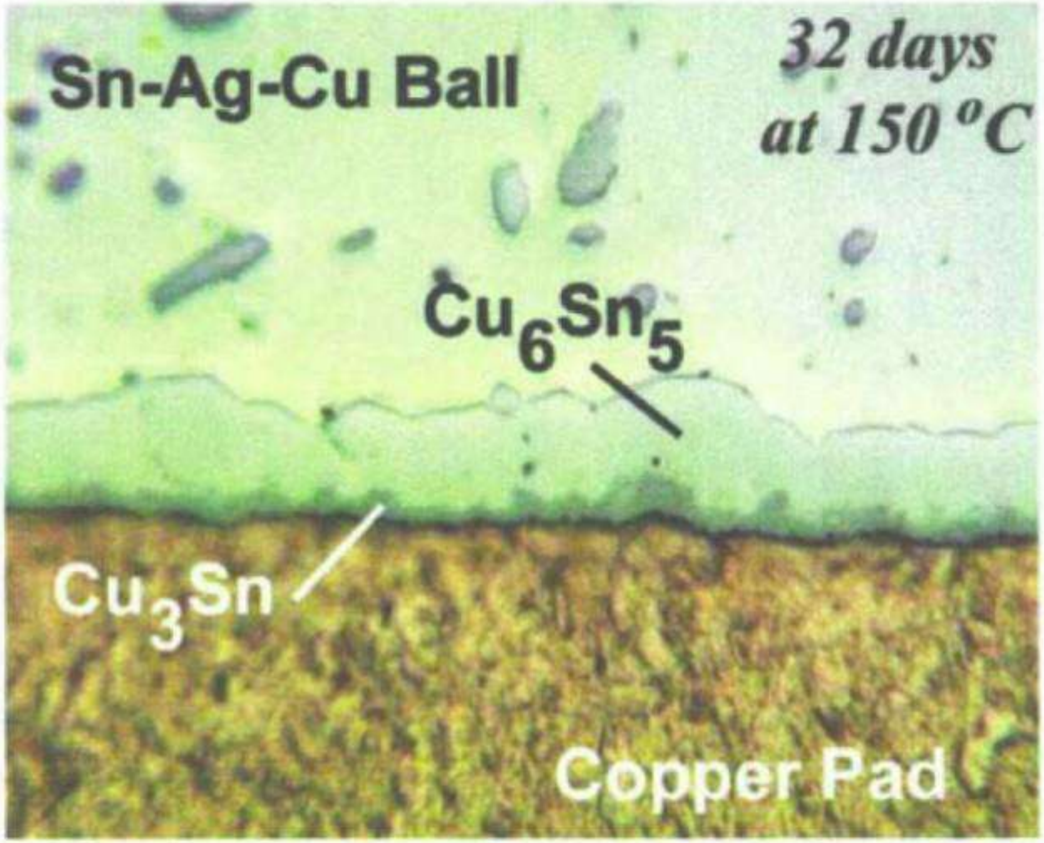
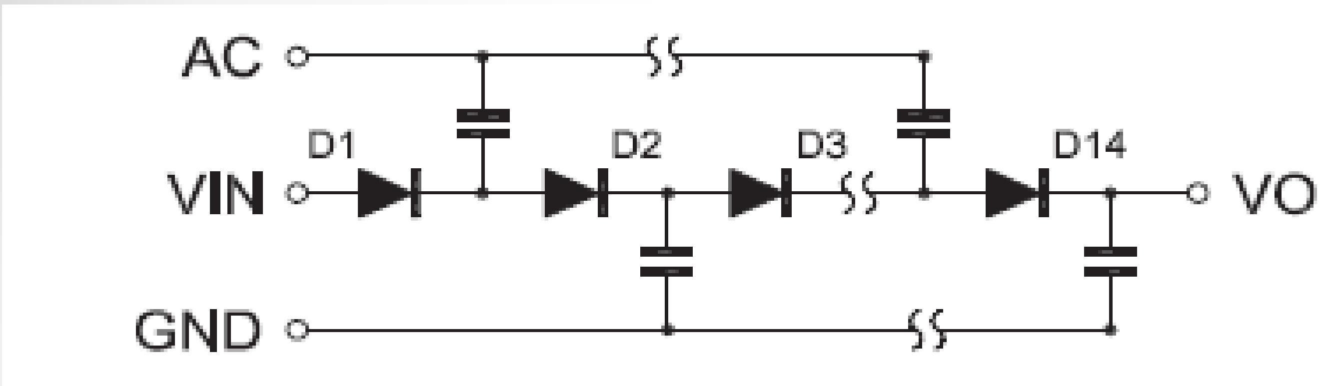
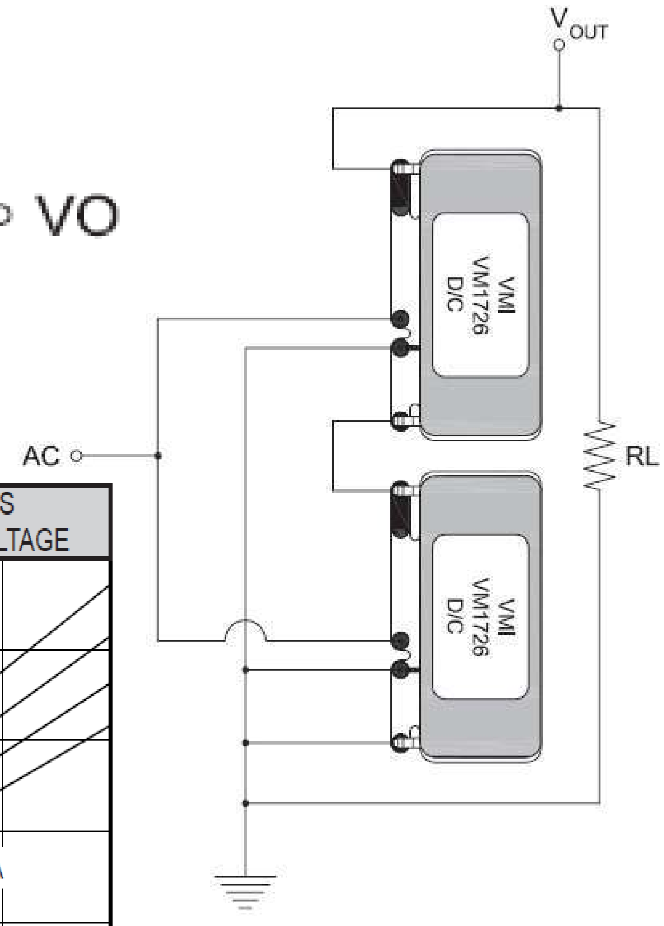
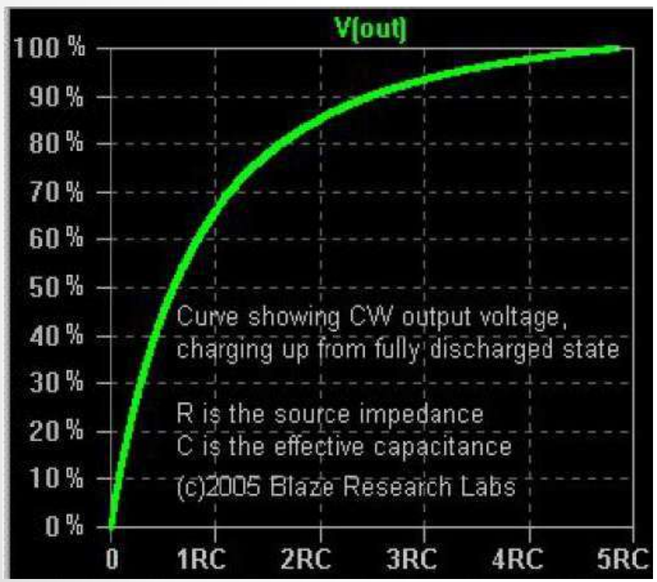


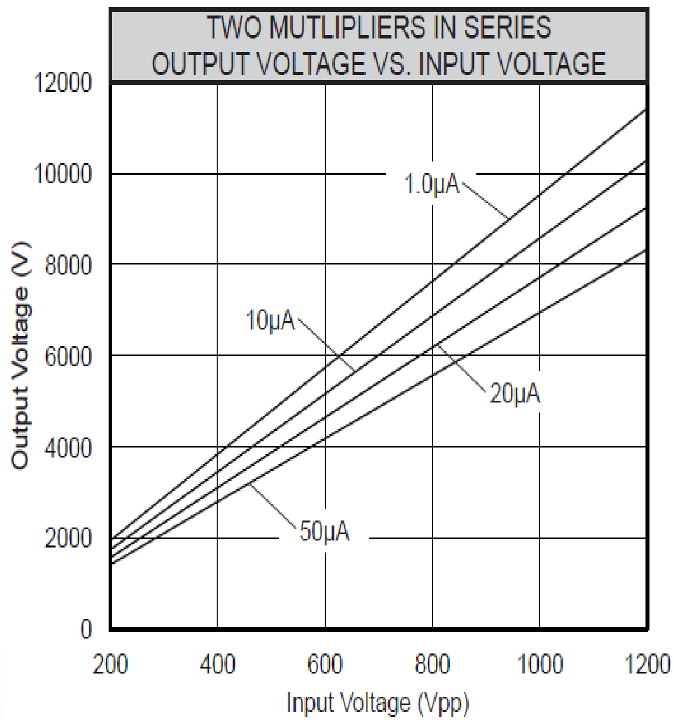
Fig. 2 – Intermetallic compounds at the interface of the copper pad and a Sn-4Ag-0.5Cu ball after 32 days of aging at 150°C.

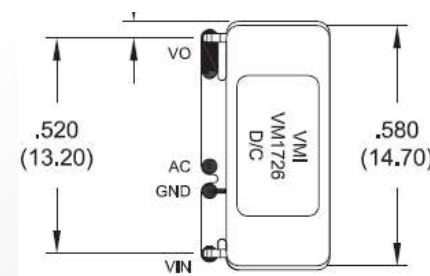
Experimentation – HV Source











Thank you for your attention!