The 2016 Morton Antler Lecture
50 Years of the Holm Conference on Electrical Contacts 1967 - 2016
Paul G. Slade

“All knowledge of reality proceeds from experience & culminates in a new experience”
(Einstein)
1953: 1st Engineering Seminar on Electrical Contact Phenomena, presented by Dr. Ragnar Holm. Sponsor: Stackpole Carbon Co. (Dr. Erle Shobert) Organizer: Prof. Ralph Armington

1954: 2nd Seminar with papers presented by Dr. Ragnar Holm and the participants

1961: The Engineering Seminar organizes the 1st ICEC, Orono, Maine. Organizer: Armington & Shobert

1967: Ragnar & Else Holm’s book published & his final presentation

1968: Renamed Holm Seminar on Electrical Contracts


1970: 1st recipient of the “Erle Shobert Prize Paper Award”

1971: The Intensive Contact Course begun Organized by Bill Campbell & Hal Wagar

1973: 1st recipient of the “Holm Scientific Achievement Award” Llewellyn Jones


1978: Ragnar Holm dies aged 91

1984: Prof. Ralph Armington retires & receives the 1st “Armington Recognition Award”

1985: The 1st “IEEE Holm Conference on Electrical Contacts”

1986: The 1st recipient of the “Erle Shobert Prize Paper Award”

1987: Ralph Armington dies

1990: Dr. Erle Shobert dies

2001: Prof. Ralph Armington dies

2002: “Mort Antler Lecture” Established

2003: The Conference now with its 3rd generation of leadership

2011: Paul & Dee-Dee Slade “Young Investigator Award” Established

2016: The Conference now with its 3rd generation of leadership


1967 - 2016: The 50 years in this lecture
1950:

1953: 1st Engineering Seminar on Electrical Contact Phenomena, presented by Dr. Ragnar Holm. Sponsor: Stackpole Carbon Co. (Dr. Erle Shobert)
Organizer: Prof. Ralph Armington

1954: 2nd Seminar with papers presented by Dr. Ragnar Holm and the participants

1961: The Engineering Seminar organizes the 1st ICEC, Orono, Maine. Organizer: Armington & Shobert

1967: Ragnar & Else Holm’s book published & his final presentation

1968: Renamed Holm Seminar on Electrical Contacts

1970:

1970: 1st recipient of the “Erle Shobert Prize Paper Award”

1971: The Intensive Contact Course begun Organized by Bill Campbell & Hal Wagar

1973: 1st recipient of the “Holm Scientific Achievement Award” Llewellyn Jones

1970: Ragnar Holm dies aged 91


1984: Prof. Ralph Armington retires & receives the 1st “Armington Recognition Award”

1985: The 1st “IEEE Holm Conference on Electrical Contacts”

1984: Prof. Ralph Armington retires & receives the 1st “Armington Recognition Award”

1985: The 1st “IEEE Holm Conference on Electrical Contacts”

1990:

1990: Dr. Erle Shobert dies

2000:

2002: “Morton Antler Lecture” Established

2001: Dr. Erle Shobert dies

2010:

2010: Prof. Ralph Armington dies

2011: Paul & Dee-Dee Slade “Young Investigator Award” Established

2016:

2016: The Conference now with its 3rd generation of leadership

1967 - 2016: The 50 years in this lecture
The Dateline of the Holm Seminars and Conferences

1953: 1st Engineering Seminar on Electrical Contact Phenomena, presented by Dr. Ragnar Holm. Sponsor: Stackpole Carbon Co. (Dr. Erle Shobert) Organizer: Prof. Ralph Armington

1954: 2nd Seminar with papers presented by Dr. Ragnar Holm and the participants

1961: The Engineering Seminar organizes the 1st ICEC, Orono, Maine. Organizer: Armington & Shobert

1967: Ragnar Holm’s book published & his final presentation

1968: Renamed Holm Seminar on Electrical Contacts

1970: 1st Engineering Seminar on Electrical Contact Phenomena, presented by Dr. Ragnar Holm. Sponsor: Stackpole Carbon Co. (Dr. Erle Shobert) Organizer: Prof. Ralph Armington

1970: 1st recipient of the “Erle Shobert Prize Paper Award”

1971: The Intensive Contact Course begun Organized by Bill Campbell & Hal Wagar

1973: 1st recipient of the “Holm Scientific Achievement Award” Llewellyn Jones


1984: Prof. Ralph Armington retires & receives the 1st “Armington Recognition Award”

1985: The 1st “IEEE Holm Conference on Electrical Contacts”

2002: “Morton Antler Lecture” Established

2001: Dr. Erle Shobert dies

2010: Prof. Ralph Armington dies

2011: Paul & Dee-Dee Slade “Young Investigator Award” Established

2016: The Conference now with its 5th generation of leadership

1967 - 2016: The 50 years in this lecture
The Dateline of the Holm Seminars and Conferences

1953: 1st Engineering Seminar on Electrical Contact Phenomena, presented by Dr. Ragnar Holm. Sponsor: Stackpole Carbon Co. (Dr. Erle Shobert) Organizer: Prof. Ralph Armington

1954: 2nd Seminar with papers presented by Dr. Ragnar Holm and the participants

1961: The Engineering Seminar organizes the 1st ICEC, Orono, Maine. Organizer: Armington & Shobert

1967: Ragnar Holm’s book published & his final presentation

1968: Renamed Holm Seminar on Electrical Contracts

1970: 1st Engineering Seminar on Electrical Contacts

1970: 1st recipient of the “Erle Shobert Prize Paper Award”

1971: The Intensive Contact Course begun Organized by Bill Campbell & Hal Wagar

1973: 1st recipient of the “Holm Scientific Achievement Award” Llewellyn Jones


1970: Ragnar Holm dies aged 91

1973: 1st recipient of the “Erle Shobert Prize Paper Award”


1984: Prof. Ralph Armington retires & receives the 1st “Armington Recognition Award”

1985: The 1st “IEEE Holm Conference on Electrical Contacts”

2002: “Morton Antler Lecture” Established

2011: Paul & Dee-Dee Slade “Young Investigator Award” Established

2010: Prof. Ralph Armington dies

2016: The Conference now with its 3rd generation of leadership

1967 - 2016: The 50 years in this lecture

2001: Dr. Erle Shobert dies
The Number of Papers Presented at the Holm Conferences

Number of Papers Presented


Holm + ICEC

9/11/2001
The Holm Conference has become increasingly International

Percentage of Papers from the USA

Holm + ICEC
International Papers & Presentations at the Holm Conference 1967 to 2015

Percentage of the Total Papers 1967 - 2016

Total % by Region
Americas 44%
Europe 31%
Asia 24%

Less than 1%(i.e.1-8 papers)
Bulgaria
Czech Republic
Norway
Kazakhstan
South Korea
Hungary
Holland
Taiwan
Brazil
Australia
Denmark
Israel
Finland
India
Greece
Serbia
Turkey
Egypt
Pakistan
The Expansion of Information

Number of transistors doubled every 2 years, Moore’s Law

1967: Aronstein’s Holm Seminar Paper on making contact to test an integrated circuit

Integrated Circuit

1960
The Expansion of Information

Number of books printed
doubled every 2.15 years

Number of transistors
doubled every 2 years,
Moore’s Law

Printing
New Scientist, 16 March, 1972: ..... the optimists argue that if microelectronics can make small computers as inexpensive as telephones then people will buy them even though they are in use for a small fraction of the time. Once in the house, or small office, new uses will be found for them and eventually they will affect life to an even greater extent than the TV.
The Effect of the Integrated Circuit on the Life & Times of the Contact Scientist

Slide Rule

Main Frame Computers with Punch-card input

Apple II 1977

Laptop Computers

1991: WWW launched
1993: in general use

1994: 24 x 10^6 Internet users

2004: 91 x 10^6 Internet users

2014: 2.9 x 10^9 Internet users

Email expands in usage

IBM PC w. easy to use software 1981

1990: Microsoft Office

1990’s: Power Point replaces Slides and Overheads at the Holm Conference

Ever increasing capability. Now used for computer graphics and high level computation

Mini Computer 1969

HP-35 1971 $$ ($350)
2016 $$ ($2500)

1st Cell Phone

Sun Work Station for Computer Graphics

Cell Phone in common usage

Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.

1991: WWW launched
1993: in general use

1994: 24 x 10^6 Internet users

2004: 91 x 10^6 Internet users

2014: 2.9 x 10^9 Internet users

Email expands in usage

Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.
The Effect of the Integrated Circuit on the Life & Times of the Contact Scientist

Main Frame Computers with Punch-card input

Slide Rule

Apple II 1977

Laptop Computers

HP-35 1971 $$ ($350) Today’s $$ ($2500)

IBM PC w. easy to use software 1981

Mini Computer 1969

Microsoft Office 1990

1991: WWW launched
1993: in general use

1994: 24 x 10^6 Internet users

2004: 91 x 10^6 Internet users

2014: 2.9 x 10^9 Internet users

Email expands in usage

1990’s: Power Point replaces Slides and Overheads at the Holm Conference

Ever increasing capability. Now used for computer graphics and high level computation

Sun Work Station for Computer Graphics

Cell Phone in common usage

Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.

The Effect of the Integrated Circuit on the Life & Times of the Contact Scientist

Main Frame Computers with Punch-card input

Apple II 1977

Laptop Computers

1991: WWW launched
1993: in general use

1994: $24 \times 10^6$
Internet users

2004: $91 \times 10^6$
Internet users

2014: $2.9 \times 10^9$
Internet users

Email expands in usage

1990: Microsoft Office

1990’s: Power Point replaces Slides and Overheads at the Holm Conference

Ever increasing capability. Now used for computer graphics and high level computation

IBM PC w. easy to use software 1981

Mini Computer 1969

HP-35 1971
$$ ($350)
Today’s $$$ ($2500)

Slide Rule

Sun Work Station for Computer Graphics

Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.

Cell Phone in common usage

1994: 24 $\times 10^6$
Internet users

2004: 91 $\times 10^6$
Internet users

2014: 2.9 $\times 10^9$
Internet users

1990’s: Power Point replaces Slides and Overheads at the Holm Conference

Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.

1991: WWW launched
1993: in general use

1990: Microsoft Office

1990’s: Power Point replaces Slides and Overheads at the Holm Conference

Ever increasing capability. Now used for computer graphics and high level computation

1994: 24 $\times 10^6$
Internet users

2004: 91 $\times 10^6$
Internet users

2014: 2.9 $\times 10^9$
Internet users
The Effect of the Integrated Circuit on the Life & Times of the Contact Scientist

- Main Frame Computers with Punch-card input
- Apple II 1977
- Laptop Computers
- HP-35 1971 $$ ($350) Today’s $$ ($2500)
- IBM PC w. easy to use software 1981
- 1st Cell Phone 1969
- Slide Rule

1976: Apple II 1977
1981: IBM PC w. easy to use software
1986: Mini Computer 1969
1990: Microsoft Office
1991: WWW launched
1993: in general use
1994: $24 \times 10^6$ Internet users
2004: $91 \times 10^6$ Internet users
2014: $2.9 \times 10^9$ Internet users

Ever increasing capability. Now used for computer graphics and high level computation

- Email expands in usage
- 1990’s: Power Point replaces Slides and Overheads at the Holm Conference
- Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.

The Effect of the Integrated Circuit on the Life & Times of the Contact Scientist

Main Frame Computers with Punch-card input

Apple II 1977

Laptop Computers

HP-35 1971

$$
($350)

Today’

s $$

($2500)

IBM PC w. easy to use software 1981

1990: Microsoft Office

1991: WWW launched 1993: in general use

1994: 24 x 10^6 Internet users

2004: 91 x 10^6 Internet users

2014: 2.9 x 10^9 Internet users

Email expands in usage

Ever increasing capability. Now used for computer graphics and high level computation

Sun Work Station for Computer Graphics

1990’s: Power Point replaces Slides and Overheads at the Holm Conference

Ever increasing user friendly software: e.g. Windows Office, Minitab, Fluent etc.

Cell Phone in common usage

1st Cell Phone

Contact Resistance

**接触电阻**

接触电阻研究的论文百分比

- SEM & 高速示波器开发
- 继续分析和FEA模型的$R_C$
- Greenwood & Williamson $R_C$模型
- $R_C$随着频率增加而增加
- 联系超导体
- RF, $R_C$考虑电容
- $V_C = \sqrt{4L(T_C^2 - T_0^2)}$
- $V_C / T_C$关系
- $R_C$薄薄膜
- 平均38%的论文
Contact Resistance

Contact to Super-Condutors

RF, $R_C$ takes Capacitance into account

Validity of $V_C/T_C$ relationship using numerical analysis

$R_C = \frac{\rho}{2a} \sqrt{\frac{\pi H}{F}}$

$V_C = \sqrt{4L(T_C^2 - T_0^2)}$

SEM & High Speed Oscilloscopes developed

Continued analytical and FEA models of $R_C$

Greenwood & Williamson $R_C$ model

$R_C$ increases as frequency increases

Sharvin Resistance

$R_C$ Thin Films

Average 38% of the papers

Percentage of Papers that measure Contact Resistance, $R_C$
### Contact Resistance

- **SEMs & High Speed Oscilloscopes developed**
- **Continued analytical and FEA models of $R_C$**
- **Greenwood & Williamson $R_C$ model**
- **Contact to Superconductors**
- **$R_C$ increases as frequency increases**
- **Sharvin Resistance**
- **$R_C$ Thin Films**
- **Validity of $V_C/T_c$ relationship using numerical analysis**
- **Average 38% of the papers**

#### Equations

- $R_C = \frac{\rho}{2} \sqrt{\frac{\pi H}{F}}$

- $V_C = \sqrt{4L(T_C^2 - T_0^2)}$
Connectors

Typically testing connectors in the Laboratory produces failures that are far greater than our experience of failures returned from the field. Dr. Rod Martens (2014)

1) Laboratory data show possible corrosion mechanisms, but take care when attempting to predict a real world connector’s field performance

2) Laboratory data useful in analyzing a failed connector
Connector research accelerates after metal prices increases.
## Minimum Contact Force for Stable Conduction

<table>
<thead>
<tr>
<th>Metal</th>
<th>Minimum Contact Force, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>Pt family (Pd)</td>
<td>0.1 – 0.5</td>
</tr>
<tr>
<td>Au plate</td>
<td>0.5 – 1.0</td>
</tr>
<tr>
<td>Ag</td>
<td>1.0 – 2.5</td>
</tr>
<tr>
<td>Au-Ag, Ag-Pd, Ag-Cu, Ag-CdO</td>
<td>1.0 – 3.0</td>
</tr>
<tr>
<td>Ag-SnO₂</td>
<td>2.5 – 4.0</td>
</tr>
<tr>
<td>Cu family (Cu-Be, Brass, Cupro-Nickels, Phosphor Bronze)</td>
<td>10 – 300</td>
</tr>
<tr>
<td>Ni, W, Al, &amp; Sn</td>
<td>10 (with wipe) – 200</td>
</tr>
<tr>
<td>Ag-W</td>
<td>10 – 100</td>
</tr>
</tbody>
</table>
## Minimum Contact Force for Stable Conduction

<table>
<thead>
<tr>
<th>Metal</th>
<th>Minimum Contact Force, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>Pt family (Pd)</td>
<td>0.1 – 0.5</td>
</tr>
<tr>
<td>Au plate</td>
<td>0.5 – 1.0</td>
</tr>
<tr>
<td>Ag</td>
<td>1.0 – 2.5</td>
</tr>
<tr>
<td>Au-Ag, Ag-Pd, Ag-Cu, Ag-CdO</td>
<td>1.0 – 3.0</td>
</tr>
<tr>
<td>Ag-SnO$_2$</td>
<td>2.5 – 4.0</td>
</tr>
<tr>
<td>Cu family (Cu-Be, Brass, Cupro-Nickels, Phosphor Bronze)</td>
<td>10 – 300</td>
</tr>
<tr>
<td>Ni, W, Al, &amp; Sn</td>
<td>10 (with wipe) – 200</td>
</tr>
<tr>
<td>Ag-W</td>
<td>10 – 100</td>
</tr>
</tbody>
</table>
Corrosion & Tarnishing

Arbitrary tests often produce arbitrary results

Mated connections resistant to surface corrosion and maintain $R_C$

Flash Au with Ni & other underplate

Studies of industrial environs

Determining gases & environs for corrosion studies

Au price unfrozen. Flash Au (hard Au) with “corrosion resistant ” underplates & Sn as alternatives

Dust effects

Mixed flowing gas testing established

Percentiles of $H_2S, SO_2, Cl_2, NO_2, NH_3, O_3$ & Humidity for simulated environ testing

Environments established
Class 1: Phone exchange
Class 2: Office
Class 3: Light industrial
Class 4: Heavy industrial

Sn plated connectors on autos sealed & unsealed showed fretting & corrosion but little change in $R_C$

Au, Ag & Sn plated pin-socket connectors show minimal $R_C$ increase in mixed gas, high humidity

Ag plate + inhibitor to replace flash Au

Au price spiked

2016
Corrosion & Tarnishing

- Arbitrary tests often produce arbitrary results

- Mated connections resistant to surface corrosion and maintain $R_C$

- Flash Au with Ni & other underplate

- Percentiles of $H_2S$, $SO_2$, $Cl_2$, $NO_2$, $NH_3$, $O_3$, & Humidity for simulated environ testing

- Environments established:
  - Class 1: Phone exchange
  - Class 2: Office
  - Class 3: Light industrial
  - Class 4: Heavy industrial

- Studies of industrial environs

- Determining gases & environs for corrosion studies

- Mated connections resistant to surface corrosion and maintain $R_C$

- Dust effects

- Mixed flowing gas testing established

- Sn plated connectors on autos sealed & unsealed showed fretting & corrosion but little change in $R_C$

- Ag plate + inhibitor to replace flash Au

- Au, Ag & Sn plated pin-socket connectors show minimal $R_C$ increase in mixed gas, high humidity

- Au price unfrozen. Flash Au (hard Au) with “corrosion resistant” underplates & Sn as alternatives

- Au price spiked
Corrosion & Tarnishing

Arbitrary tests often produce arbitrary results

Mated connections resistant to surface corrosion and maintain $R_C$

Flash Au with Ni & other underplate

Determining gases & environs for corrosion studies

Studies of industrial environs

Percentiles of $H_2S$, $SO_2$, $Cl_2$, $NO_2$, $NH_3$, $O_3$ & Humidity for simulated environ testing

Environments established
Class 1: Phone exchange
Class 2: Office
Class 3: Light industrial
Class 4: Heavy industrial

Au price unfrozen. Flash Au (hard Au) with “corrosion resistant” underplates & Sn as alternatives

Dust effects

Mixed flowing gas testing established

Sn plated connectors on autos sealed & unsealed showed fretting & corrosion but little change in $R_C$

Au, Ag & Sn plated pin-socket connectors show minimal $R_C$ increase in mixed gas, high humidity

Ag plate + inhibitor to replace flash Au

Arbitrary tests often produce arbitrary results.

Coupons in tarnishing ambients

Mated connections resistant to surface corrosion and maintain $R_C$

Flash Au with Ni & other underplate

Determining gases & environs for corrosion studies

Studies of industrial environs

Percentiles of $H_2S$, $SO_2$, $Cl_2$, $NO_2$, $NH_3$, $O_3$ & Humidity for simulated environ testing

Environments established
- Class 1: Phone exchange
- Class 2: Office
- Class 3: Light industrial
- Class 4: Heavy industrial

Au, Ag & Sn plated pin-socket connectors show minimal $R_C$ increase in mixed gas, high humidity

Ag plate + inhibitor to replace flash Au

Dust effects

Mixed flowing gas testing established

Sn plated connectors on autos sealed & unsealed showed fretting & corrosion but little change in $R_C$

Au price unfrozen. Flash Au (hard Au) with “corrosion resistant ” underplates & Sn as alternatives

Au price spiked

Corrosion & Tarnishing

**Arbitrary tests often produce arbitrary results**

**Mated & lubricated connections resistant to surface corrosion and maintain $R_c$**

**Coupons in tarnishing ambients**

**Flash Au with Ni & other underplate**

**Studies of industrial environs**

**Determining gases & environs for corrosion studies**

**Au price unfrozen. Flash Au (hard Au) with “corrosion resistant” underplates & Sn as alternatives**

**Dust effects**

**Mixed flowing gas testing established**

**Percentiles of $H_2S$, $SO_2$, $Cl_2$, $NO_2$, $NH_3$, $O_3$ & Humidity for simulated environ testing**

**Environments established**
- Class 1: Phone exchange
- Class 2: Office
- Class 3: Light industrial
- Class 4: Heavy industrial

**Au, Ag & Sn plated pin-socket connectors show minimal $R_c$ increase in mixed gas, high humidity**

**Other surface materials studied**

**Ag plate + inhibitor to replace flash Au**

**Sn plated connectors on autos sealed & unsealed showed fretting & corrosion but little change in $R_c$**

**1966**

**1976**

**1986**

**1996**

**2006**

**2016**
Fretting

1966

Ag price doubles

1976

Bus stab connection for motor control centers change from Ag plate to Sn plate

1986

First Fretting Paper

1996

Intermittence f(vibration frequency), Cu & Ag

2006

Vibration external to pin & socket little effect on \( R_c \)

2016

Sn plated Cu 100K km in autos show good reliability

Au price unfrozen. Flash Au & Sn as alternatives

1st comprehensive description & model

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

Pd contacts in air + benzene show stable \( R_c \)

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

In a typical vibe environment no fretting observed

Au vs. Sn or Sn-Pb fails with vibration

F-16 crash due to fretting Au vs. Sn-Pb connector 100hr relube w. inhibitor

Sn plated Cu 100Hz, 50μm wipe, voltage to arcing

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts
Fretting

In the mid 1970’s our industry was faced with the high & unstable price of gold. A strong movement was started to use Sn platings as alternatives to gold on connector contacts. In a great many cases a simple plating substitution was made, with no further changes in connector design or contact configuration.......Our lab began to investigate persistent failures of tin plated connectors in field service. I was amazed at how good the parts looked. The platings were still bright with no evidence of corrosion, film growth or contamination at the contact interface. There were small black or grey spots here and there, but at first those were written off as wear marks. But we noticed, almost accidentally, that the black spots tended to be located at exactly where we assumed physical contact to occur in the mated contacts. Could we be seeing something like Fretting Corrosion?

Jim Whitley, Holm 1987
Fretting

- Ag price doubles

Bus stab connection for motor control centers change from Ag plate to Sn plate

- First Fretting Paper

- Au vs. Sn or Sn-Pb fails with vibration

- 1st comprehensive description & model

- Intermittence f(vibration frequency), Cu & Ag

- Intermittence for Cu low up to 10K cycles even tho’ $R_c$ Hi (Sn at 1K cycles)

- Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

- In a typical vibe environment no fretting observed

- Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

- Vibration external to pin & socket little effect on $R_c$

- Sn plated Cu 100Hz, 50μm wipe, voltage to arcing

- Au price unfrozen. Flash Au & Sn as alternatives

- 1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

- Au vs. Sn or Sn-Pb fails with vibration

- Pd contacts in air + benzene show stable $R_c$

- F-16 crash due to fretting Au vs. Sn-Pb connector 100hr relube w. inhibitor

- Sn plated Cu connectors, 100K km in autos show good reliability

- Average 12% of the papers since 1974
Fretting

Experimental analysis from plated rider on a plated flat plane

Ni rider on Ni flat
Cu rider on Cu flat
Au rider on Cu flat

50g, 20μm wipe

R_C, ohms

10^0 10^1 10^2 10^3 10^4 10^5 10^6

Cycles

Antler, Holm 1984
Fretting

Ag price doubles

Bus stab connection for motor control centers change from Ag plate to Sn plate

First Fretting Paper

Au price unfrozen. Flash Au & Sn as alternatives

1st comprehensive description & model

Au vs. Sn or Sn-Pb fails with vibration

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

Pd contacts in air + benzene show stable $R_c$

Intermittence f(vibration frequency), Cu & Ag

Intermittence for Cu low up to 10K cycles even tho’ $R_c$ Hi (Sn at 1K cycles)

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

In a typical vibe environment no fretting observed

1st comprehensive description & model

Vibration external to pin & socket little effect on $R_c$

Sn plated Cu 100Hz, 50μm wipe, voltage to arcing

Sn plated Cu connectors, 100K km in autos show good reliability

F-16 crash due to fretting Au vs. Sn-Pb connector 100hr relube w. inhibitor

Fretting

1966

Ag price doubles

1976

Bus stab connection for motor control centers change from Ag plate to Sn plate

1986

First Fretting Paper

Au vs. Sn or Sn-Pb fails with vibration

1st comprehensive description & model

1996

Intermittence f(vibration frequency), Cu & Ag

Intermittence for Cu low up to 10K cycles even tho’ \( R_C \) Hi (Sn at 1K cycles)

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

F-16 crash due to fretting Au vs. Sn-Pb connector 100hr relube w. inhibitor

1996

Vibration external to pin & socket little effect on \( R_C \)

Sn plated Cu 100Hz, 50\( \mu \)m wipe, voltage to arcing

In a typical vibe environment no fretting observed

2006

Sn plated Cu connectors, 100K km in autos show good reliability

2016

Au price unfrozen. Flash Au & Sn as alternatives

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

1st comprehensive description & model
Fretting

Ag price doubles

Bus stab connection for motor control centers change from Ag plate to Sn plate

First Fretting Paper

Au vs. Sn or Sn-Pb fails with vibration

Intermittence f(vibration frequency), Cu & Ag

Intermittence for Cu low up to 10K cycles even tho’ $R_C$ Hi (Sn at 1K cycles)

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

Sn plated Cu 100Hz, 50μm wipe, voltage to arcing

In a typical vibe environment no fretting observed

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

F-16 crash due to fretting Au vs. Sn-Pb connector 100hr relube w. inhibitor

Sn plated Cu connectors, 100K km in autos show good reliability

1st comprehensive description & model

Vibration external to pin & socket little effect on $R_C$

Lubrication of PAG & PEE

Pd contacts in air + benzene show stable $R_C$

Au price unfrozen. Flash Au & Sn as alternatives

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

Sn plated Cu 100Hz, 50μm wipe, voltage to arcing

Vibration external to pin & socket little effect on $R_C$

Sn plated Cu connectors, 100K km in autos show good reliability

Fretting

Ag price doubles

Bus stab connection for motor control centers change from Ag plate to Sn plate

First Fretting Paper

Au vs. Sn or Sn-Pb fails with vibration

1st comprehensive description & model

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

Intermittence f(vibration frequency), Cu & Ag

Intermittence for Cu low up to 10K cycles even tho’ $R_C$ Hi (Sn at 1K cycles)

Vibration external to pin & socket little effect on $R_C$

Sn plated Cu 100Hz, 50μm wipe, voltage to arcing

Au price unfrozen. Flash Au & Sn as alternatives

Pd contacts in air + benzene show stable $R_C$

In a typical vibe environment no fretting observed

F-16 crash due to fretting Au vs. Sn-Pb connector relube w. inhibitor

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

Sn plated Cu connectors, 100K km in autos show good reliability
Fretting

1966
- Ag price doubles

1976
- Bus stab connection for motor control centers change from Ag plate to Sn plate

1986
- Intermittence f(vibration frequency), Cu & Ag
- Intermittence for Cu low up to 10K cycles even tho’ $R_C$ Hi (Sn at 1K cycles)

1996
- Lubrication of PAG & PEE restores fretted Au to Sn-Pb & Sn-Pb to Sn-Pb Contacts

2006
- In a typical vibe environment no fretting observed

2016
- Sn plated Cu 100Hz, 50μm wipe, voltage to arcing
- Vibration external to pin & socket little effect on $R_C$

- Sn plated Cu connectors, 100K km in autos show good reliability

1st mention of Mil-Spec inhibitors to reduce fretting (Sn-Pb vs. Au)

1st comprehensive description & model

Au vs. Sn or Sn-Pb fails with vibration

Au price unfrozen. Flash Au & Sn as alternatives

Pd contacts in air + benzene show stable $R_C$
Connector Lubrication

- Although they are generally non-conducting, good contact reduces lubricant thickness so good electrical conduction between metals occurs
- They do conduct heat, but this effect in contact performance has not been studied. How does this affect the Kohlrausch equation?
- Generally reduces connector corrosion and increases fretting life
- Use must be tested for long term benefits especially for expected ambients

Use problems
  - Maintenance in place
  - Stability
  - Dust attraction
  - Long term benefits

- F-16 inspect lubricated connection yearly
- Polyphenylether (PPE), Polyalkalyne glycol (PAG), some MIL Spec inhibitors have shown promise for electronic connections (little interest since Abbott’s original paper)
- Bolted Al bus & crimped Al cable, wire brushed under inhibitor & mated with a joint compound result in long term life
Estimate of Contact Lubricant Uses for Electronic Connectors, 2016

Survey Results, iNEMI Connector Reliability Test Recommendations Project, 2016
Intermetallics

• Golden rule: never mix different metals in a contact interface: (Oberg et al 1996). **Often ignored!**

• Formation rate obeys Arrhenius equation:

\[(\text{thickness})^2 = k \times \text{time}\]

\[k = k_0 \exp(-\text{activation energy}/RT)\]

• **Laboratory experiments:** Usually performed at high temperatures. At usual ambient temperatures the formation rate is usually slow: e.g. after 7 years at 50°C some formed with Cu-Sn & Ni-Sn.

• **Formation:** Continues until one of the metals is consumed

• **Resistivity:** Typically 3 to 8 times that of Cu

• **Au & Al:** AuAl₂ (purple plague) & Au₅Al₂ (white plague)

• **Au & Cu:** AuCu, AuCu₃: **Au & Sn:** AuSn₄

• **Ni & Al:** NiAl₃, Ni₂Al₃, Ni₅Al₃, Ni₃Al, NiAl: **Ni & Sn:** Ni₃Sn₄

• **Cu & Sn:** Cu₆Sn₅, Cu₃Sn

• **Al & Cu or Brass:** Cu₄Al₃, Cu₂Al, CuAl₂ & CuAl

• **Ag & Al:** Ag₂Al, Ag₃Al: **Ag & Sn:** Ag₃Sn
Intermetallics

- **Golden rule:** never mix different metals in a contact interface: (Oberg et al 1996). **Often ignored!**
- **Formation rate** obeys Arrhenius equation:
  
  \[(\text{thickness})^2 = k \times \text{time}\]
  
  \[k = k_0 \exp(- \text{activation energy}/RT)\]

- **Laboratory experiments:** Usually performed at high temperatures. At usual ambient temperatures the formation rate is usually slow: e.g. after 7 years at 50°C some formed with Cu-Sn & Ni-Sn.
- **Formation:** Continues until one of the metals is consumed

**Resistivity:** Typically 3 to 8 times that of Cu
- Au & Al: \(\text{AuAl}_2\) (purple plague) & \(\text{Au}_5\text{Al}_2\) (white plague)
- Au & Cu: \(\text{AuCu}, \text{AuCu}_3\)
- Au & Sn: \(\text{AuSn}_4\)
- Ni & Al: \(\text{NiAl}_3, \text{Ni}_2\text{Al}_3, \text{Ni}_5\text{Al}_3, \text{Ni}_3\text{Al}, \text{NiAl}\)
- Ni & Sn: \(\text{Ni}_3\text{Sn}_4\)
- Cu & Sn: \(\text{Cu}_6\text{Sn}_5, \text{Cu}_3\text{Sn}\)
- Al & Cu or Brass: \(\text{Cu}_4\text{Al}_3, \text{Cu}_2\text{Al}, \text{CuAl}_2, \text{CuAl}\)
- Ag & Al: \(\text{Ag}_2\text{Al}, \text{Ag}_3\text{Al}\)
- Ag & Sn: \(\text{Ag}_3\text{Sn}\)
Intermetallics

• Golden rule: never mix different metals in a contact interface: (Oberg et al 1996). Often ignored!

• Formation rate obeys Arrhenius equation:
  \[(\text{thickness})^2 = k \times \text{time}\]
  
  \[k = k_0 \exp(- \text{activation energy/RT})\]

• Laboratory experiments: Usually performed at high temperatures. At usual ambient temperatures the formation rate is usually slow: e.g. after 7 years at 50C some formed with Cu-Sn & Ni-Sn.

• Formation: Continues until one of the metals is consumed

• Resistivity: Typically 3 to 8 times that of Cu

• Au & Al: AuAl\(_2\) (purple plague) & Au\(_5\)Al\(_2\) (white plague)

• Au & Cu: AuCu, AuCu\(_3\): Au & Sn: AuSn\(_4\)

• Ni & Al: NiAl\(_3\), Ni\(_2\)Al\(_3\), Ni\(_5\)Al\(_3\), Ni\(_3\)Al, NiAl: Ni & Sn: Ni\(_3\)Sn\(_4\)

• Cu & Sn: Cu\(_6\)Sn\(_5\), Cu\(_3\)Sn

• Al & Cu or Brass: Cu\(_4\)Al\(_3\), Cu\(_2\)Al, CuAl\(_2\) & CuAl

• Ag & Al: Ag\(_2\)Al, Ag\(_3\)Al: Ag & Sn: Ag\(_3\)Sn
Whiskers

- Sn plate with a small percentage of Pb did not form whiskers.
- Since 2005, 14 papers on Sn whiskers have been presented at the Holm Conference compared to 8, 1967 to 2004.
- Matt Sn less susceptible to whisker formation than bright tin, but their formation depends upon crystal structure and grain.
- Annealing a Sn plate helps, but does not entirely solve the problem. A search for non toxic additives to Sn continues: One possibility is Bi.
- Ag forms whiskers, but requires a AgS surface to form them.
- Other stressed metal platings have shown whisker formation: e.g. Au, Zn, Cd.
Residential Wiring

Studies of failures in household connections that can result in dwelling fires

- Price of Cu increases 400%
- Use of Al wiring in homes
- 1st paper on floating arc
- Plated Al household twist connection failures
- Al twist connection failures
- Al household screw connection failures
- 1st paper on a loose Cu connection
- General problems with Al household connections
- Ni plated Al Household connection failures
- Stress relaxation of bolted Al wires slowly results in higher $R_C$ & failure
- Papers on loose connections & molten bridges and arcing and burn your house down
- Loos connections in receptacle failures
- Development of the low current arc fault detector for household circuit breakers
- Intermittent faults in wires & cables

Mass produced home smoke detectors 1971

Residential Wiring

Studies of failures in household connections that can result in dwelling fires

Price of Cu increases 400%

1st paper on floating arc

Use of Al wiring in homes

Al twist connection failures

Plated Al Household twist connection failures

1st paper on a loose Cu connections

Stress relaxation of bolted Al wires slowly results in higher $R_C$ & failure

General problems with Al household connections

Ni plated Al Household connection failures

Loose connections in receptacle failures

Mass produced home smoke detectors 1971

Al household screw connection failures

Intermittent faults in wires & cables

Use of Al wiring in homes

Development of the low current arc fault detector for household circuit breakers

Papers on loose connections & molten bridges and arcing and burn your house down

Studies of failures in household connections that can result in dwelling fires

Residential Wiring

1967

1st paper on floating arc

Price of Cu increases 400%

Use of Al wiring in homes

1976

Plated Al household twist connection failures

Al twist connection failures

Mass produced home smoke detectors 1971

1986

General problems with Al household connections

Stress relaxation of bolted Al wires slowly results in higher $R_C$ & failure

Studies of failures in household connections that can result in dwelling fires

1996

Loose connections in receptacle failures

Ni plated Al household connection failures

1971

1st paper on a loose Cu connection

1996

Papers on loose connections & molten bridges and arcing and burn your house down

2006

Intermittent faults in wires & cables

Development of the low current arc fault detector for household circuit breakers

2016
Switching with Arcing

Circuit switching using electrical contacts has not been superseded by electronic switching except for specialty operations. Electrical contacts plus electronic detection, sensing and tripping will be the partnership for the future.

The electric arc is used with opening contacts to interrupt the current in electric circuits and isolate a load side from the line side.

“If nature had not given us the electric arc we would have had to invent one”

Slepian. 1930’s
Contact Materials for Switching Contacts

90% of Holm Papers on Switching Contain Ag Based Contacts

Less than 1%
Ag-Cu-(C, Ni or Zn)
Ag-Ni-(C, Mg or WC)
Ag-Pd-(C, Ni, Mg or C)
Ag-Fe, Ag-FeO_x
Ag-Si, Ag-Re, Ag-Zn,
Ag-Zn-(Sn or Al), Ag-Cd.
Ag-Cr, Ag-La_2O_3, Ag-CuO
Ag-NiO, Ag-TiO_2
Ag-W-(Ni, Re, or CdO)
Ag-WC-(C, Co, Ni or Zr)
Ag-TiC, Ag-(Ti,W)C
Au alloys, Au+ additives
Pb, Pd-(Al. Pb, Ni, Si or Ru)
W-Co, Cr, Fe-Ni, C, Re,
RuO_2,
Sb, Ir, Cd, Co, Zn, In, GaP,
Ti, Ti-(Si, C, N or Ag)
HTSC’s
Percentage of Papers Ag-CdO and Ag-SnO$_2$

Contact Type of Materials

Restrictions on use of Cd

1$^{st}$ Paper w. Ag-SnO$_2$
Ag-CdO vs. Ag-SnO₂, Ag-SnO₂/InO₂ & Other Ag-MeO Contact Materials

- Continuous development of Ag-CdO (manufacturing) & Ag-CdO + additives
- Continuous development of Ag-SnO₂, Ag-SnO₂-In₂O₃, Ag-SnO₂+additives
- Many Ag-MeO types evaluated
- Prediction: Ag-SnO₂ will replace Ag-CdO in 10 yrs.
- Make erosion ac switching Ag-CdO & Ag-SnO₂
- Guidelines for use of Ag-SnO₂
- Release of Cd from Ag-CdO contacts in a fire unlikely
- RoHS rules still allow Cd in Ag-CdO contacts
- My 1st first experiments with switching with Ag-SnO₂ at 20A with contacts from Chugai
- Patents for Ag-SnO₂ & Ag-InO₂-SnO₂ contacts
- Patent for WO₃ addition to Ag-SnO₂
- 1st paper with Ag-SnO₂ & Ag-ZnO contacts
Ag-CdO vs. Ag-SnO$_2$, Ag-SnO$_2$/InO$_2$ & Other Ag-MeO Contact Materials

- Continuous development of Ag-CdO (manufacturing) & Ag-CdO + additives
- Continuous development of Ag-SnO$_2$, Ag-SnO$_2$/In$_2$O$_3$, Ag-SnO$_2$+additives
- Many Ag-MeO types evaluated
- Prediction: Ag-SnO$_2$ will replace Ag-CdO in 10 yrs.
- Make erosion ac switching Ag-CdO & Ag-SnO$_2$
- Guidelines for use of Ag-SnO$_2$
- Release of Cd from Ag-CdO contacts in a fire unlikely
- RoHS rules still allow Cd in Ag-CdO contacts

My 1st first experiments with switching with Ag-SnO$_2$ at 20A (ac) 110V with contacts from Chugai

Patents for Ag-SnO$_2$ & Ag-InO$_2$-SnO$_2$ contacts

1st paper with Ag-SnO$_2$ & Ag-ZnO contacts

Patent for WO$_3$ addition to Ag-SnO$_2$
Ag-CdO vs. Ag-SnO$_2$, Ag-SnO$_2$/InO$_2$ & Other Ag-MeO Contact Materials

Continuous development of Ag-CdO (manufacturing) & Ag-CdO + additives

Continuous development of Ag-SnO$_2$, Ag-SnO$_2$-In$_2$O$_3$, Ag-SnO$_2$+additives

Prediction: Ag-SnO$_2$ will replace Ag-CdO in 10 yrs.

Many Ag-MeO types evaluated

Make erosion ac switching Ag-CdO & Ag-SnO$_2$

Guidelines for use of Ag-SnO$_2$

Release of Cd from Ag-CdO contacts in a fire unlikely

Patents for Ag-SnO$_2$ & Ag-InO$_2$-SnO$_2$ contacts

My 1st first experiments with switching with Ag-SnO$_2$ at 20A with contacts from Chugai

1st paper with Ag-SnO$_2$ & Ag-ZnO contacts

Patent for WO$_3$ addition to Ag-SnO$_2$

RoHS rules still allow Cd in Ag-CdO contacts

Ag-CdO vs. Ag-SnO₂, Ag-SnO₂/InO₂ & Other Ag-MeO Contact Materials

Continuous development of Ag-CdO (manufacturing) & Ag-CdO + additives

Continuous development of Ag-SnO₂, Ag-SnO₂-In₂O₃, Ag-SnO₂+additives

Prediction: Ag-SnO₂ will replace Ag-CdO in 10 yrs.

Many Ag-MeO types evaluated

Make erosion ac switching Ag-CdO & Ag-SnO₂

Guidelines for use of Ag-SnO₂

Release of Cd from Ag-CdO contacts in a fire unlikely

Patents for Ag-SnO₂ & Ag-InO₂-SnO₂ contacts

Patent for WO₃ addition to Ag-SnO₂

1st paper with Ag-SnO₂ & Ag-ZnO contacts

My 1st first experiments with switching with Ag-SnO₂ at 20A with contacts from Chugai

Patent for W0₃ addition to Ag-SnO₂


RoHS rules still allow Cd in Ag-CdO contacts

Continuous development of Ag-SnO₂, Ag-SnO₂-In₂O₃, Ag-SnO₂+additives
Ag-CdO vs. Ag-SnO₂, Ag-SnO₂/InO₂ & Other Ag-MeO Contact Materials

Continuous development of Ag-CdO (manufacturing) & Ag-CdO + additives

My 1st first experiments with switching with Ag-SnO₂ at 20A with contacts from Chugai

Patents for Ag-SnO₂ & Ag-InO₂-SnO₂ contacts

1st paper with Ag-SnO₂ & Ag-ZnO contacts

Prediction: Ag-SnO₂ will replace Ag-CdO in 10 yrs.

Continuous development of Ag-SnO₂, Ag-SnO₂-In₂O₃, Ag-SnO₂+additives

Many Ag-MeO types evaluated

Guidelines for use of Ag-SnO₂

Make erosion ac switching Ag-CdO & Ag-SnO₂

Patent for WO₃ addition to Ag-SnO₂

Release of Cd from Ag-CdO contacts in a fire unlikely

RoHS rules still allow Cd in Ag-CdO contacts

DC Switching

Low current dc telephone relays, activation & showering arc, Pd and Ag-Pd contacts

Automobile relays, 14V dc, Ag, Ag-Ni, Ag-CdO & Ag SnO₂ contact arc erosion

Changes in the contact surface after arcing as a result of ambient effects

1st MEMS paper

Permanent magnets providing a very high transverse magnetic field gives very high arc voltage

42V dc

> 100V dc

Connector disconnect problem at 42V

Description of metallic phase arc & gaseous phase arc erosion

New data of minimum current for arc formation in 14V to 50V dc circuits

DC Switching

Low current dc telephone relays, activation & showering arc, Pd and Ag-Pd contacts

Automobile relays, 14V dc, Ag, Ag-Ni, Ag CdO & Ag SnO₂ contact arc erosion

Changes in the contact surface after arcing as a result of ambient effects

Permanent magnets providing a very high transverse magnetic field gives very high arc voltage

1st MEMS paper

42V dc

> 100V dc

Description of metallic phase arc & gaseous phase arc erosion

Connector disconnect problem at 42V

New data of minimum current for arc formation in 14V to 50V dc circuits

DC Switching

Low current dc telephone relays, activation & showering arc, Pd and Ag-Pd contacts

Automobile relays, 14V dc, Ag, Ag-Ni, Ag CdO & Ag SnO₂ contact arc erosion

Changes in the contact surface after arcing as a result of ambient effects

New data of minimum current for arc formation in 14V to 50V dc circuits

Description of metallic phase arc & gaseous phase arc erosion

Connector disconnect problem at 42V

Permanent magnets providing a very high transverse magnetic field gives very high arc voltage

1st MEMS paper

42V dc

> 100V dc
DC Switching

- Low current dc telephone relays, activation & showering arc, Pd and Ag-Pd contacts
- Automobile relays, 14V dc, Ag, Ag-Ni, Ag CdO & Ag SnO₂ contact arc erosion
- Changes in the contact surface after arcing as a result of ambient effects
- 1st MEMS paper
  - 42V dc
- Permanent magnets providing a very high transverse magnetic field gives very high arc voltage
- Description of metallic phase arc & gaseous phase arc erosion
- Connector disconnect problem at 42V
- > 100V dc
- New data of minimum current for arc formation in 14V to 50V dc circuits
Low current dc telephone relays, activation & showering arc, Pd and Ag-Pd contacts

Automobile relays, 14V dc, Ag, Ag-Ni, Ag CdO & Ag SnO₂ contact arc erosion

Changes in the contact surface after arcing as a result of ambient effects

New data of minimum current for arc formation in 14V to 50V dc circuits

Description of metallic phase arc & gaseous phase arc erosion

Connector disconnect problem at 42V

Permanent magnets providing a very high transverse magnetic field gives very high arc voltage

1st MEMS paper

The most significant development in dc switching

Automobile relays, 14V & 42V dc, open contacts when arc voltage = circuit voltage current interrupted.
In 1997 the Prius Hybrid with > 200V battery: later fully electric autos & PVs.

Use of Nd-Fe-B magnets to give transvers B field (34mT) across open contacts to interrupt up to 10A, 320V. Considered as normal arc blowing.

Use of magnets to give transvers B field (20-30mT) across open bridging contacts to interrupt up to 50A, 500V. Considered as normal arc blowing.

The arc length with the B field is too short to give 500V!

Use of magnets to give transvers B field (30-90mT) across open bridging contacts to interrupt up to 50A, 700V. Considered as normal arc blowing.

Use of magnets to give transvers B field across open bridging contacts to interrupt dc circuits up to 700V results in compact dc relay design for electric autos and PVs. There is no coherent theory of how the high arc voltage develops. It cannot be just arc lengthening.
The most significant development in dc switching

Automobile relays, 14V & 42V dc, open contacts when arc voltage = circuit voltage current interrupted. In 1997 the Prius Hybrid with > 200V battery: later fully electric autos and PVs.

Use of Nd-Fe-B magnets to give transversal B field (34mT) across open contacts to interrupt up to 10A, 320V. Considered as normal arc blowing.

In 1997, the Prius Hybrid had a > 200V battery. Later fully electric autos and PVs used magnets to give a transversal B field (34mT) across open contacts to interrupt up to 10A, 320V. This was considered normal arc blowing.

1st paper on the use of high B-field magnets to give transversal B field (> 13mT) across opening contacts to interrupt 10A, 42V. Considered as normal arc blowing.

Use of magnets to give transversal B field (> 13mT) across opening contacts to interrupt 10A, 42V. Initially considered as normal arc blowing.

Use of magnets to give transversal B field (20-30mT) across open bridging contacts to interrupt up to 50A, 500V. Initially considered as normal arc blowing.

The arc length with the B field is too short to give 500V!

Use of magnets to give transversal B field (30-90mT) across open bridging contacts to interrupt up to 50A, 700V. Considered as normal arc blowing.

Use of magnets to give transversal B field across open bridging contacts to interrupt dc circuits up to 700V results in compact dc relay design for electric autos and PVs. There is no coherent theory of how the high arc voltage develops. It cannot be just arc lengthening.
The most significant development in dc switching

Automobile relays, 14V & 42V dc, open contacts when arc voltage = circuit voltage current interrupted.

In 1997 the Prius Hybrid with > 200V battery: later fully electric autos and PVs.

Use of Nd-Fe-B magnets to give transverse B field (34mT) across open contacts to interrupt up to 10A, 320V. Considered as normal arc blowing.

B field 0.53T

No Magnet

4A, 500V

Use of magnets to give transverse B field across open bridging contacts to interrupt up to 50A, 700V. Considered as normal arc blowing.

Use of magnets to give transverse B field (30-90mT) across open bridging contacts to interrupt up to 50A, 700V. Considered as normal arc blowing.

Use of magnets to give transvers B field across open bridging contacts to interrupt dc circuits up to 700V results in compact dc relay design for electric autos and PVs. There is no coherent theory of how the high arc voltage develops. It cannot be just arc lengthening.

1st paper on the use of high B-field magnets to give transverse B field (> 13mT) across opening contacts to interrupt 10A, 42V. Considered as normal arc blowing.

The arc length with the B field is too short to give 500V!
The most significant development in dc switching

Automobile relays, 14V & 42V dc, open contacts when arc voltage = circuit voltage current interrupted. In 1997 the Prius Hybrid with > 200V battery: later fully electric autos and PVs.

Use of Nd-Fe-B magnets to give transvers B field (34mT) across open contacts to interrupt up to 10A, 320V. Considered as normal arc blowing

B field 0.53T

No Magnet

4A, 500V

Use of magnets to give transvers B field (20-30mT) across open bridging contacts to interrupt up to 50A, 500V. Considered as normal arc blowing

The arc length with the B field is too short to give 500V!

Use of magnets to give transvers B field across open bridging contacts to interrupt dc circuits up to 700V results in compact dc relay design for electric autos and PVs. There is no coherent theory of how the high arc voltage develops. It cannot be just arc lengthening

1st paper on the use of high B-field magnets to give transvers B field (> 13mT) across opening contacts to interrupt 10A, 42V. Considered as normal arc blowing
Arc erosion studies. Ratio of papers with currents < 100A to those with currents > 100A = 0.55

Observation of arc motion into arc quenching systems

Max weld force as a function of energy into contact:
\[ F_{W\text{(weld)}} = K \times E^{2/3} \]

Difference between make arc erosion and break arc erosion for Ag-CdO and Ag-SnO$_2$ contacts

1$^{\text{st}}$ model of arc motion into an arc channel

Changes in the contact surface after arcing as a result of ambient effects
AC Switching

Arc erosion studies. Ratio of papers with currents < 100A to those with currents > 100A = 0.55

Observation of arc motion into arc quenching systems

Max weld force as a function of energy into contact: 
$$F_{W(weld)} = K \times E^{2/3}$$

1ST model of arc motion into an arc channel

Difference between make arc erosion and break arc erosion for Ag-CdO and Ag-SnO$_2$ contacts

Changes in the contact surface after arcing as a result of ambient effects

Arc erosion studies. Ratio of papers with currents < 100A to those with currents > 100A = 0.55

Observation of arc motion into arc quenching systems

Max weld force as a function of energy into contact:
\[ F_{W(weld)} = K \times E^{2/3} \]

Changes in the contact surface after arcing as a result of ambient effects

Difference between make arc erosion and break arc erosion for Ag-CdO and Ag-SnO₂ contacts

1ST model of arc motion into an arc channel
Arc erosion studies. Ratio of papers with currents < 100A to those with currents > 100A = 0.55

Observation of arc motion into arc quenching systems

Max weld force as a function of energy into contact: $F_{W(weld)} = K \times E^{2/3}$

Difference between make arc erosion and break arc erosion for Ag-CdO and Ag-SnO$_2$ contacts

1st model of arc motion into an arc channel

Changes in the contact surface after arcing as a result of ambient effects
AC Switching

Arc motion off contacts

Arc erosion studies. Ratio of papers with currents < 100A to those with currents > 100A = 0.55

Observation of arc motion into arc quenching systems

Max weld force as a function of energy into contact:
\[ F_{W(\text{weld})} = K \times E^{2/3} \]

Difference between make arc erosion and break arc erosion for Ag-CdO and Ag-SnO₂ contacts

1ˢᵗ model of arc motion into an arc channel

Changes in the contact surface after arcing as a result of ambient effects
Effect of Silicone Lubricants, Sealants and Potting Compounds on Arcing Contacts

- Silicones shown to migrate over long distances to relay contacts
- Comparison of silicones & SiC or SiO₂ from sand blasting in R_c after low current dc arcing
- R_c increases linearly switching 0.5 to 500mA in presence of Silicone rubber
- Silicones coatings, encapsulants & potting compounds all a source of trouble
- Effect of 100mA switching frequency
- High R_c after 300 operations at 150A ac
- Effect of silicone vapor concentration and 120mA dc switching frequency
- Silicone vapor formation rate on contact surfaces
- Dimethyl Silicones: D_n
- \((\text{CH}_3\text{SiO})_n\)
- Acrylic based polymeric materials show promise as silicone free encapsulants
- Description of the formation of SiO₂ and carbon compounds on contact surfaces after arcing in silicone vapors

Silicones shown to migrate over long distances to relay contacts

Comparison of silicones & SiC or SiO₂ from sand blasting in Rₚ after low current dc arcing

Rₚ increases linearly switching 0.5 to 500mA in presence of Silicone rubber

Effect of silicone vapor concentration and 120mA dc switching frequency

Silicone vapor formation rate on contact surfaces

Silicones coatings, encapsulants & potting compounds all a source of trouble

Effect of 100mA switching frequency

High Rₚ after 300 operations at 150A ac

Silicone vapor formation rate on contact surfaces

Effect of silicone vapor concentration and 120mA dc switching frequency

Description of the formation of SiO₂ and carbon compounds on contact surfaces after arcing in silicone vapors

Silicone vapor formation rate on contact surfaces

Acrylic based polymeric materials show promise as silicone free encapsulants

Dimethyl Silicones: Dₙ

(CH₃)₂SiO]ₙ

Acrylic based polymeric materials show promise as silicone free encapsulants
Effect of Silicone Lubricants, Sealants and Potting Compounds on Arcing Contacts

Silicones shown to migrate over long distances to relay contacts

Comparison of silicones & SiC or SiO$_2$ from sand blasting in $R_C$ after low current dc arcing

$R_C$ increases linearly switching 0.5 to 500mA in presence of Silicone rubber

Effect of silicone vapor concentration and 120mA dc switching frequency

Silicone vapor formation rate on contact surfaces

Silicones coatings, encapsulants & potting compounds all a source of trouble

High $R_C$ after 300 operations at 150A ac

Effect of 100mA switching frequency

Silicone vapor formation rate on contact surfaces

Comparison of silicones & SiC or SiO$_2$ from sand blasting in $R_C$ after low current dc arcing

Effect of silicone vapor concentration and 120mA dc switching frequency

Silicone vapor formation rate on contact surfaces

Silicones coatings, encapsulants & potting compounds all a source of trouble

Acrylic based polymeric materials show promise as silicone free encapsulants

Description of the formation of SiO$_2$ and carbon compounds on contact surfaces after arcing in silicone vapors

Dimethyl Silicones: Dn

(CH$_3$)$_2$SiO]$_n$

Acrylic based polymeric materials show promise as silicone free encapsulants
Effect of Silicone Lubricants, Sealants and Potting Compounds on Arcing Contacts

Silicones shown to migrate over long distances to relay contacts

Silicones coatings, encapsulants & potting compounds all a source of trouble

Effect of 100mA switching frequency

Comparison of silicones & SiC or SiO₂ from sand blasting in Rₐ after low current dc arcing

Effect of silicone vapor concentration and 120mA dc switching frequency

Silicone vapor formation rate on contact surfaces

Rₐ increases linearly switching 0.5 to 500mA in presence of Silicone rubber

Description of the formation of SiO₂ and carbon compounds on contact surfaces after arcing in silicone vapors

Acrylic based polymeric materials show promise as silicone free encapsulants

Dimethyl Silicones: Dₙ

(CH₃)₂SiO]ᵥ

D₄

Silicones coatings, encapsulants & potting compounds all a source of trouble

Effect of 100mA switching frequency

High Rₐ after 300 operations at 150A ac

Silicone vapor formation rate on contact surfaces

Effect of Silicone Lubricants, Sealants and Potting Compounds on Arcing Contacts

Silicones shown to migrate over long distances to relay contacts.

Silicones coatings, encapsulants & potting compounds all a source of trouble.

Effect of silicone vapor concentration and 120mA dc switching frequency.

Effect of 100mA switching frequency.

High $R_C$ after 300 operations at 150A ac.

$R_C$ increases linearly switching 0.5 to 500mA in presence of Silicone rubber.

Silicone vapor formation rate on contact surfaces.

Effect of silicone vapor concentration and 120mA dc switching frequency.

Comparison of silicones & SiC or SiO$_2$ from sand blasting in $R_C$ after low current dc arcing.

Silicones coatings, encapsulants & potting compounds all a source of trouble.

Effect of silicone vapor concentration and 120mA dc switching frequency.

Silicone vapor formation rate on contact surfaces.

Silicones coatings, encapsulants & potting compounds all a source of trouble.

Effect of silicone vapor concentration and 120mA dc switching frequency.

Silicone vapor formation rate on contact surfaces.

Effect of silicone vapor concentration and 120mA dc switching frequency.

Silicone vapor formation rate on contact surfaces.

Description of the formation of SiO$_2$ and carbon compounds on contact surfaces after arcing in silicone vapors.

Acrylic based polymeric materials show promise as silicone free encapsulants.

Silicones coatings, encapsulants & potting compounds all a source of trouble.

Effect of silicone vapor concentration and 120mA dc switching frequency.

Silicone vapor formation rate on contact surfaces.

Description of the formation of SiO$_2$ and carbon compounds on contact surfaces after arcing in silicone vapors.

Acrylic based polymeric materials show promise as silicone free encapsulants.

Silicone vapor formation rate on contact surfaces.

Description of the formation of SiO$_2$ and carbon compounds on contact surfaces after arcing in silicone vapors.

Acrylic based polymeric materials show promise as silicone free encapsulants.

Silicone vapor formation rate on contact surfaces.

Description of the formation of SiO$_2$ and carbon compounds on contact surfaces after arcing in silicone vapors.

Acrylic based polymeric materials show promise as silicone free encapsulants.
The Nobel Prize

Usually is awarded to scientists who have beavered long and hard in a laboratory, but sometimes serendipity can lead to the award.

For example: Penzias & Wilson were awarded the Nobel Prize in Physics in 1978 for stumbling on the microwave background radiation from the big bang.

In 1964 They had some irritating interference in their supersensitive 6m horn antenna.

They eliminated all potential interferences including pigeon poop, but still found a residual noise 100 times greater than they expected spread evenly across the sky.

They concluded that the noise originated from somewhere outside our galaxy, but only when they discussed it with a Princeton physicist that it was discovered what they had accidentally observed.
Activation

• Carbon deposit on switching contact surfaces after a low current (< 1A) dc arc.

• Problem identified by Bell researchers with their telephone relays from the 1950’s to 1975. Detailed analysis of its structure 1971 & 1975.

• Caused by trace hydrocarbon gases in the ambient air probably from plasticizers in the coil windings.

• The mushroom like deposits led to longer arcing times and to relay failures

• 1975 Holm Conference paper showed these structures.

• It can occur at higher currents but the carbon can be eroded.
Buckminsterfullerenes (Bucky-Balls)

A spherical fullerene molecule of $C_{60}$ with a structure that resembles a soccer ball.

First claimed generation of $C_{60}$ by Kroto, Heath, O’Brian, Curl, & Smalley (Rice University) in 1985 firing a laser beam into a block of C

Kroto, Heath, & Smalley Awarded the 1996 Nobel Prize in Chemistry

Did the contact scientists in Bell Columbus organization miss out on a Nobel prize?

My own team of plasma researchers manufactured Bucky-Balls in the late 1980’s using an arc discharge in air containing a hydro-carbon gas.
Bucky-Ball creation by an arc in a hydrocarbon ambient

Gray: Holm Conference 1975. A low current (0.5A) arc in air plus toluene.

Analysis showed balls of carbon material 45nm in diameter

An 8A arc in benzene plus argon

High resolution transmission electron microscope showed giant fullerenes 20 – 60nm in diameter

10 years before Kroto et al’s Bucky-Ball announcement Gray had produced them. A missed opportunity?
Key Rules of Thumb

1) Contact Resistance

\[ R_c = \frac{\rho}{2\alpha} \sqrt{\frac{\pi H}{F}} \]

2) Temperature of the contact spot

\[ V_c = \sqrt{4L(T_c^2 - T_0^2)} \]

3) Blow-Off force from current passing through closed contacts

\[ F_B = 4.8 \times 10^{-7} i^2 \text{ N} \]

4) Maximum welding force as function of energy into the contacts \([K \text{ is } f(\text{contact material})]\)

\[ F_w = KE_c^{2/3} \]

5) Threshold closed contact welding current for ‘n’ regions of contact

\[ i_w = \frac{2U_m (\sqrt{n}) \sqrt{F}}{\left[ \rho_0 \left[ 1 + \frac{2}{3} \alpha (T_1 - T_0) \right] \right]^2 \pi \left( 0.1H \right) + 4U_m^2 (\beta) } \]
Future Trends

• Connectors
  • Ag plate + inhibitors will replace Au for some electronic connectors
  • Research on innovative coatings for electronic RF connectors will employ capacitive coupling so protective non-conducting surfaces will be used
  • Ni will continue as the most common underplate, but work for more protective combinations of underplates will continue.
  • Sn & Ni plating will continue for auto, appliance & household connectors
  • Awareness of fretting will ensure that motion of the contact interface is taken into account when designing and applying connectors (electronic to power)
  • Lubrication will be more common
  • Effect of heat transfer through lubricant outside the conduction region will be analyzed
  • Al will not be used for household wiring
• **Switches**
  - Electronic sensing and tripping systems applied to switches of all types will expand
  - MEMS switches will find a commercial application and may become hermetically sealed with a non oxidizing gas
  - Ag-SnO$_2$ contact material will gradually be the contact material of choice for currents below 4kA in air. Although Ag and Ag-Ni will continue for low current relays.
  - High voltage (> 100V) dc switches with permanent magnets will produce a new range of compact relays for auto and photo-voltaic applications. There will be a gradual theoretical understanding of the high arc voltage development
Thank You