VTT EXPERT SERVICES LTD

Business from technology

Ageing performance of electromagnetic relays
–
evaluation based on a 13 years in-service study and life testing

Helge Palmén, 18th of October, 2012

OCTOBER 18TH 2012
RDM CAMPUS
ROTTERDAM

EUROPEAN CEEES SEMINAR
EUROPEAN RELIABILITY AND ENVIRONMENTAL TESTING CONNECTED

FHI PLATFORM OMGEVINGSTECHNOLOGIE

VTT Group structure 2012

V T T Technical Research Centre of Finland

(State-owned research centre under the domain of the Ministry of Employment and the Economy)

R&D
- Research personnel
- Research resources
- Project execution
- Competence development

Group Services
- Support functions

Strategic Research
- Self-financed and jointly funded research

Business Development
- Strategic planning and international operations
- New business development
- Technology and business information management
- Patents

Business Solutions
- Management of customer accounts
- Contract research
- Technology licensing as a part of contract research sales

Separation of economic and non-economic activities.

VTT Expert Services Ltd
- Specialist reports and assessments
- Certification and approval services
- Testing. inspection and calibration

Labtium Ltd

Enas Ltd

VTT Memsfab Ltd
- Contract manufacturing of micro- and nano-electronic materials and devices

VTT Ventures Ltd
- Management of spin-offs

VTT International Ltd
- Administration and development of international joint ventures and contact points

VTT Brasil LTDA

Biorefining solutions for the Brazilian market:
- Wood and fibre processing
- Biotechnical processing
- Energy production

VTT Expert Services Ltd – Business areas

KEY FIGURES

- Turnover 22 MEUR
- Employees 220
- Income from abroad 13 %
- Customers 2500, mainly domestic companies
- 45 % from real estate & construction
- 15 000 assignments

Certification and Product Approvals

Building Products and Systems

Structural performance and safety

Electrotechnical, Electronic and Healthcare Products

Construction Consultations and Real Estate Markets

Fire Safety

Analytical expert services

VTT Expert Services Ltd, Electrotechnical, electronic and healthcare products

Electronics reliability

- Physical quality of products, expert services
- Electronics design and manufacturing processes, consulting
- Definition of test requirements and design of test programs (product testing, reliability testing)
- Failure and reliability analyses of electronic products
- EMC measurements and consulting

Testing and inspection

- Planning of tests during product development and test services
- Environmental testing - temperature, humidity, tightness (dust, water), mechanical and corrosion – radiation, LOCA at VTT also
- Calibration of speed measurement radars

Testing and certification of Ex equipment

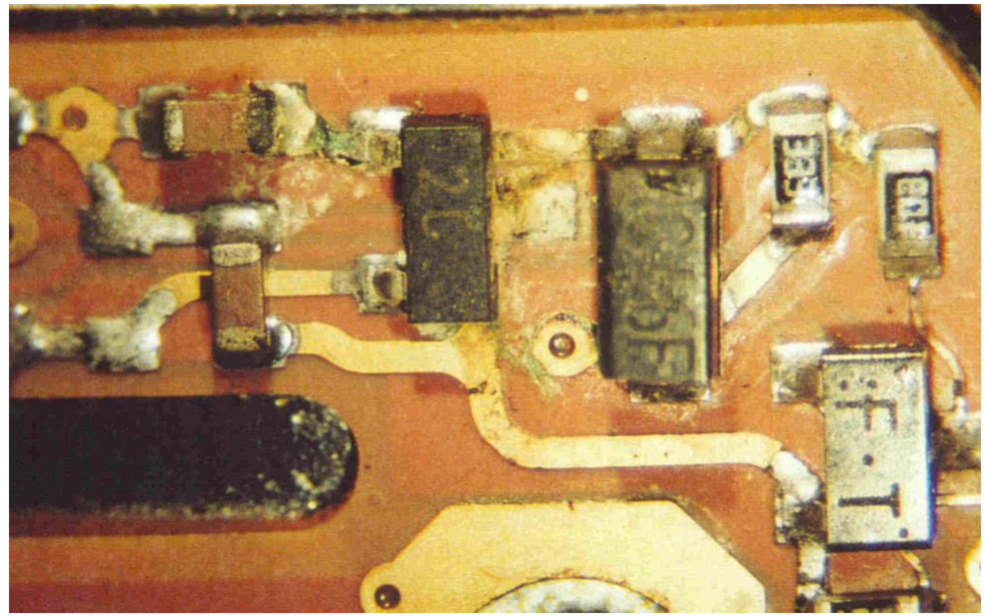
- IECEx Certification
- ATEX Notified Body
- Ex-training

VTT EXPERT SERVICES OY

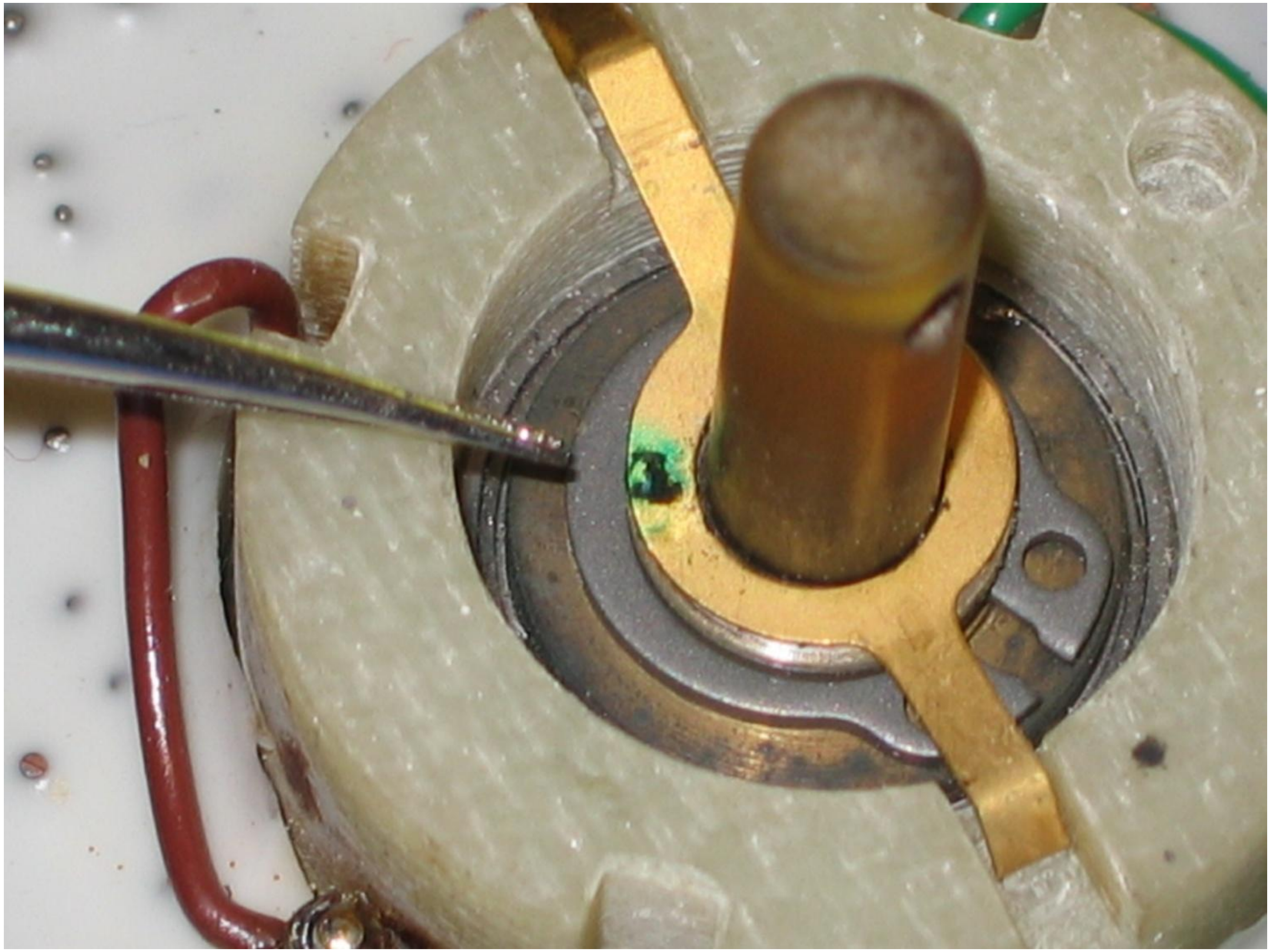
FHI PLATFORM OMGEVINGSTECHNOLOGIE

Electronics reliability

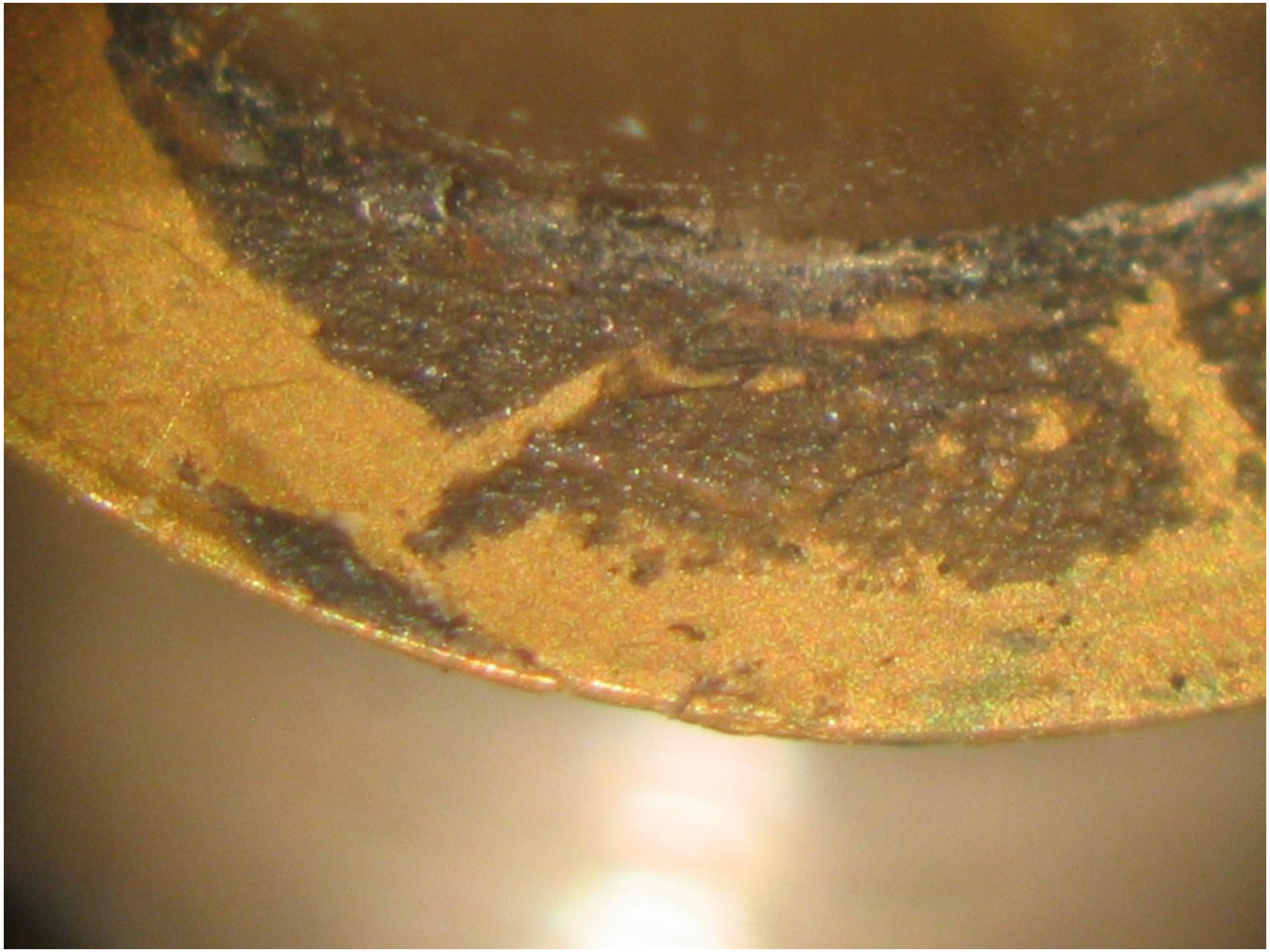
- Reliability evaluation
- Accelerated stress testing
- Accelerated life-tests
- Test planning
- Failure analysis
- Standardisation
  TC56, SC45A



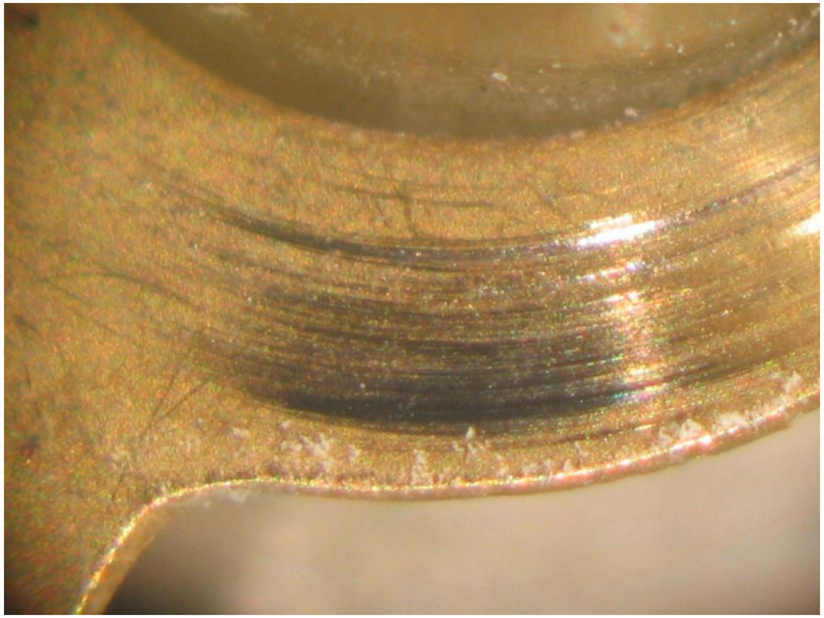
Corrosion on a mobile phone PCB

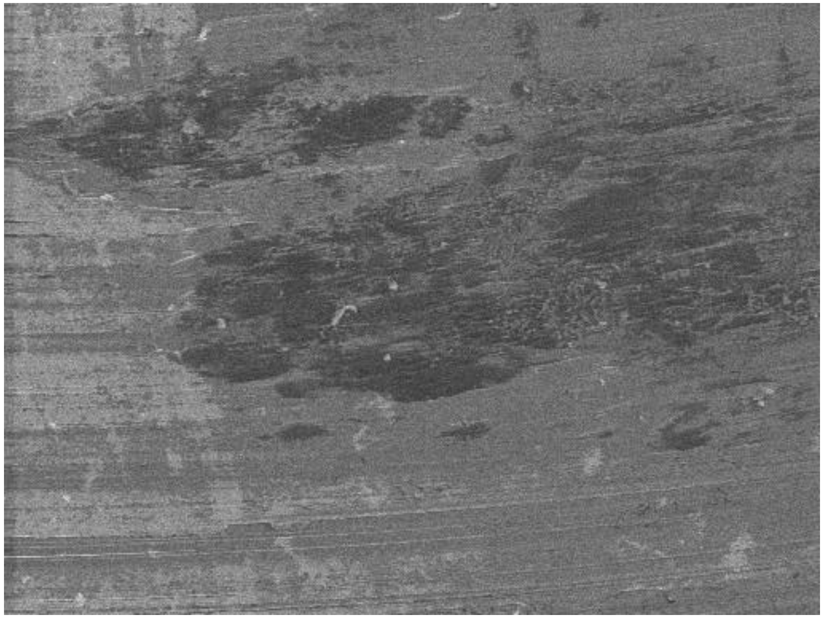


Corrosion on position transmitter contact

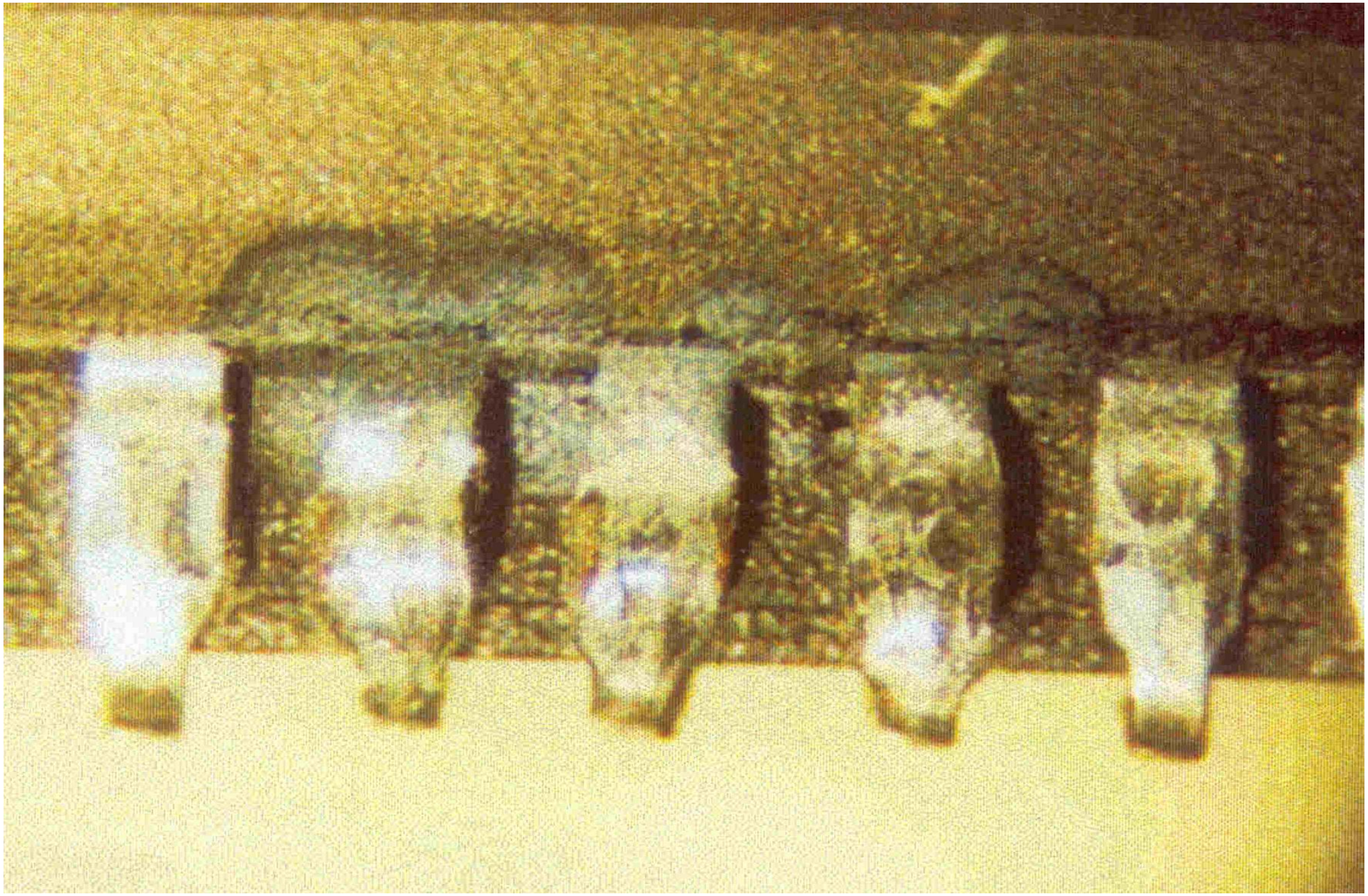


Corrosion products and other impurities on the contact surface (after 25 years of operation)

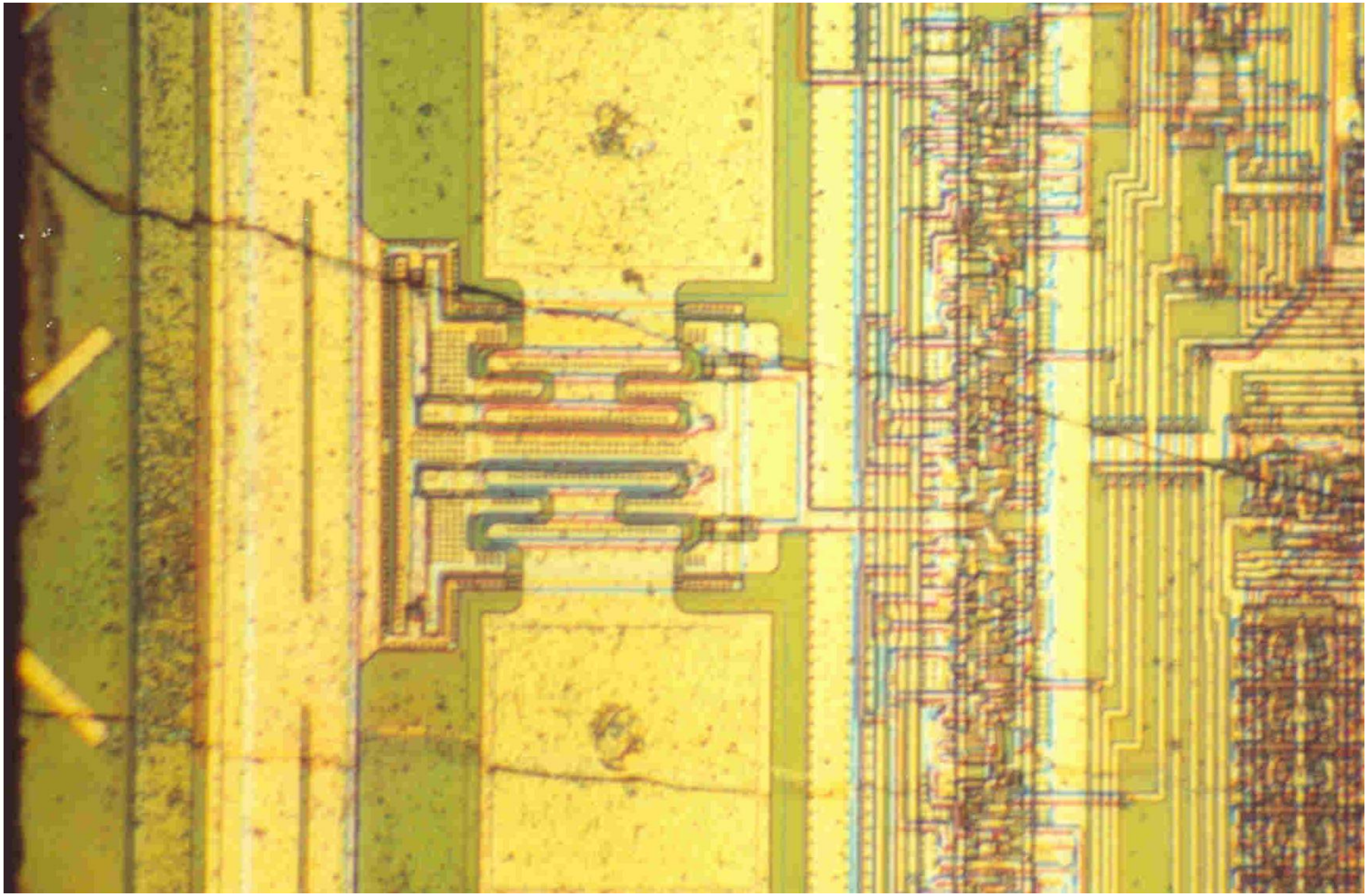




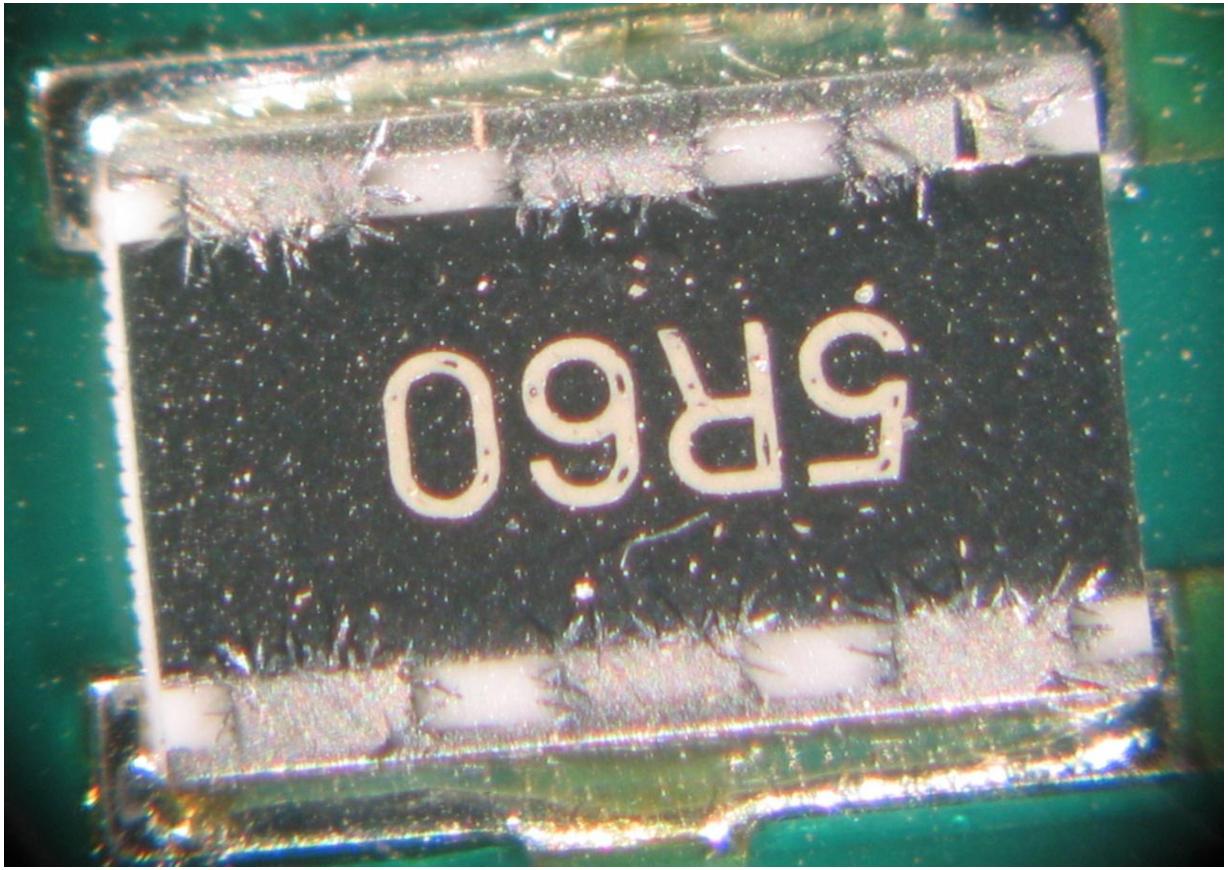
Wear of contact surface – on the right: light areas gold, grey areas nickel and dark areas copper



Corrosion of IC external leads

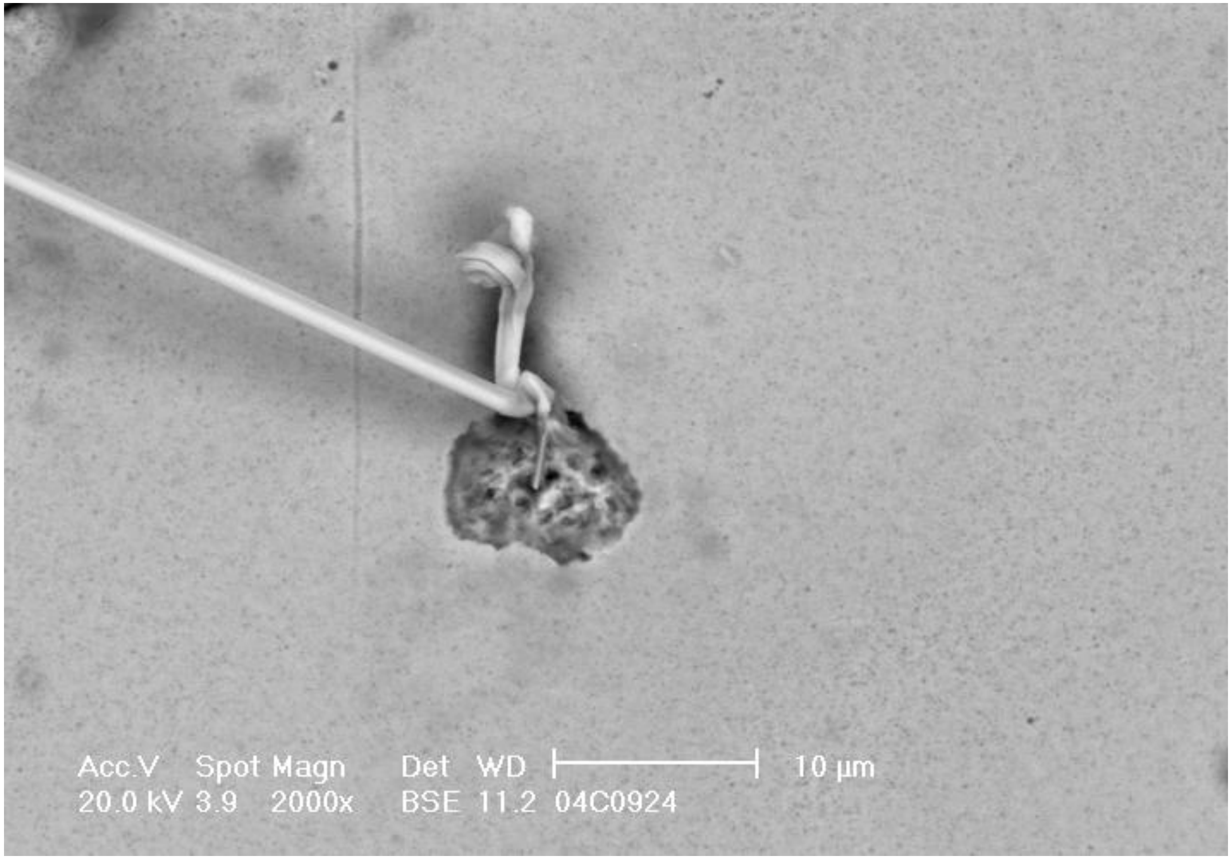


Cracks on an plastic encapsulated IC



Silver dendrites chip resistor end contacts

Origin of zinc whisker



A test for zinc whiskers:
- 150 ºC 168 h vs.
the standard 85 ºC 85 %RH for 2000h is better
(Masters thesis R. Riihiaho. Testing of whisker growth On zinc coatings, TUT 2011)

Qualification of equipment and components for very long use – We need to know / find out:

- The life cycle environmental and electrical stresses: temperature (and variations), humidity, contaminants, vibration, radiation, EMC etc. – accident conditions included or not?
- Effects of these stresses on I&C equipment and components, parts and materials (models – acceleration for testing, mitigation for use)
- Test methods – environmental, life, radiation, LOCA etc.
- Field experience (if available)
- Theoretical modelling and analysis

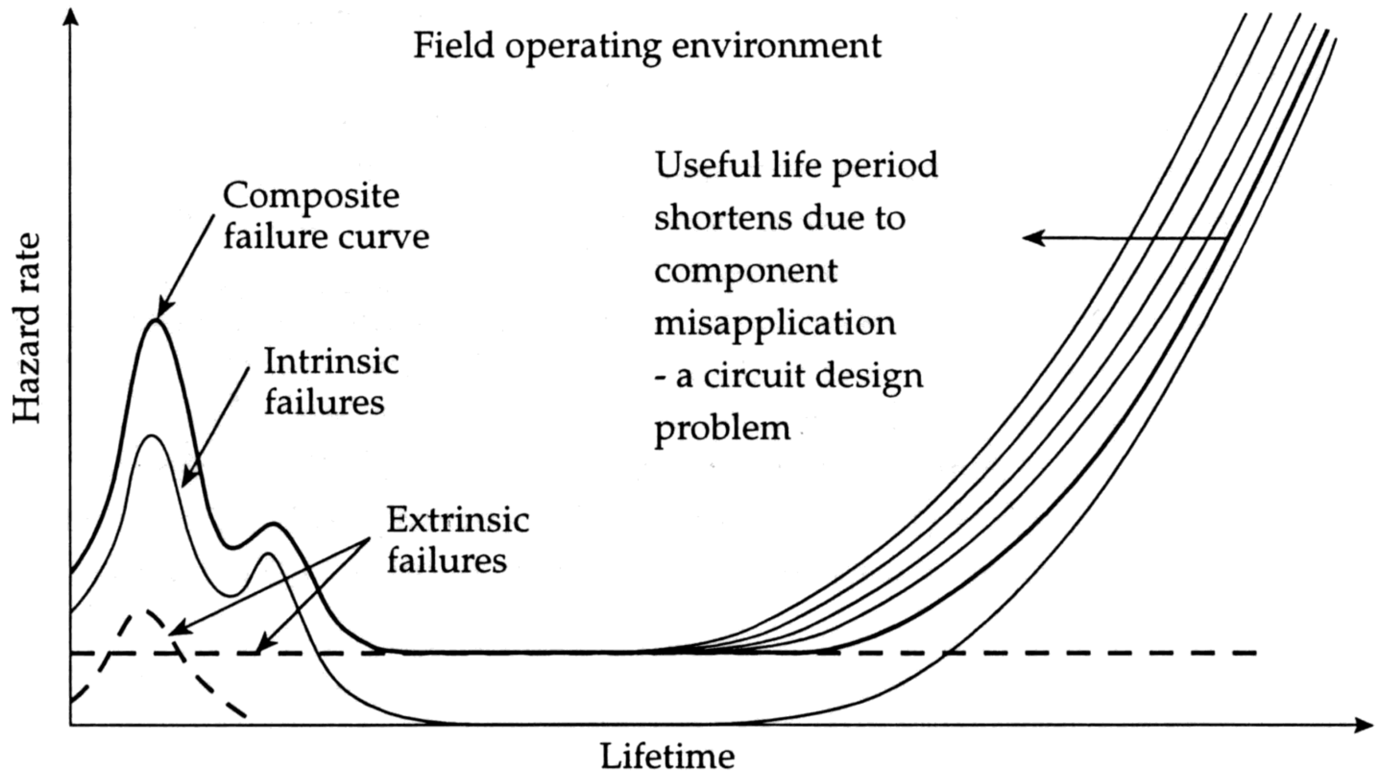
In the nuclear field:

- Standards and for example guides given by the Radiation Authority for NPP use emphasise both type testing, analysis and use experience
- Qualified life or qualified condition, on-going qualification / condition monitoring

-> Participating in standards development, for example IEC SC45A, WG A10 is very valuable

Life testing

- Simulation of product lifetime
    - transport
    - storage
    - installation
    - operation
- Purpose to find
    - λ, MTTF
    - failure mechanisms



Evaluation of relay ageing

Purpose of the study

- To evaluate relay aging and to get an estimate of their usable lifetime before the onset of any failures or degradation

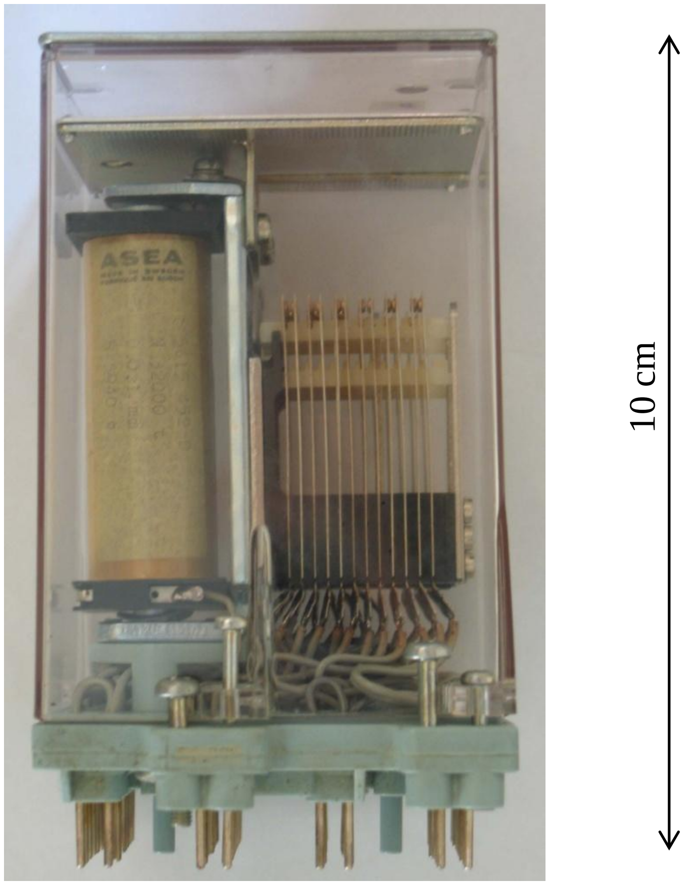
In-service measurements

- About 40 relays were chosen to be evaluated/measured at TVO 1 and TVO 2 in 1999, 2000, 2002 (TVO1), 2003 and 2004 (TVO2) and 2012 (TVO 1)
- The plants had started in 1978 and 1980

Life testing (2002-2004)

- Step stress test,
- life tests of RXMA and RXMM relays

Example of the relays, RXMA 2 RK211 189-AN:



- 110 V
- 10 NO and 5 NC contacts
- 5 A
- Environment:
  - T_A=20 °C, RH = 50 %
  - inside cabinet: 40 °C, RH->20 %

Acceleration factor

In life testing a need to estimate acceleration factors exist for:

- Temperature
- Change of temperature
- Humidity
- Mechanical stress
- Other considerations

Temperature

- Arrhenius:

$$A = t_{ref}/t_{test} = e^{[E_{A}/k * (1/Tref - 1/Ttest)]}$$

- Activation energies, problems:
  - depend on failure mechanism
  - not always known
  - multiple failure mechanisms exist

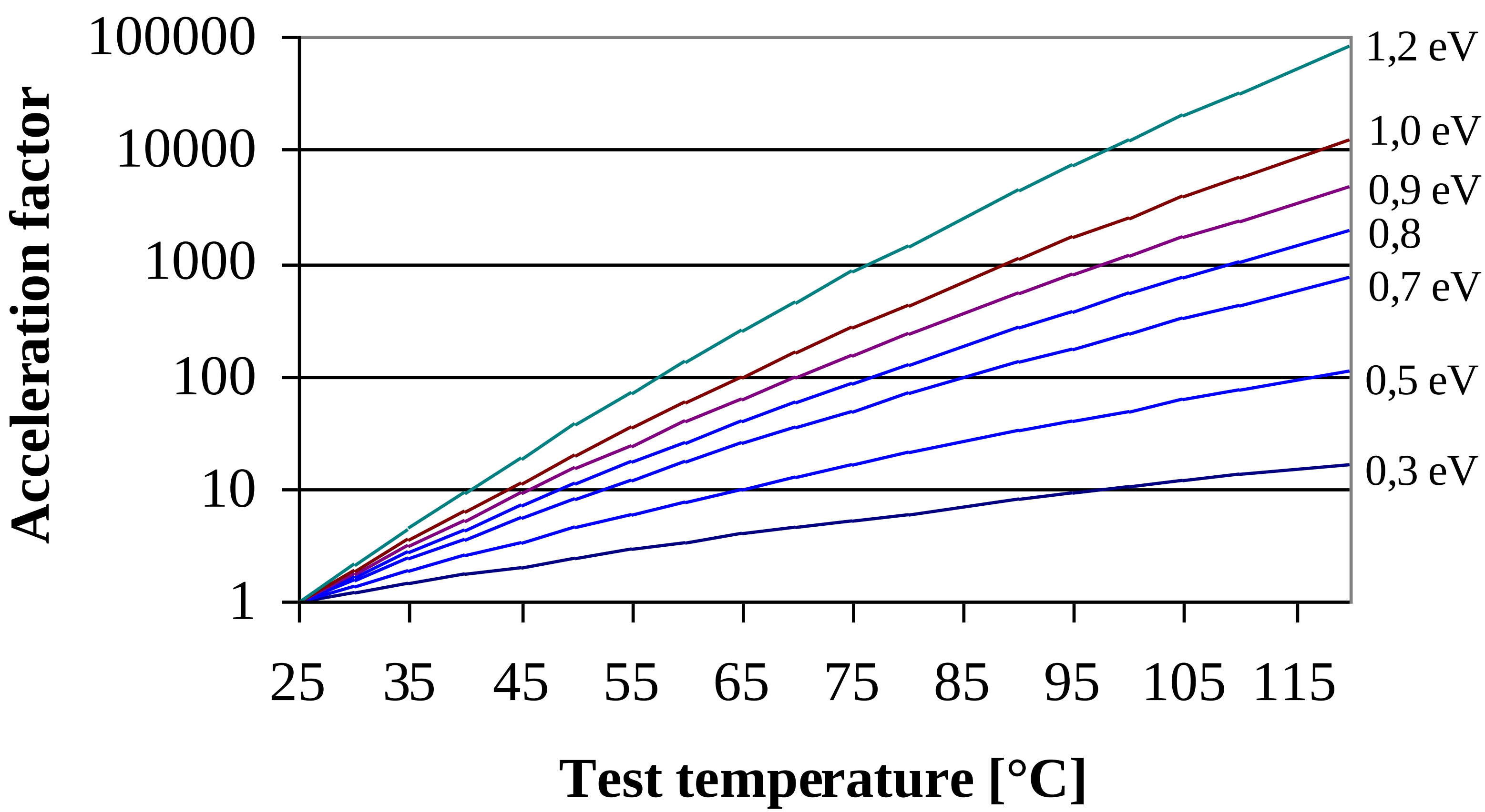
Activation energies

Failure mechanism (semiconductor devices)	Activation energy, E_A [eV]
▪ Ionic contamination	1,0
▪ Dielectric breakdown (TDDB)	0,2 - 0,35 (0,3)
▪ Hot carrier trapping in oxide	-0,06
▪ Electromigration	0,5
▪ Contact electromigration	0,9
(Al at sidewall)	0,8 - 1,4
▪ Contact metal migration through barrier layer	1,8
▪ Au-Al intermetallic growth	1,0
▪ Corrosion, electrolytic	0,79 - 0,9

Failure mechanisms for other components, parts, materials etc.:

- Many polymers: 0,75…1,6; Delrin, Arnite: about 1,0…1,05 eV for tensile strength
- Swedish SKI report: 0,8 eV recommend if no better info exists

Effect of activation energy on acceleration factor



Acceleration factors, continued

Change of temperature

The acceleration factor is made of two factors ($n \geq 1$):

$$A = \frac{cycles/day_{test}}{cycles/day_{use}} \; x \left(\frac{\Delta t_{test}}{\Delta t_{use}} \right)^{n}$$

Acceleration factors, continued
Humidity

- Model presented by Peck (1987) for plastic encapsulated integrated circuits

$$A = t_{ref}/t_{test} = (RH_{test}/RH_{ref})^3 * e^{[E_A/K * (1/T_{ref} - 1/T_{test})]}$$

where the activation energy for corrosion is 0,9 eV.

Acceleration factors, continued

Mechanical stress

MIL-STD810E, gives for sinusoidal and random vibration respectively:

$$g\ (\mathrm{ref}) / g\ (\mathrm{test}) = [\ T\ (\mathrm{test}) / T\ (\mathrm{ref})\ ]^{1/6}$$

where g is the sinusoidal level of vibration (peak acceleration, g), and

$$W\ (\mathrm{ref}) / W\ (\mathrm{test}) = [\ T\ (\mathrm{test}) / T\ (\mathrm{ref})\ ]^{1/4}$$

where W is the random vibration level (acceleration power spectral density g^2/Hz)

Acceleration factors, continued

Other considerations:

- time compression - ON/OFF cycles (length/frequency)
- EMI, EOS

In-service study of relays in a nuclear power plant

Conditions

- Controlled environment for temperature and humidity (20 ºC, 50 % RH but inside the cabinet + 35…40 ºC and less humidity, no vibration, no radiation)

Goals

- Detection of even minor changes or deterioration
- The effect of the spacer material (“Delrin” vs. “Arnite”)
  - In addition to relays, electrolytic capacitors, electronic boards and backplane connections are under study simultaneously

Relay failures

- The relay coil
- The relay contacts
- Auxiliary components: contact spacers, plugs, sockets etc.
- Zinc plated parts grow whiskers

Aging mechanisms

Contacts:

- Contact corrosion, oxidation and / or contamination
- Contact welding or pitting due to excessive current
- Coil burn-out or insulation material degradation
- Chemical attack

Spring materials – fatigue (incorrect material)?

Spacers:

- degradation of the material at high temperature (loss of plasticiser)

Examples of degraded spacers and oxidised contacts in pictures 1-3

Relay measurements

- Contact resistance, coil resistance (using a milliohm meter and a multimeter respectively), switching parameters

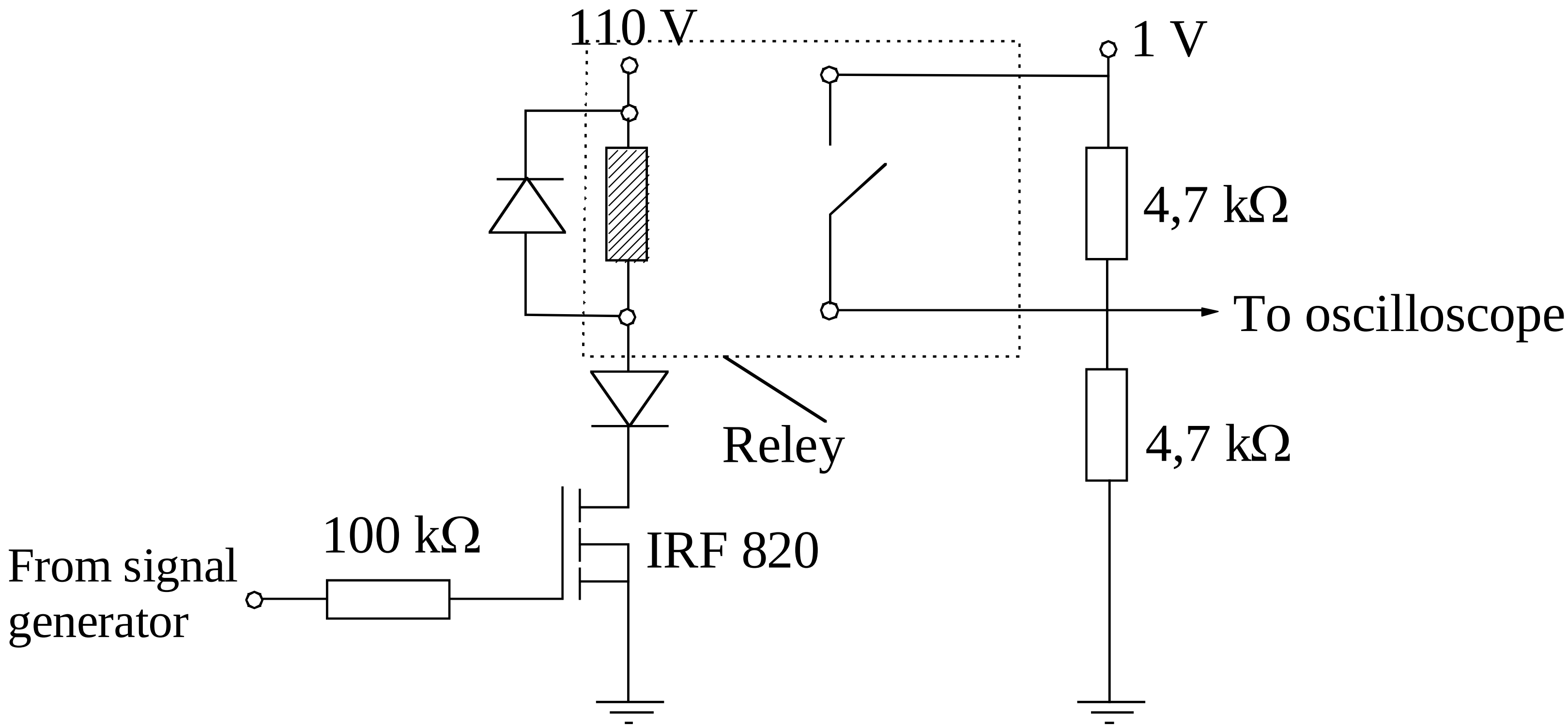


Figure 1. Relay measurement setup.

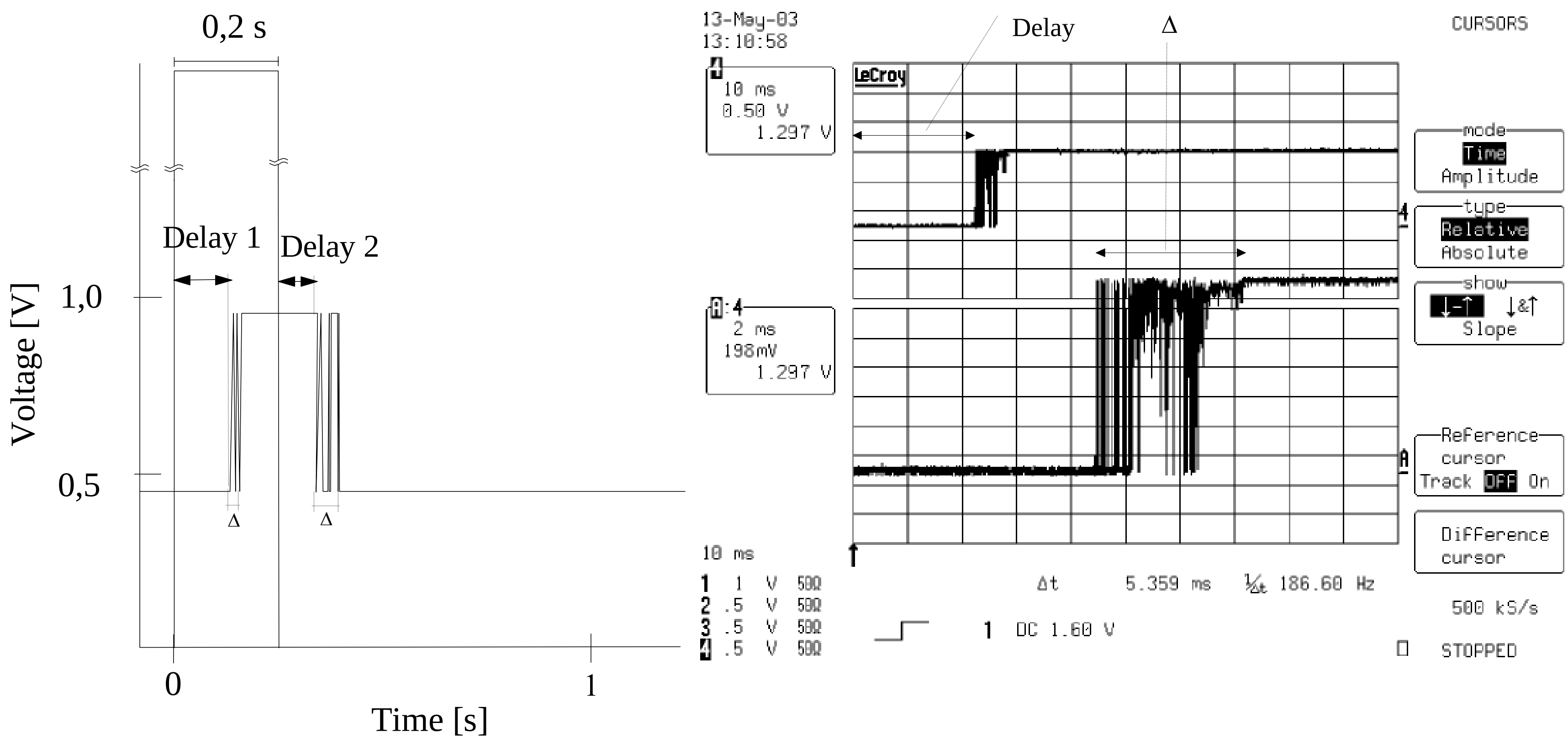


Figure 2. Output waveform

Results, summary

	RK211188-AN (all released in plant)	RK211189-AN (NO, all energised in plant)	RK211189-AN (NC)	RK211049-AN	RK211074-AN (NO)	RK211074-AN (NC)
Delay 1	-	+	+	+	-	-
Δ1	+/-	-	-	+/-	+	+/-
Delay 2	+/-	+	+/-	-	+/-	+/-
Δ2	+/-	+/-	+	+/-	+/-	+
Contact resistance	++	+/-[1)]	+/-[1)]	+[1)]	+[1)]	+/-[1)]
Coil resistance [3)]	+/-	+		+	+	

Notes:

\+ minor increase, ++ increased +++ large increase, +/- no significant change, - minor decrease, -- decreased -- large decrease

1) mixed - (RK211189, NO: 2 +, 1 -, NC: 1 +, 2 -, RK211049: 4+, 1 -, RK211074, NO: 3 +, 1 -, NC: 2 +, 2 -) – for some of the relays this is easily explained based on the actual state of the contact: for an open contact there is an increase and for a closed contact decrease

3) maximum of 10 % change for some relays of the lot

Examples of results

Relay type RK211188-AN, normally open contacts:

Year	Relay code	Delay1*),	Δ[ms]	Delay 2*),	Δ[ms]	Coil resis-tance [kΩ]	Contact resis-tance [mΩ]	Origin	Condition
1999	RE17.D2.125	22,5	1,3	18,7	3,7	4,06	40,6	Original	Released
2004		21,1	2,9	19,6	3,8	4,07	90,0		
1999	RE17.D17.325	21,7	1,7	16,7	9,9	3,90	40,1	Original	Released
2004		20,2	2,3	18,4	10,3	3,88	60,0		
1999	RS17.D2.113	21,2	2,4	17,1	7,0	4,04	33,7	Original	Released
2003		21,9	2,6	19,0	8,0	4,07	36,9		
1999	RS17.D17.125	21,8	1,4	20,7	5,9	4,02	35,3	Original	Released
2004		20,2	1,6	19,7	7,1	4,04	43,8		
1999	RS18.D22.149	22,3	1,1	24,2	4,3	3,95	42,0	Original	Released
2004		20,8	1,2	22,8	4,6	3,93	61,7		

(Original: in use from the start of the plant, OL 1, 1977-)

No significant changes in the delays or oscillation, contact resistance has increased (except for some relays that had been operated more than few times)

Examples, cont.

RK211188-AN	Delay 1*), Δ[ms]		Delay 2*), Δ[ms]		Coil resistance [kΩ]	Contact resistance [mΩ]
Mean, 1999	23,2	1,6	15,0	10,4	3,9	34,8
Mean, 2012	22,9	2,4	16,9	10,6	4,0	35,5

Original relays, released at plant, NO contacts.

Examples, cont.

RK211189-AN	Delay1[*)], Δ[ms]		Delay 2[*)], Δ[ms]		Coil resistance [kΩ]	Contact resistance [mΩ]
mean 1999 (NO contacts)	31,4	1,7	23,4	2,5	6,4	38,9
mean 2012 (NO contacts)	32,8	1,6	23,7	2,6	6,5	39,6
mean 1999 (NC contacts)	17,5	6,4	32,2	13,5		157,4[*)]
mean 2012 (NC contacts)	19,0	5,4	31,2	15,4		53,1

As the relays were activated, the NO contacts were actually closed and NC contacts open.

[*)]The relay had been operated during outages (testing) and therefore the contact resistance had decreased.

Examples, cont.

Relay type RK 211 074-AN, activated

RK211074-AN	Delay 1, Δ[ms]		Delay 2, Δ[ms]		Coil resistance [kΩ]	Contact resistance [mΩ]
- NO	33,2	4,5	54,4	7,3	10,231 kΩ	37,9
- NC	19,3	4,6	93,9	14,2		70,9
- NO	29,1	12,3	50,3	10,4	9,64	166,9
- NC	11,7	9,0	80,8	29,5		117,9

The delay when activated has decreased and the delay when released has increased, contact oscillation has also increased. Contact resistance has also decreased (the relay has been operated).

Life testing

Step stress test, principle:

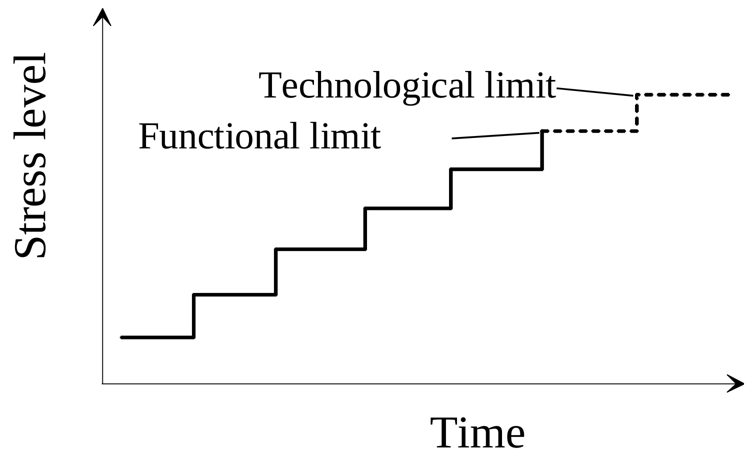
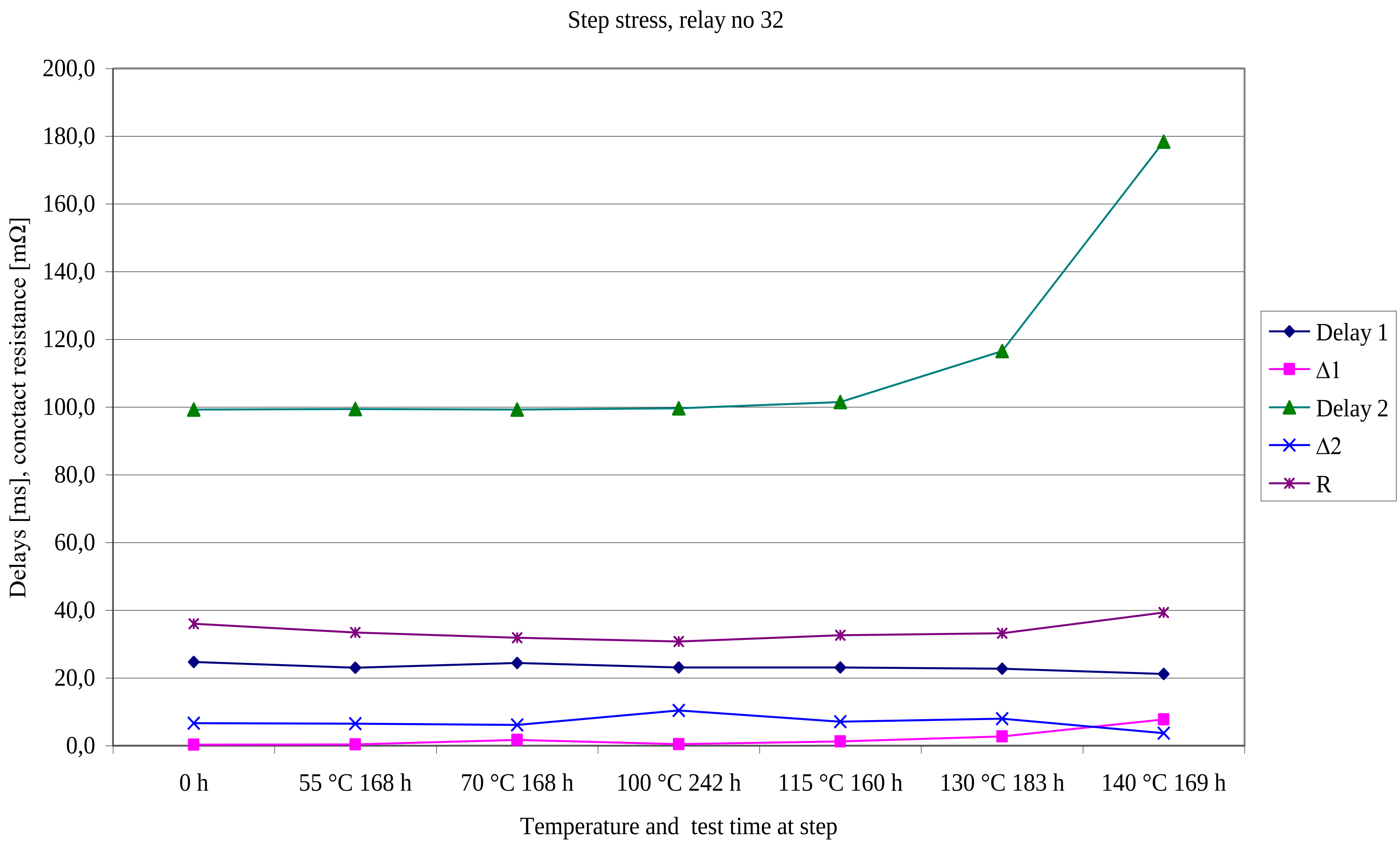


Figure Principle of step-stress testing

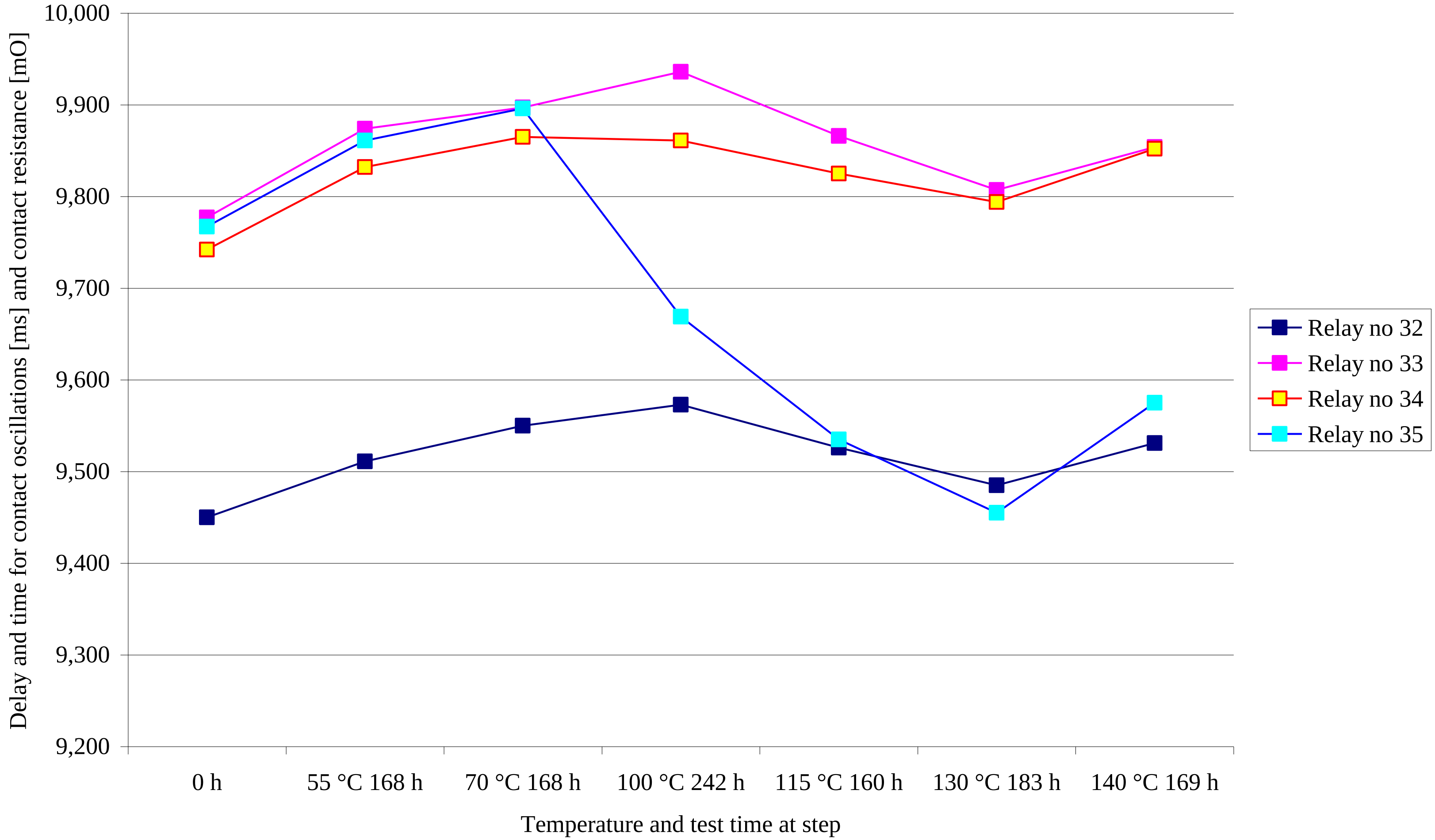
The test is continued until enough margin has been reached, all fail or irrelevant failures start to appear

Following steps were used: **55 °C for 168 h, 70 °C for 168 h, 100 °C for 242 h, 115 °C for 160 h, 130 °C for 169 h and 140 °C for 169 h**.

Step stress test results



- Figure Step stress test results for one relay



- Figure Coil resistances in step stress test.

Life test

RXMA (31), 110 V

- two relays with Arnite spacers (all other relays were with Delrin), these had been in use for 10 years on the plant, energised, relays no. 1 and 2
- two relays of same type with Delrin spacers, these had been in use for 10 years on the plant, relays no. 3 and 4 (energised), and relay no. 25 of different type had also been 10 years in use
- one new relay, no. 15
- relays that had been in use from the starting of the plants (about 25 years) and removed for life testing, relays no. 5 – 14, 16 – 24, 26 - 31, 36-41
- relays no. 39 and 40 (as 4.), not energised

RXMM type relays (9)

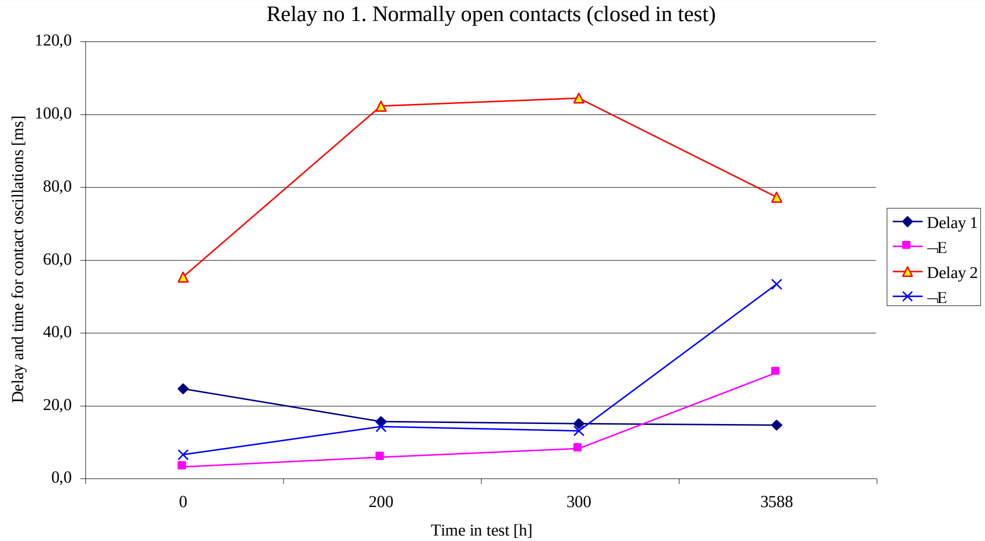
- 24 V (three RK214003-AD and three RK214005-AD relays), 110 V (three RK214003-AN relays) and 48 V relays (two RK214002-AD relays)

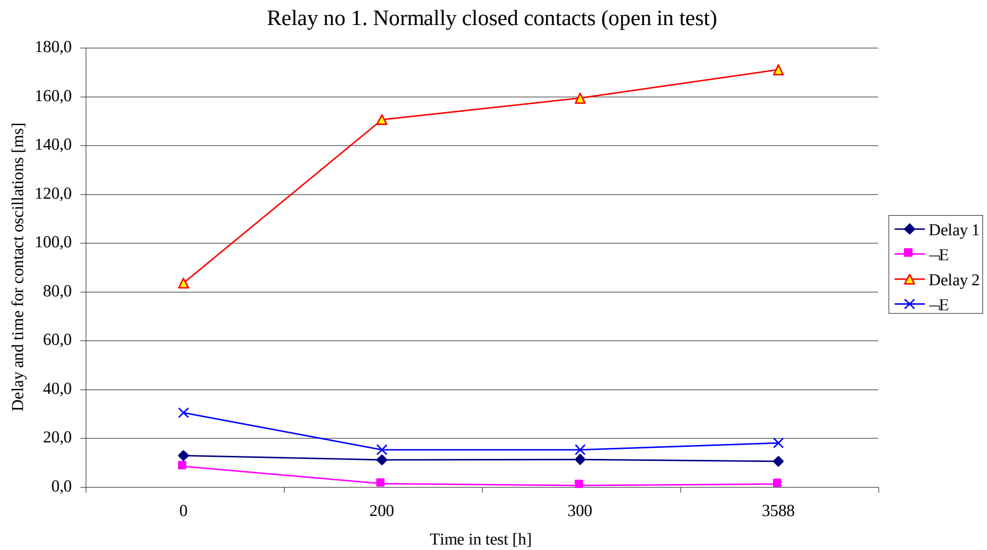
The test time 300 h and 3788 correspond about 19 and 240 (!) years respectively if an activation energy of 0,8 eV is assumed

Relay no 1 RK211074-AN	Spacer material: Arnite (10 years in plant , energised)							
	Normally open contacts (five per relay)				Normally closed contacts (two per relay)			
Time in test [h]	Delay 1	Δ1	Delay 2	Δ2	Delay 1	Δ1	Delay 2	Δ2
0	24,3	2,9	55,0	12,3	12,4	8	83,1	30
200	15,3	5,5	101,9	13,9	10,6	0,8	150,1	14,8
300	14,7	7,9	104,1	12,7	10,8	0,2	158,9	14,8
3788	14,3	28,8	76,9	53,0	10,0	0,7	170,5	17,5

	Contact resistances, mean value[mΩ]		Coil [kΩ]
	Normally open contacts	Normally closed contacts	
0	49,0	1130,0	9,657
200	106,2	115,0	9,713
300	118,6	705,5	9,534
3788	540,0	1994,5	9,531

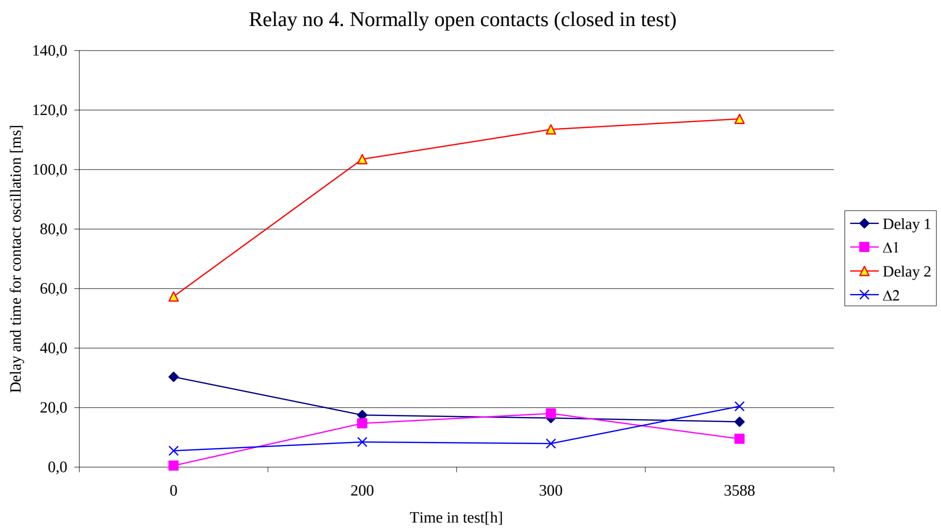
Note: The NO and NC contacts in activated relays were actually closed and open respectively


Relay no 1. Normally open contacts (closed in test)
Delay and time for contact oscillations [ms]
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0
200
300
3588
Time in test [h]
Delay 1
E
Delay 2
E


Relay no 1. Normally closed contacts (open in test)
Delay and time for contact oscillations [ms]
180,0
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0
200
300
3588
Time in test [h]
Delay 1
E
Delay 2
E

Relay no 4 RK211074-AN	Spacer material: Delrin (10 years in plant, energised)							
	Normally open contacts (five per relay)				Normally closed contacts (two per relay)			
Time in test [h]	Delay 1	Δ1	Delay 2	Δ2	Delay 1	Δ1	Delay 2	Δ2
0	30,3	0,5	57,3	5,5	21,2	5,2	72,3	5
200	17,5	14,7	103,5	8,4	14,9	0,1	137,9	4,9
300	16,5	18,0	113,5	7,9	14,7	0	155	1,6
3588	15,2	9,5	117,0	20,4	14,7	4,8	140,9	19

	Contact resistances, mean [mΩ]		Coil [kΩ]
	Normally open contacts	Normally closed contacts	
0	33,3	116,0	9,549
200	38,8	39,5	9,565
300	53,6	129,5	9,467
3588	77,0	2150,0	9,424



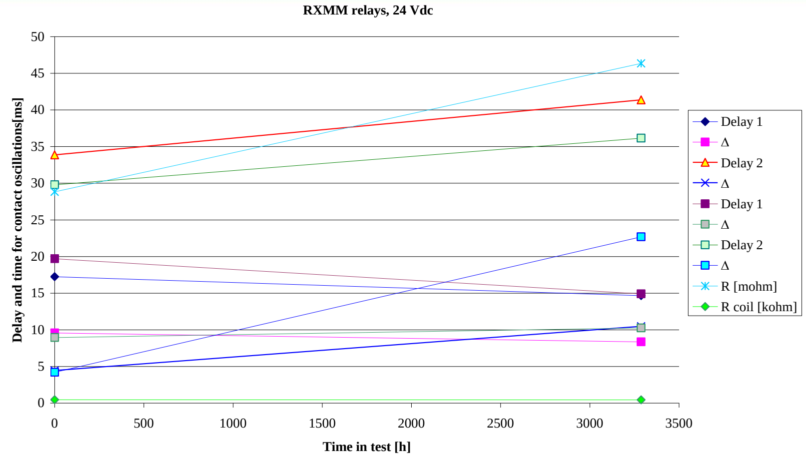


Figure 8. Average values of five 24 Vdc RXMM type relays (including mostly normally open and normally closed contacts). Test temperature 95 – 100 °C, four of the relays energised.

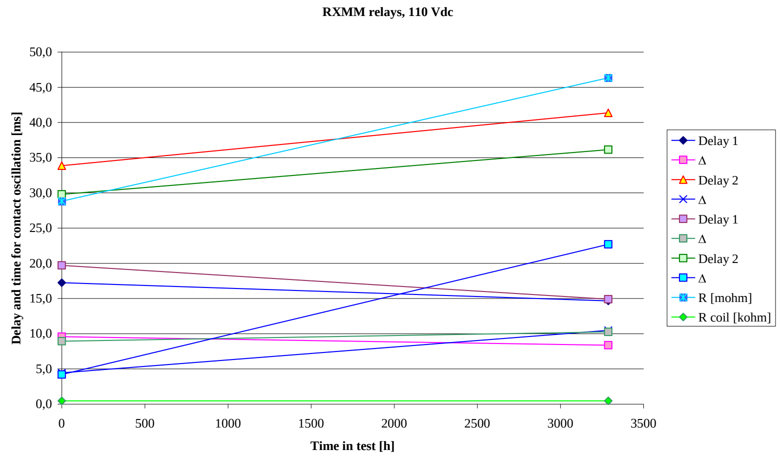


Figure 9. Average values of three 110 Vdc RXMM type relays (normally open contacts). Test temperature about 125 °C, relays energised.

In use:

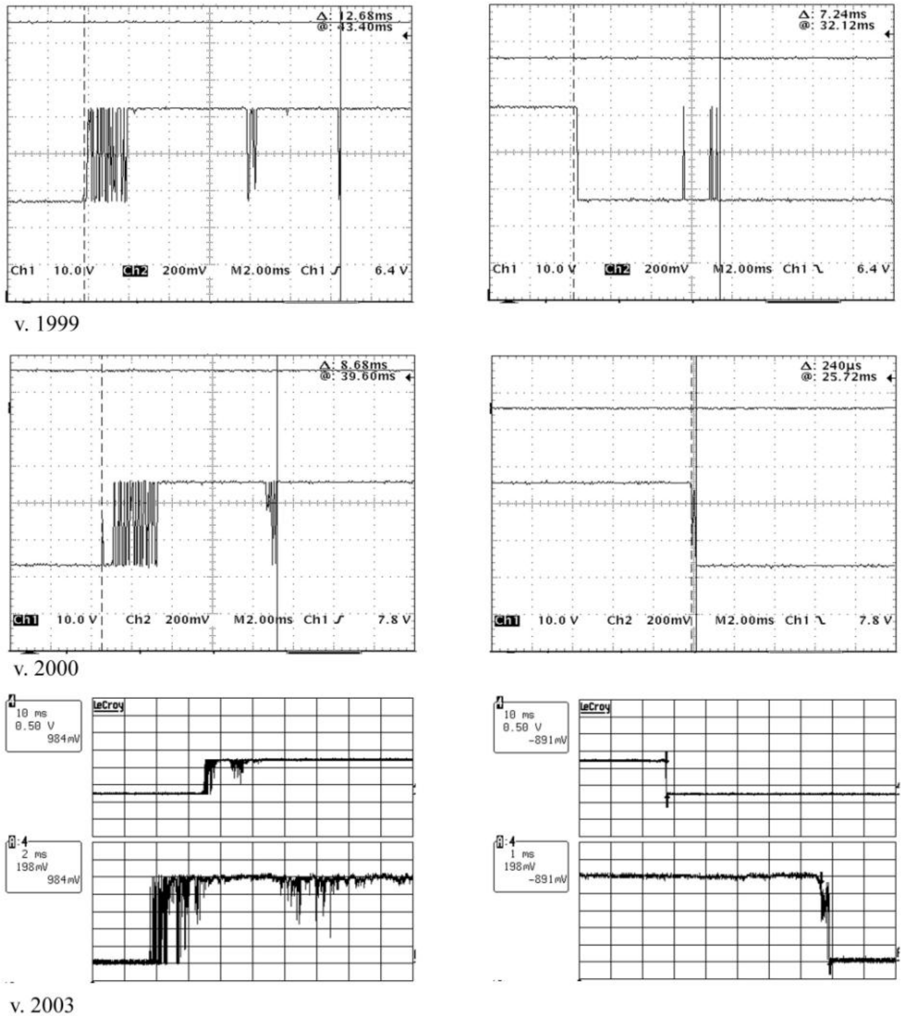
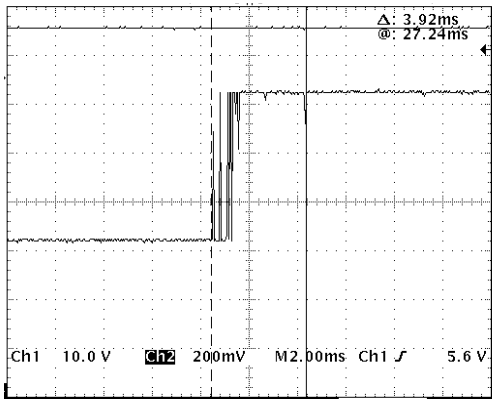
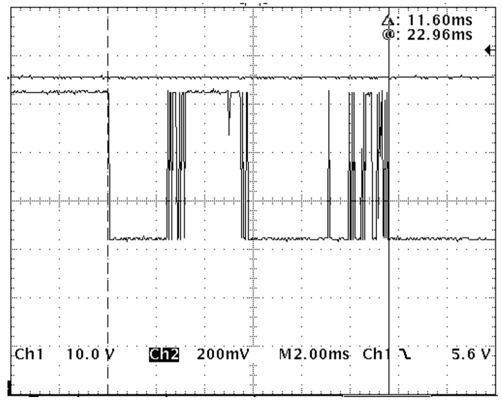


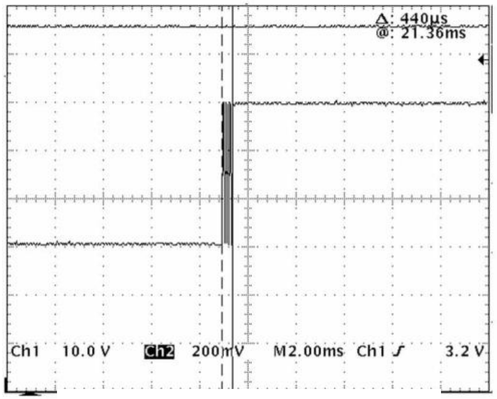
Figure 3. Output voltage waveforms for relay RK 211 189-AN (RQ3.D2.313), normally open contacts 112-111 (energised in plant). Contact resistance changed from 56,9 mΩ to 88,1 mΩ from 1999 to 2003.



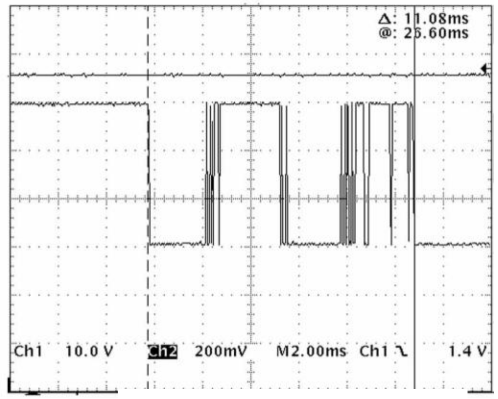
a) 1999. Relay activated



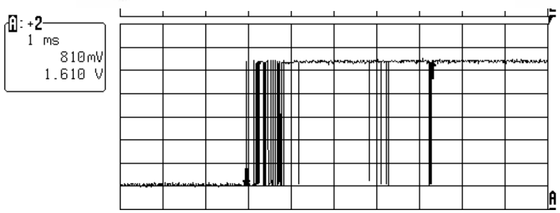
Relay released



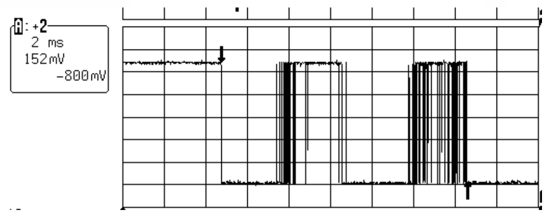
b) 2002. Relay activated



Relay released



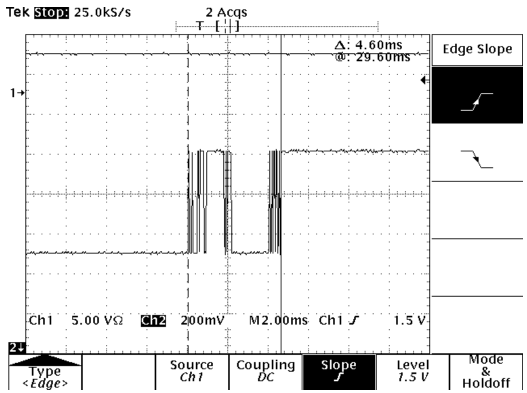
c) v. 2012. Relay activated

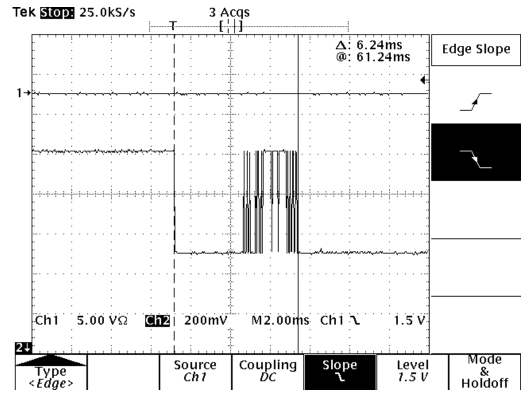


Relay released

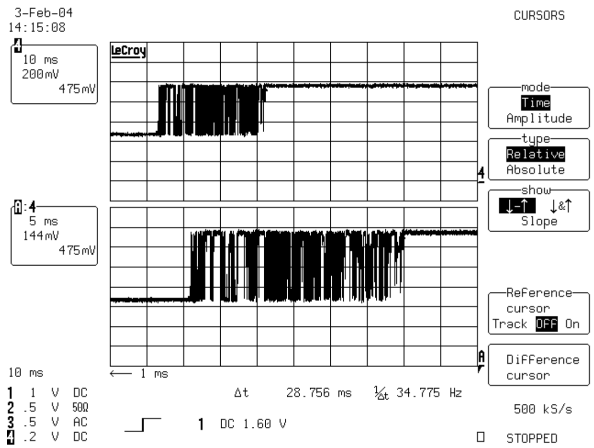
Typical output waveforms on relay type RK 21 188-AN, released on plant, NO contacts

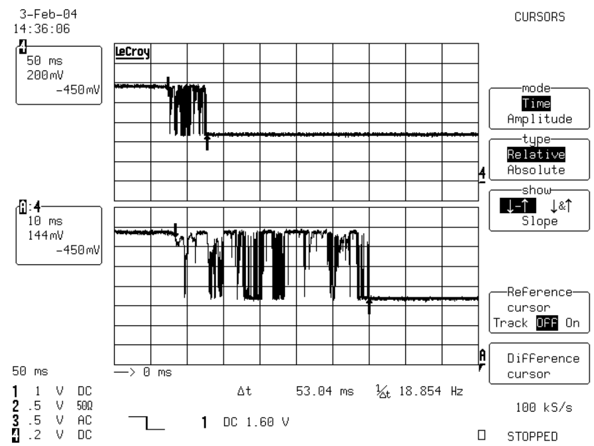
In test:





Relay no. 1, 0 h RK211074-AN (1.RR15.D2.143) NO contacts 28-12 (closed in test).

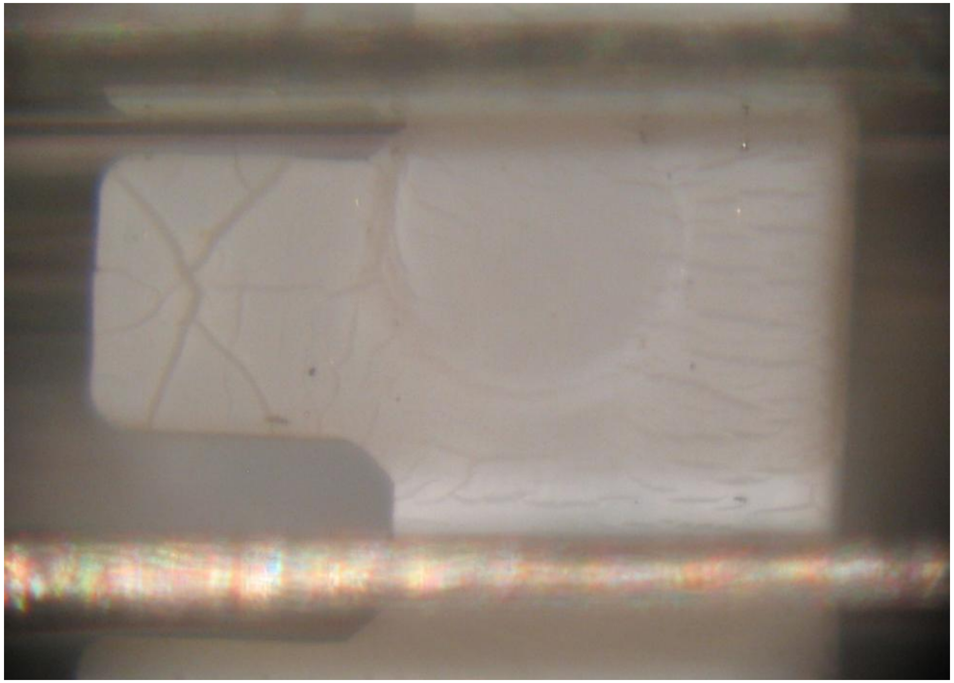




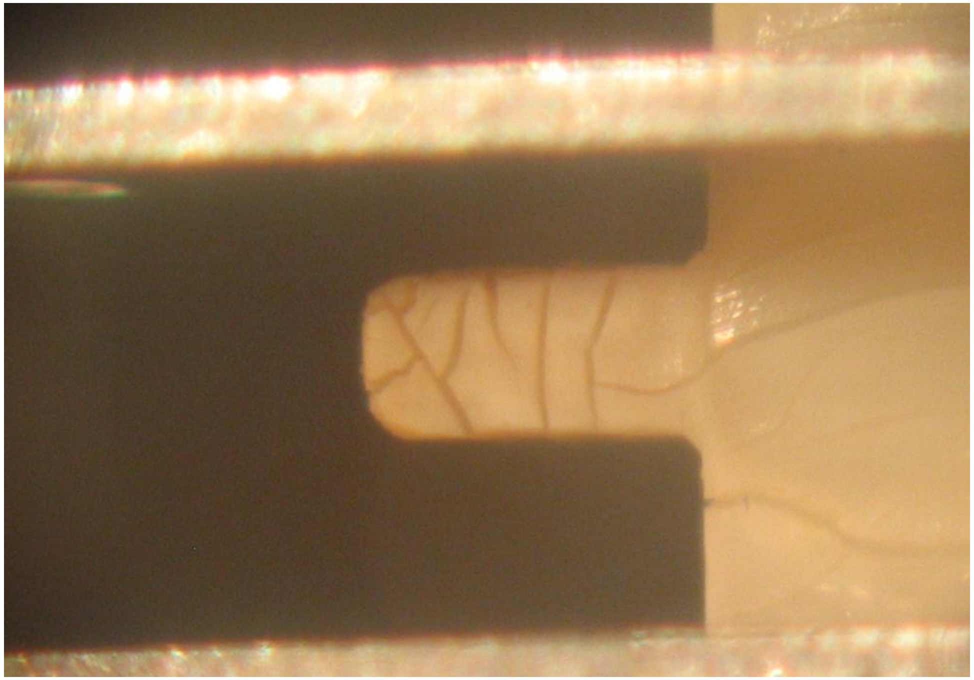
Relay no. 1, 3588 h, RK211074-AN (1.RR15.D2.143). Contact resistance changed from 39 mΩ to 65 mΩ.

The test time 3588 hours corresponds to 230 years (EA = 0,8 eV)

Pictures, examples

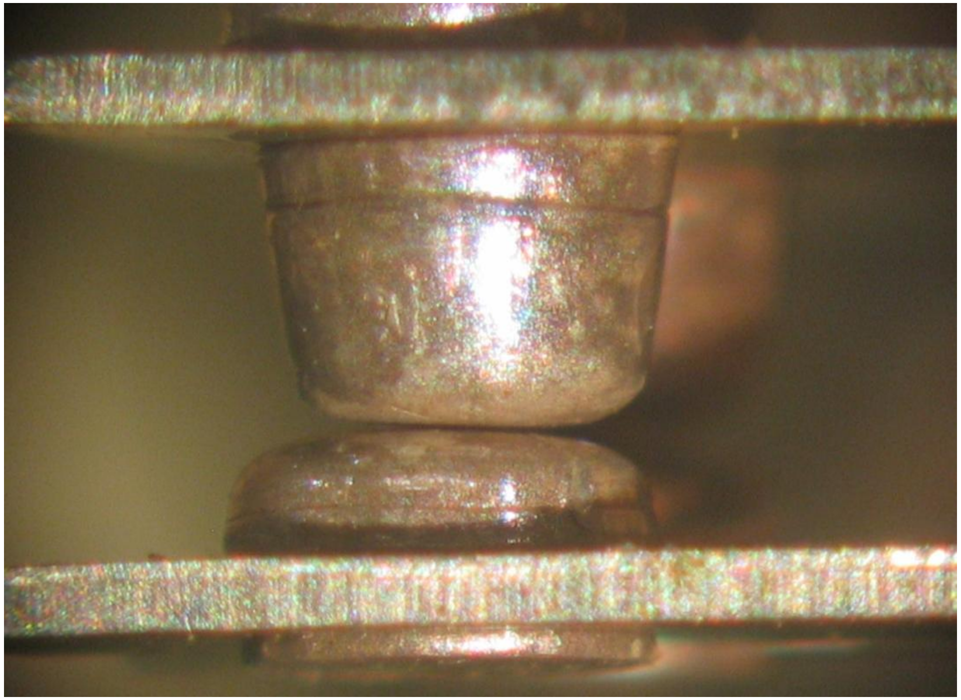


Picture 1. Degradation of relay spacer material (relay from plant, RXMA 2, RK 211189-AN).

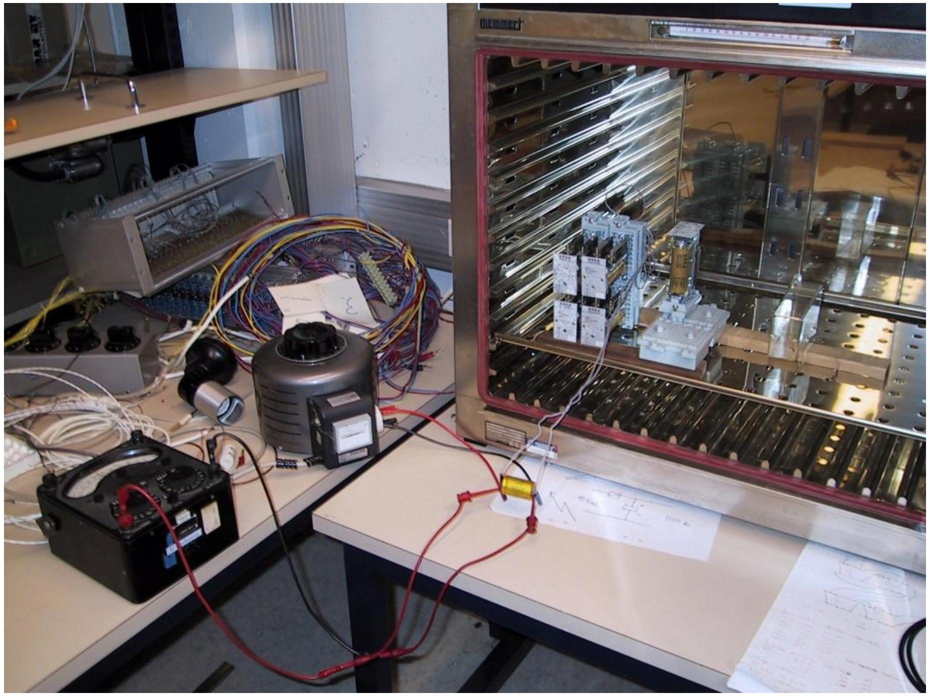


Picture 2. Similar behaviour in life test (relay no 13, RXMA 1RK211188-AN).

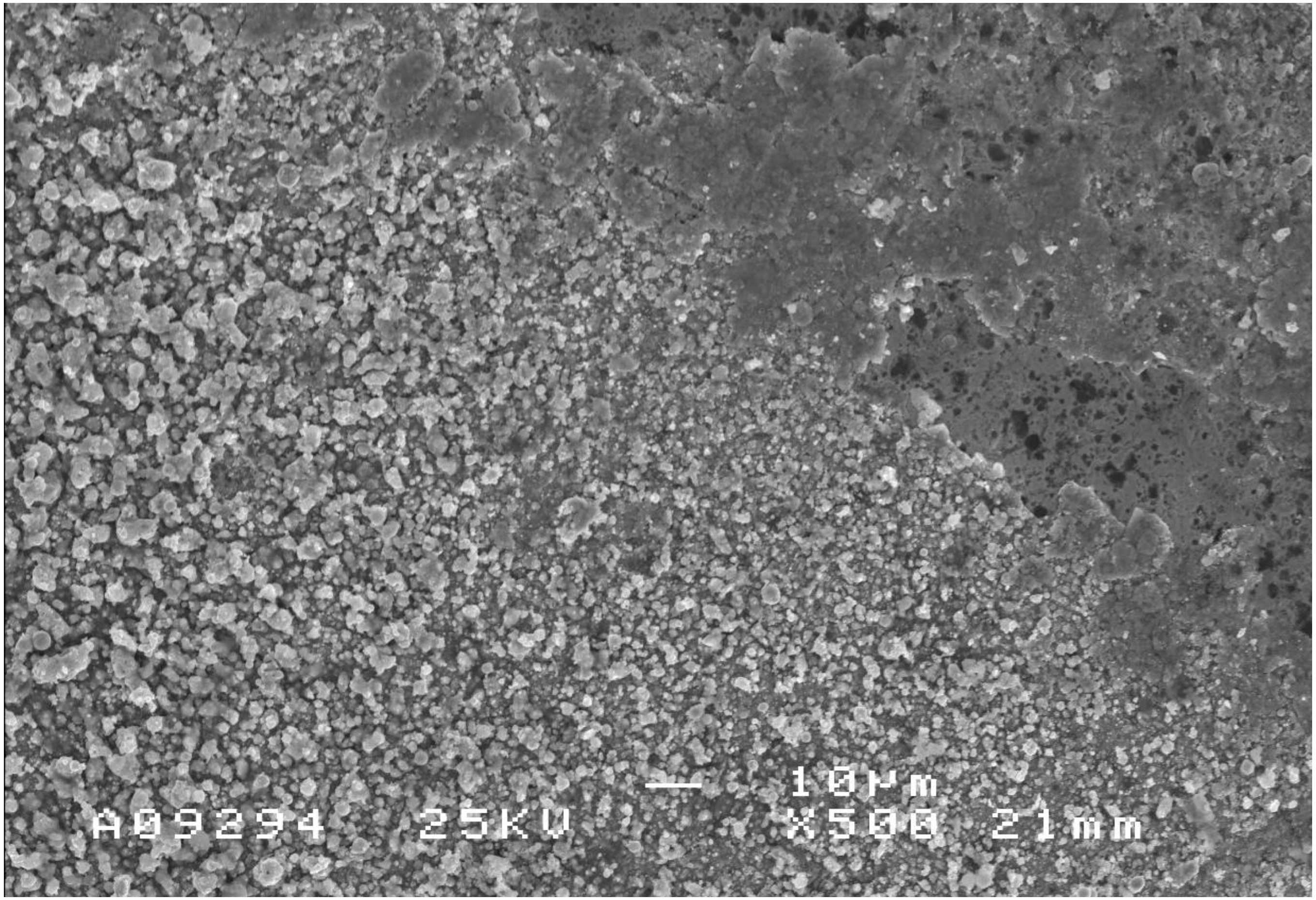
Pictures, continued



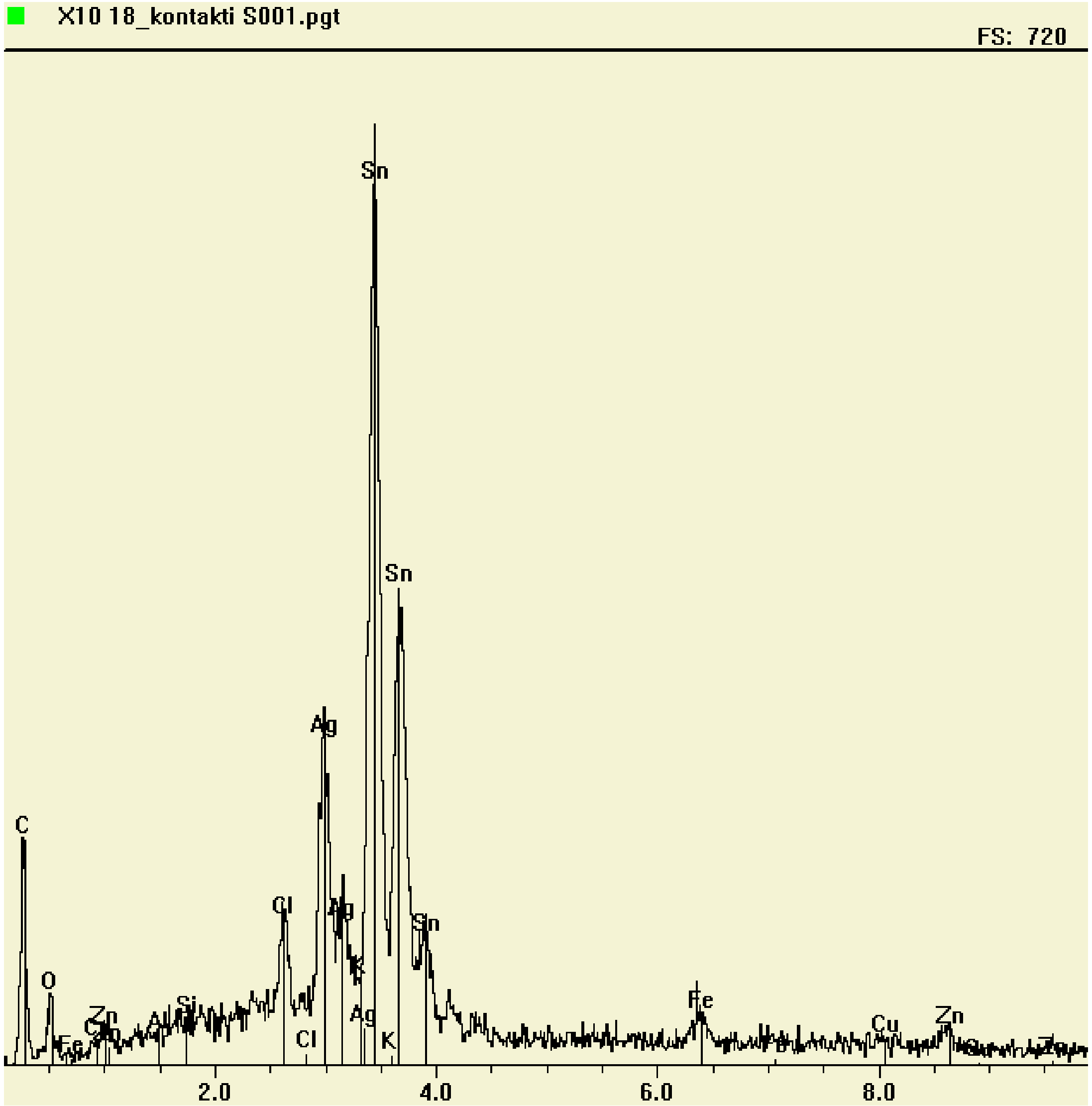
Picture 3. Oxidised relay contacts.



Picture 4. Test setup for step stress test.



SEM micrograph of the relay contact on the previous slide

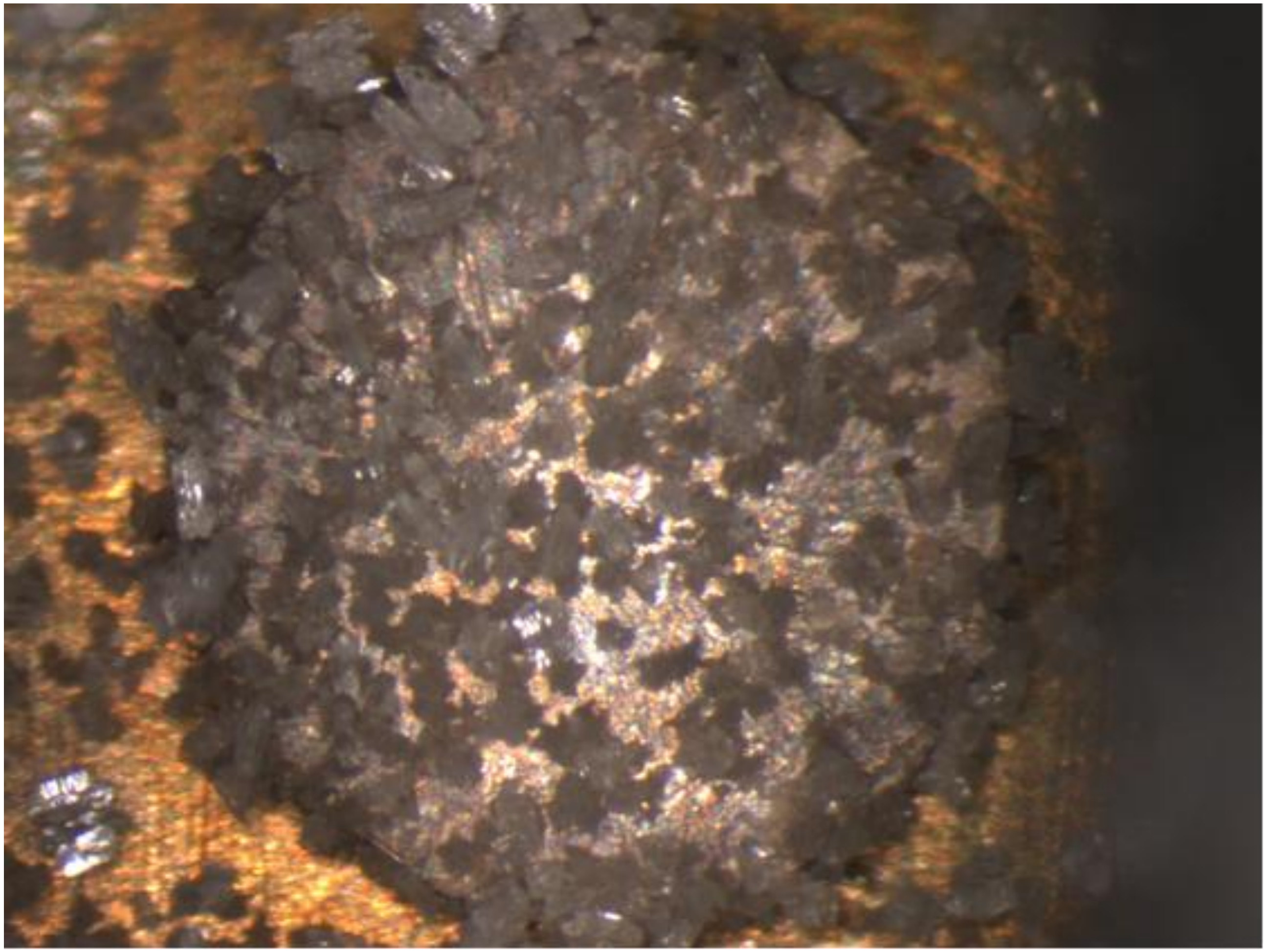

X10 18_kontakti S001.pgt
FS: 720
Sn
Sn
Ag
C
Cl
Ag
Sn
O
Zn
Fe
Si
Al
Ag
Cl
K
Fe
Cu
Zn
2.0
4.0
6.0
8.0

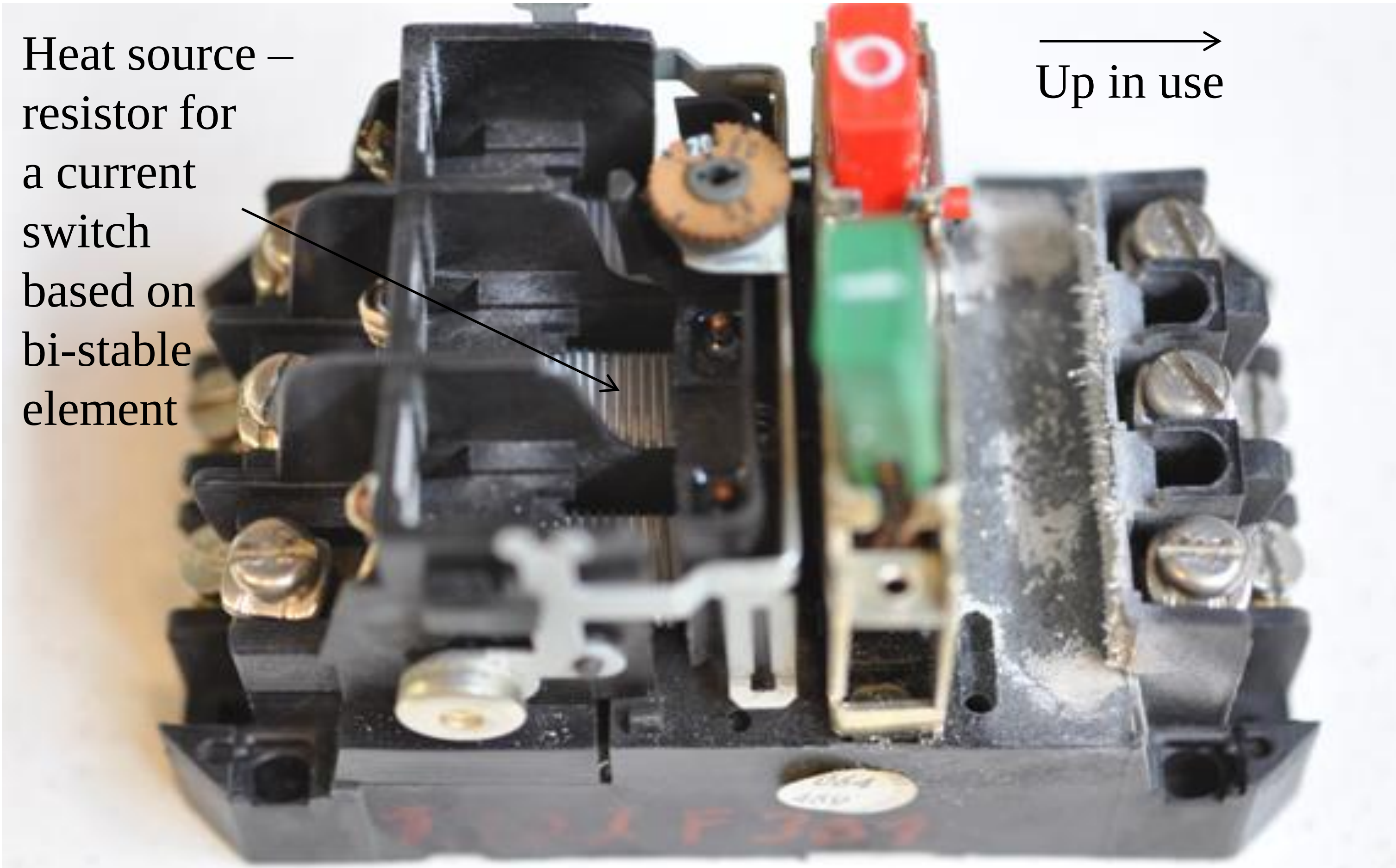
Relay performance in use – life testing, conclusion

- Minor changes were observed in thirteen years in the field – contact resistance being most sensitive (but, if the relay is operated several times, the contact resistance decreases)
- Life testing:
  - spacer degradation (material dependent) - Arnite did not show colour changes or deformation compared to Delrin
  - spring material fatigue, delay 2 (release of relay)
  - contact oxidation, chemical phenomena (impurities)

    -> increase of contact resistance, in some cases a mechanical effect (spacer deformation)
  - earliest time for replacement expected: at least 10 years

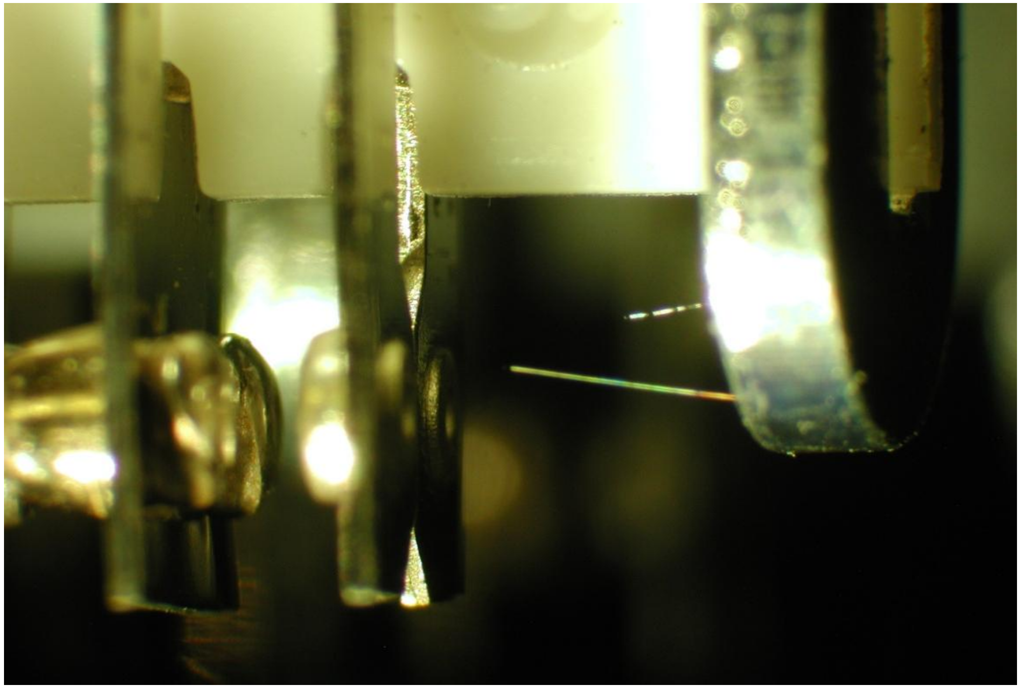
Examples, other types of relays
Adipic acid chrystals on contactor contacts



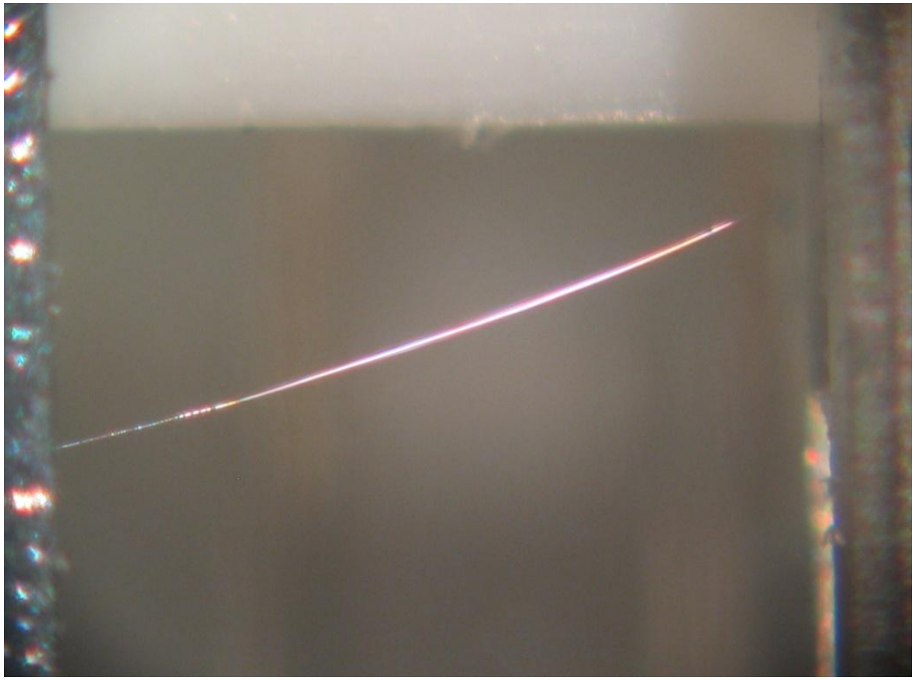


The adipic acid has come from the housing plastic (polyamide), due to degradation of the material (heat, time)

Examples, continued

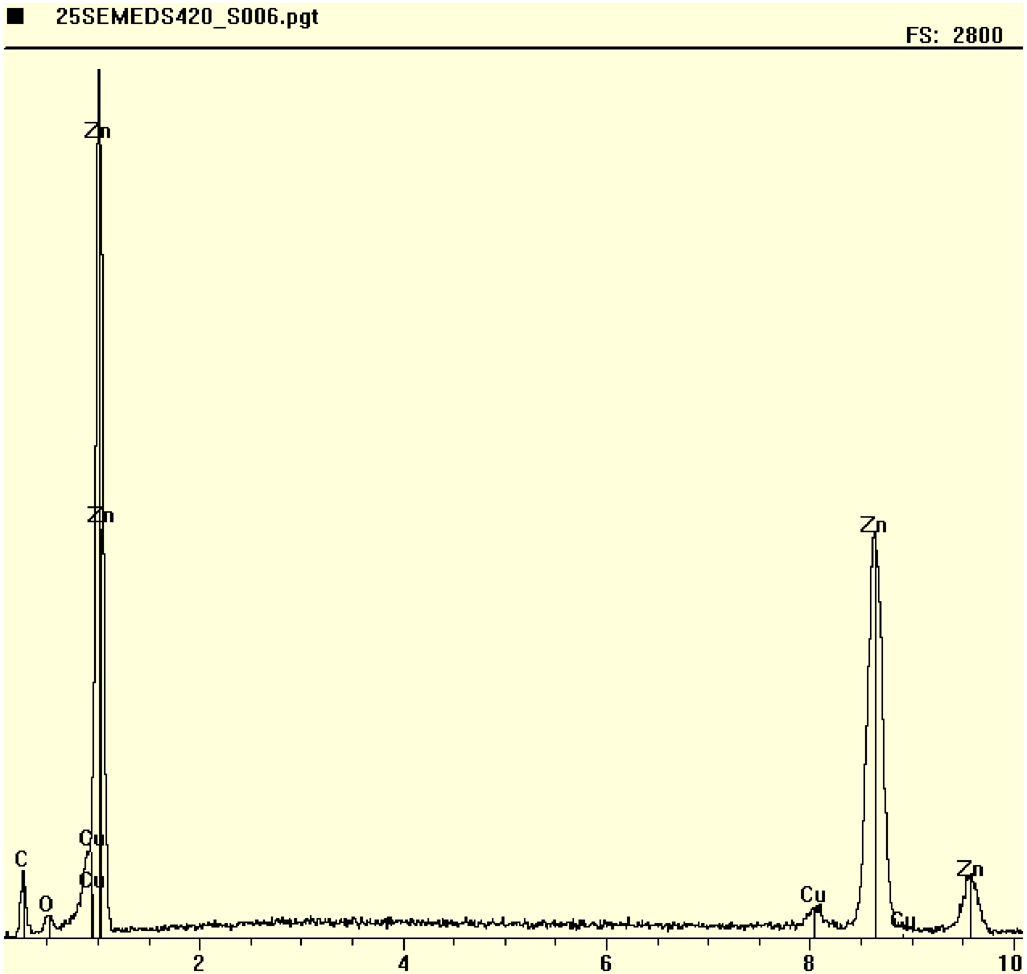


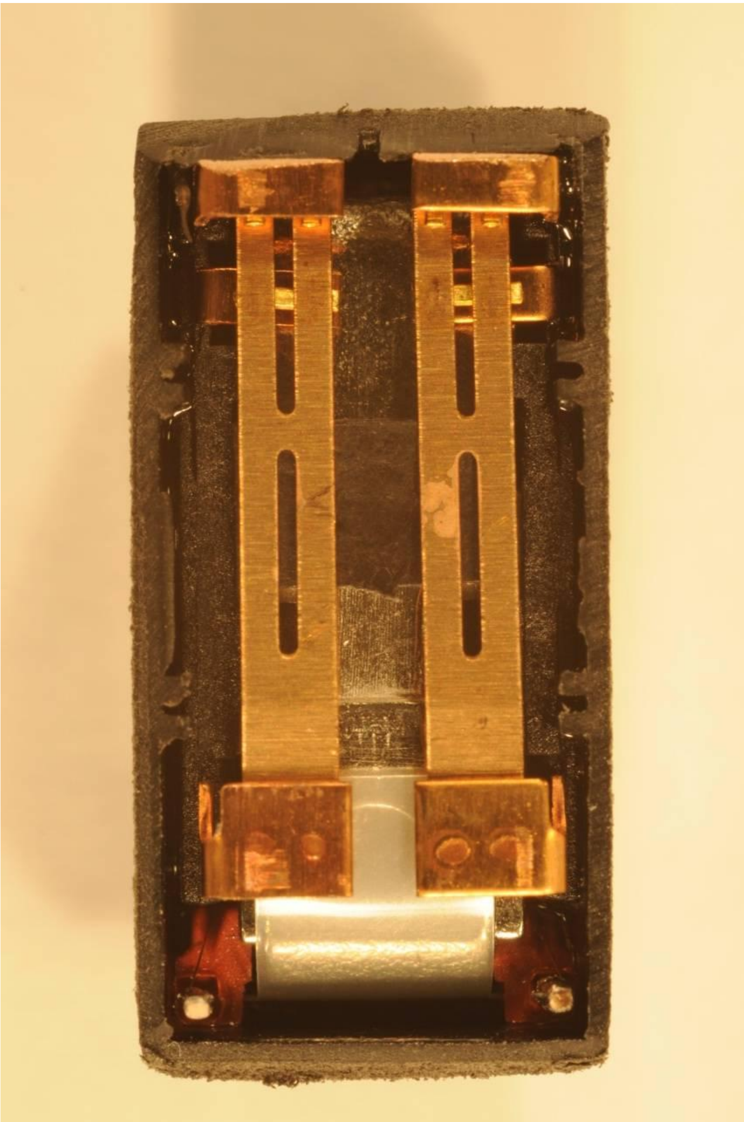
Picture 5. Whiskers grown on the zinc plated end part of the relay.



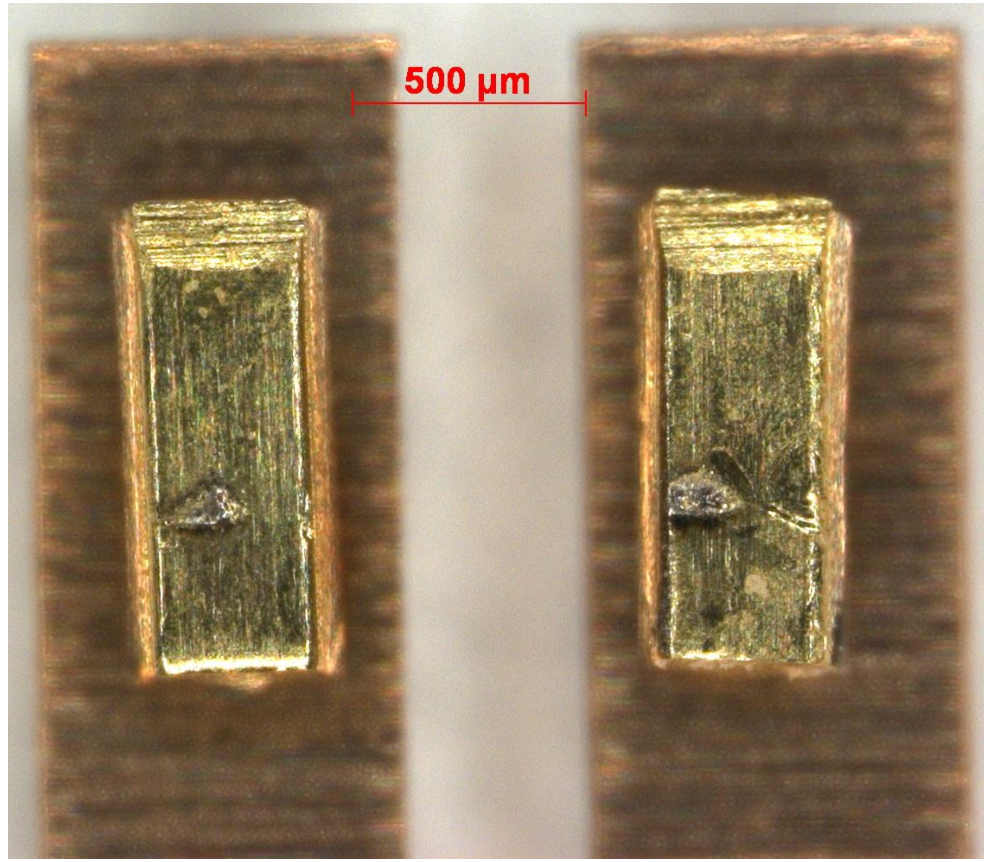
Picture 6. Whisker on another relay.

Whisker material analysis:



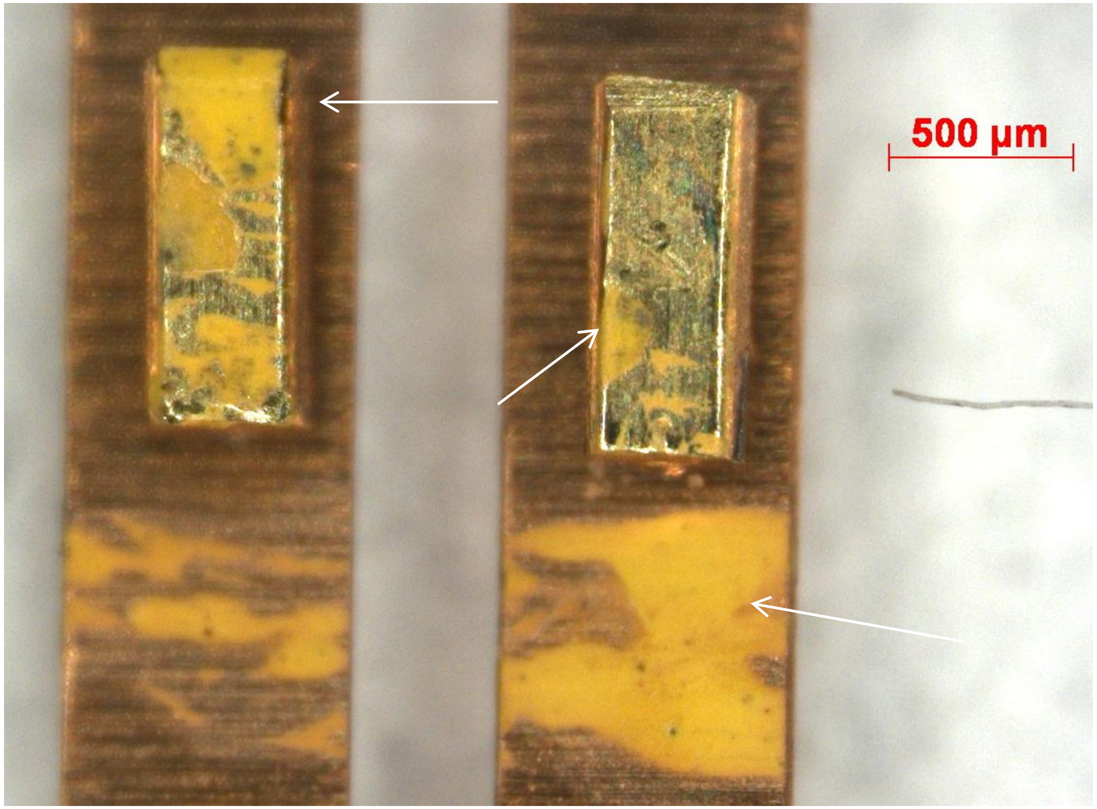


Miniature relays

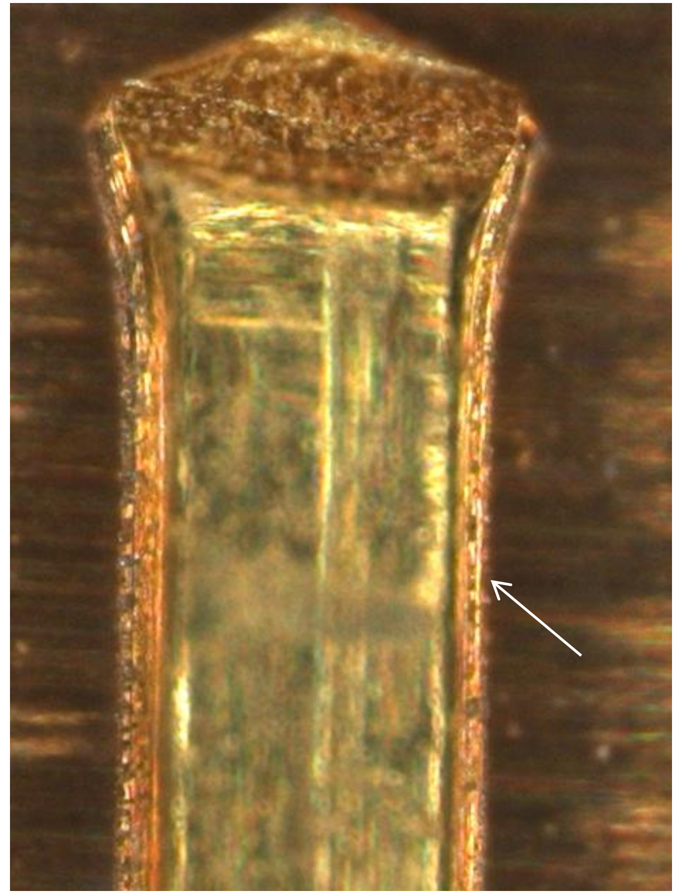


Melted contact points due to arcing (base material visible)

Miniature relays, continued

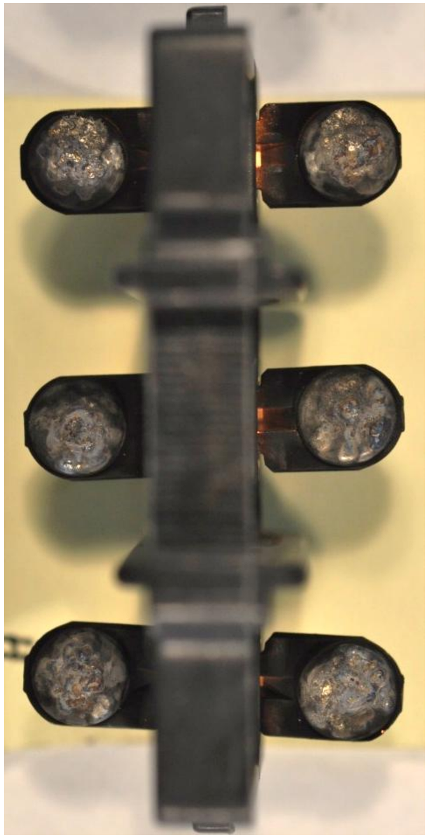


Foreign material on relay contacts
(elemental analysis showed phosphorus and oxygen,
IR-analysis: organic acid and it's salt)

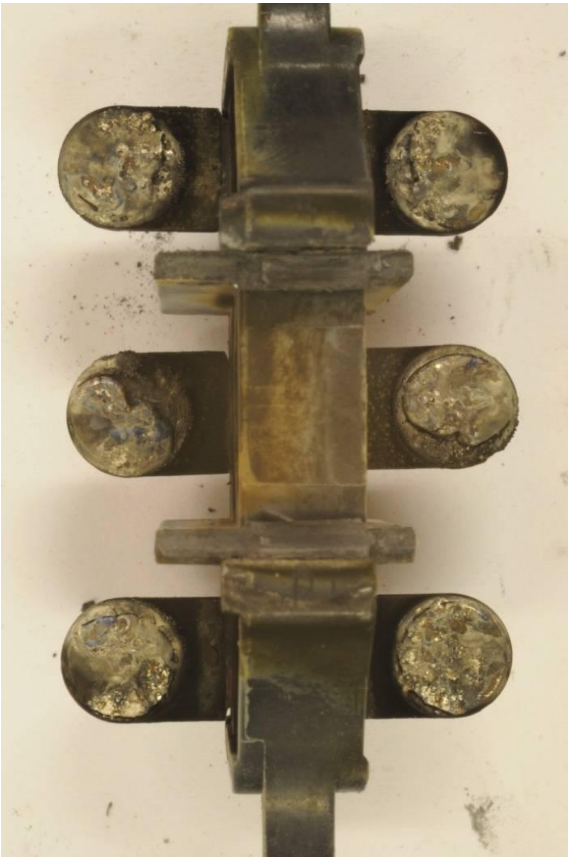


Small crystals (P, O also)

Contactor contacts, used in high current switching (heating control)



After several months

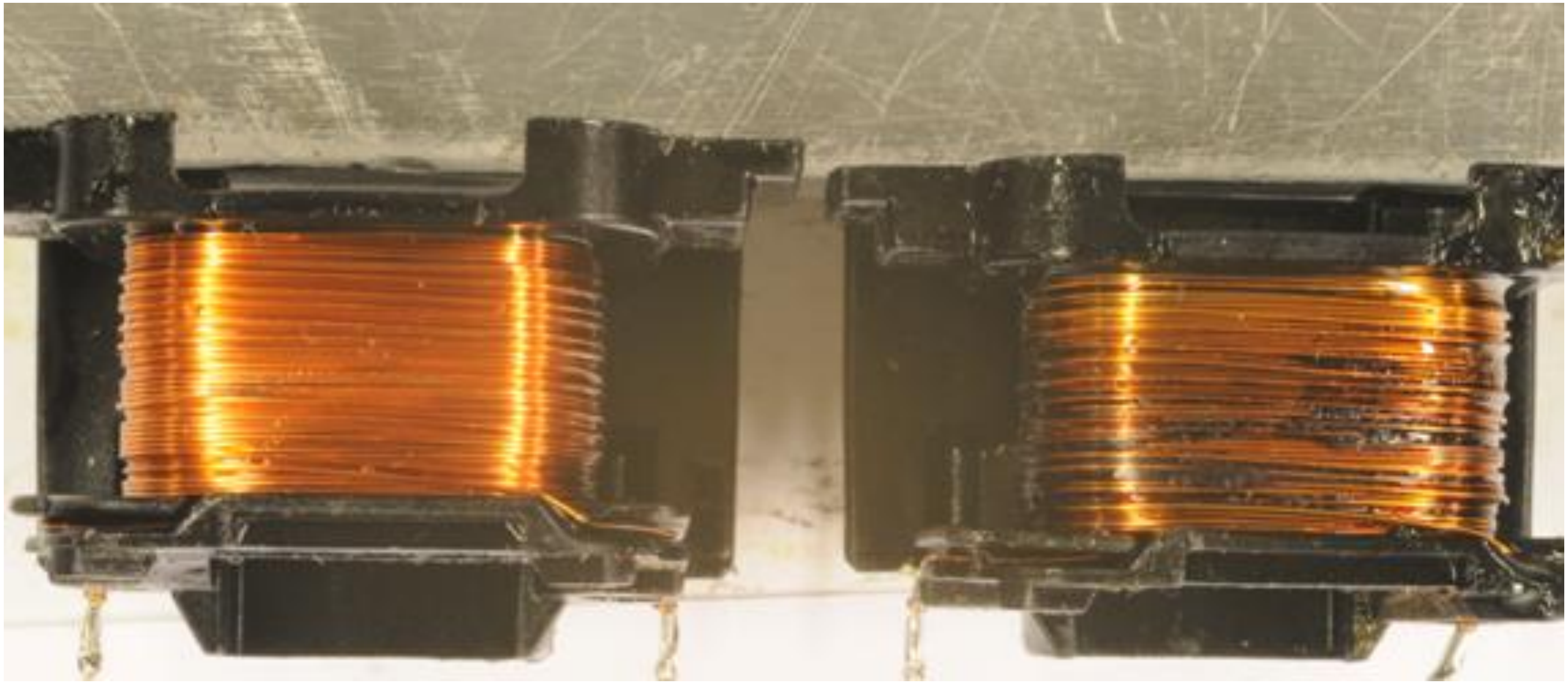


After 1 – 2 years

After about 3 years (note: one contact broken off due to melting of support piece)

- the contact material is silver cadmium oxide

Coil burn-out and swelling (left)



Thank you for your attention!