The 2016 Morton Antler Lecture

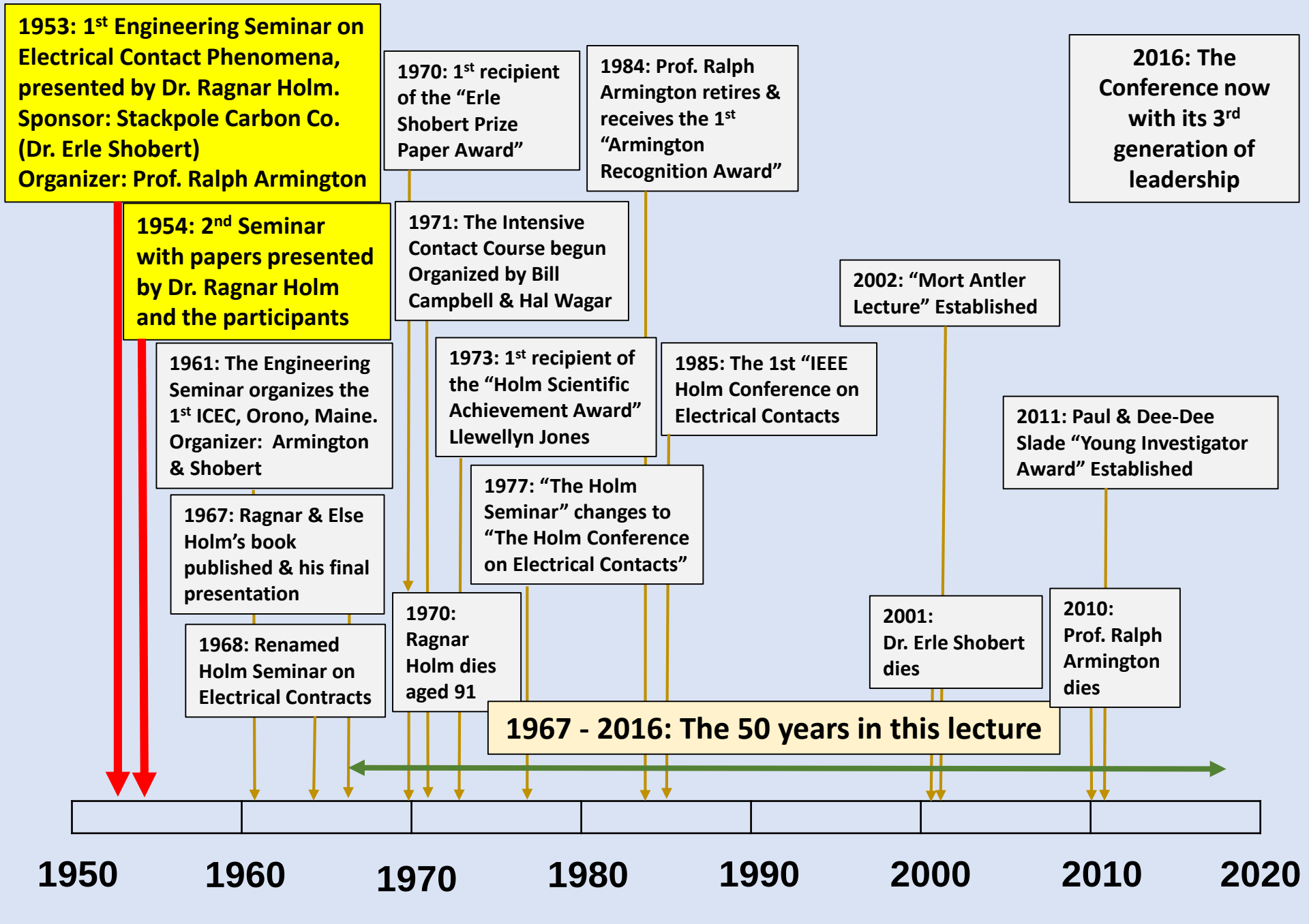
50 Years of the Holm Conference on Electrical Contacts 1967 - 2016

Paul G. Slade

“All knowledge of reality proceeds from experience & culminates in a new experience”

(Einstein)

The Dateline of the Holm Seminars and Conferences



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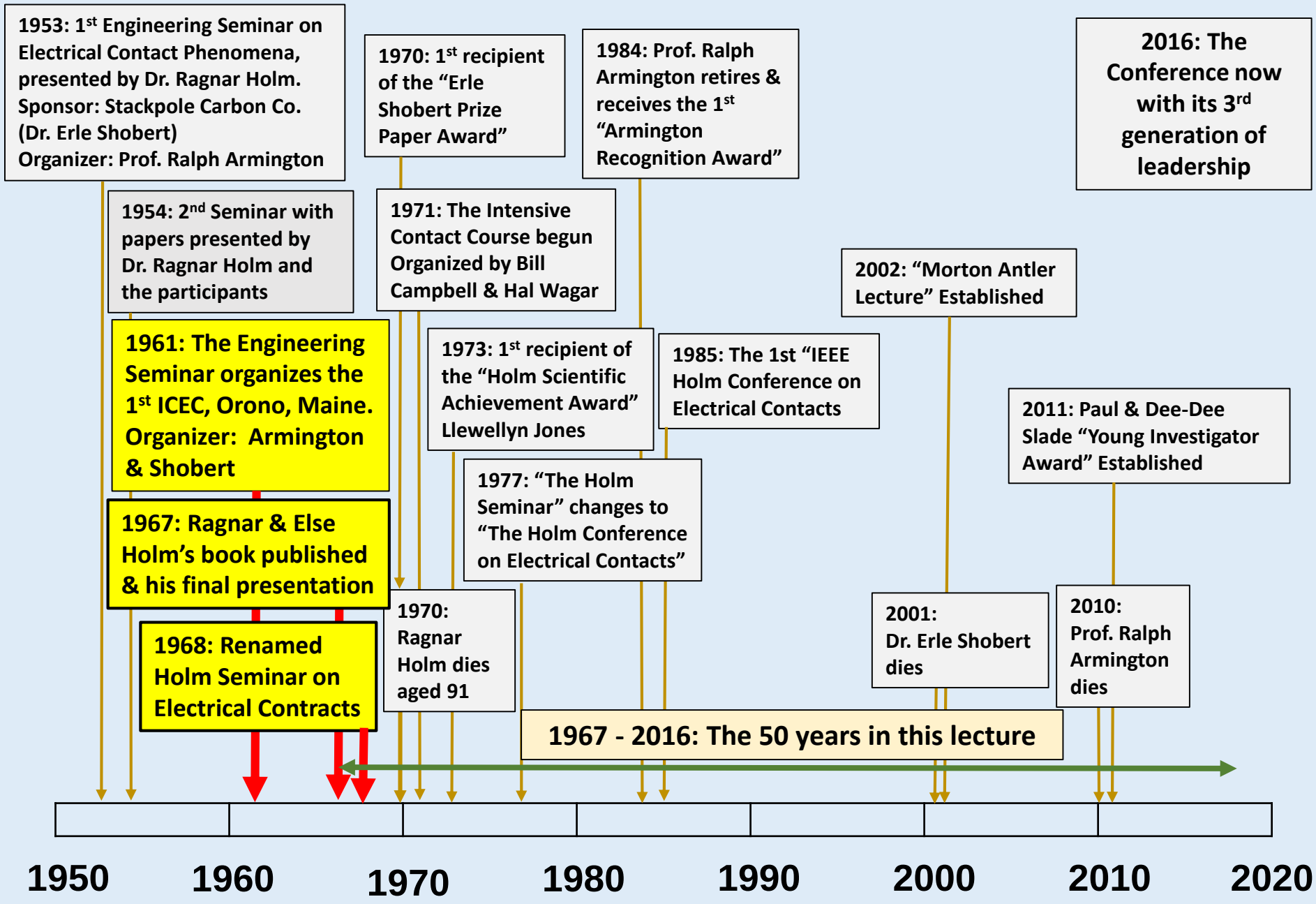

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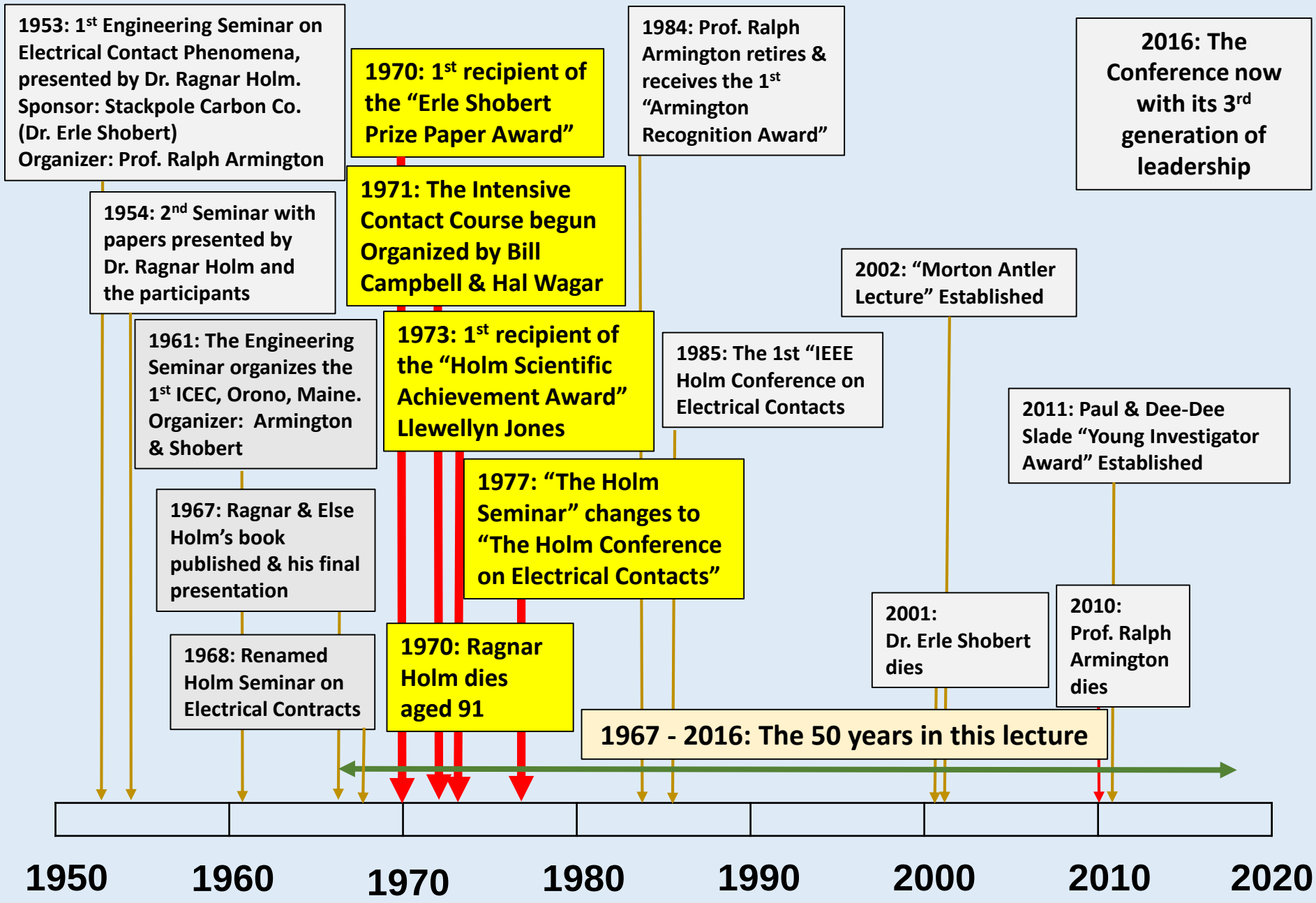

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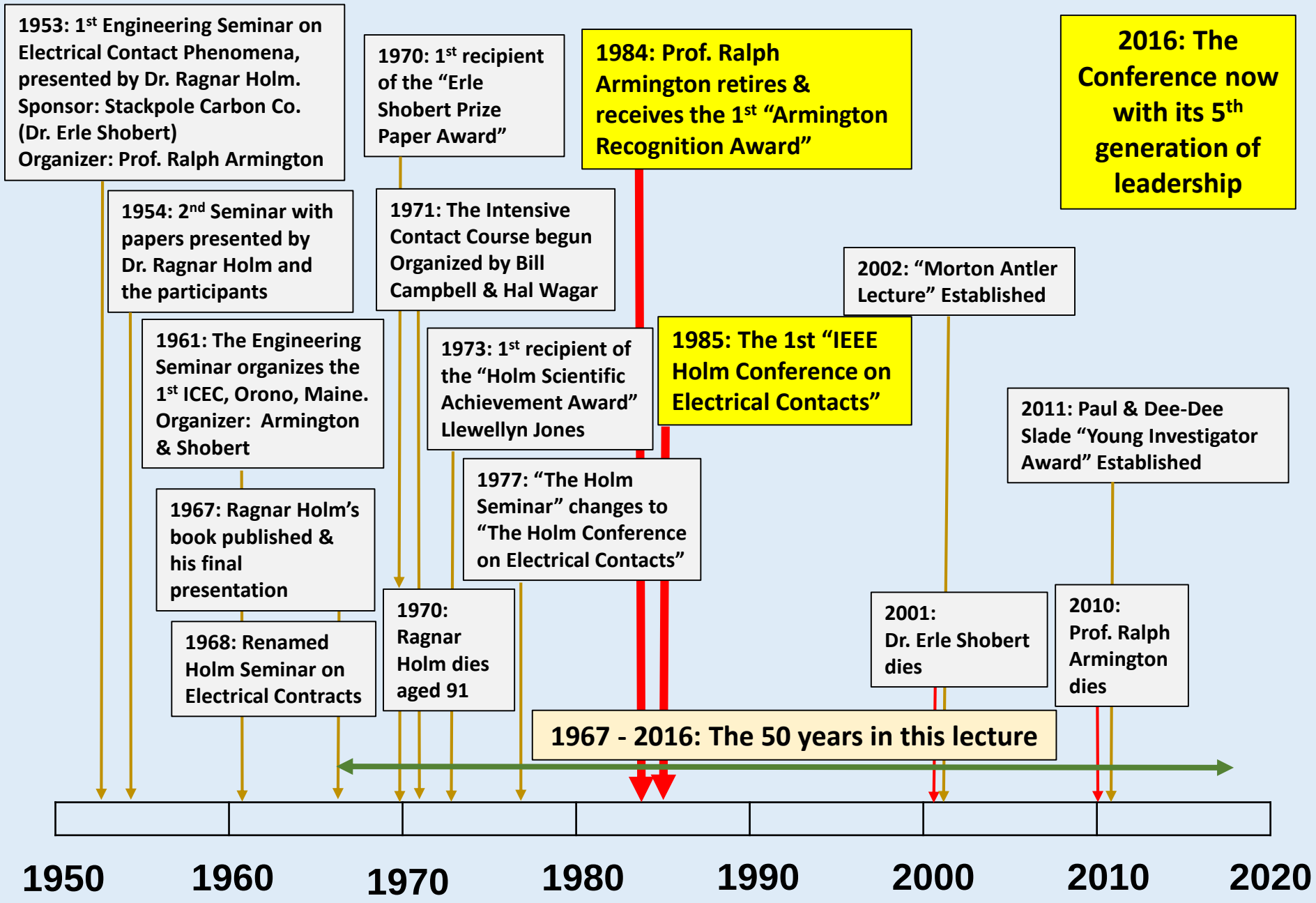

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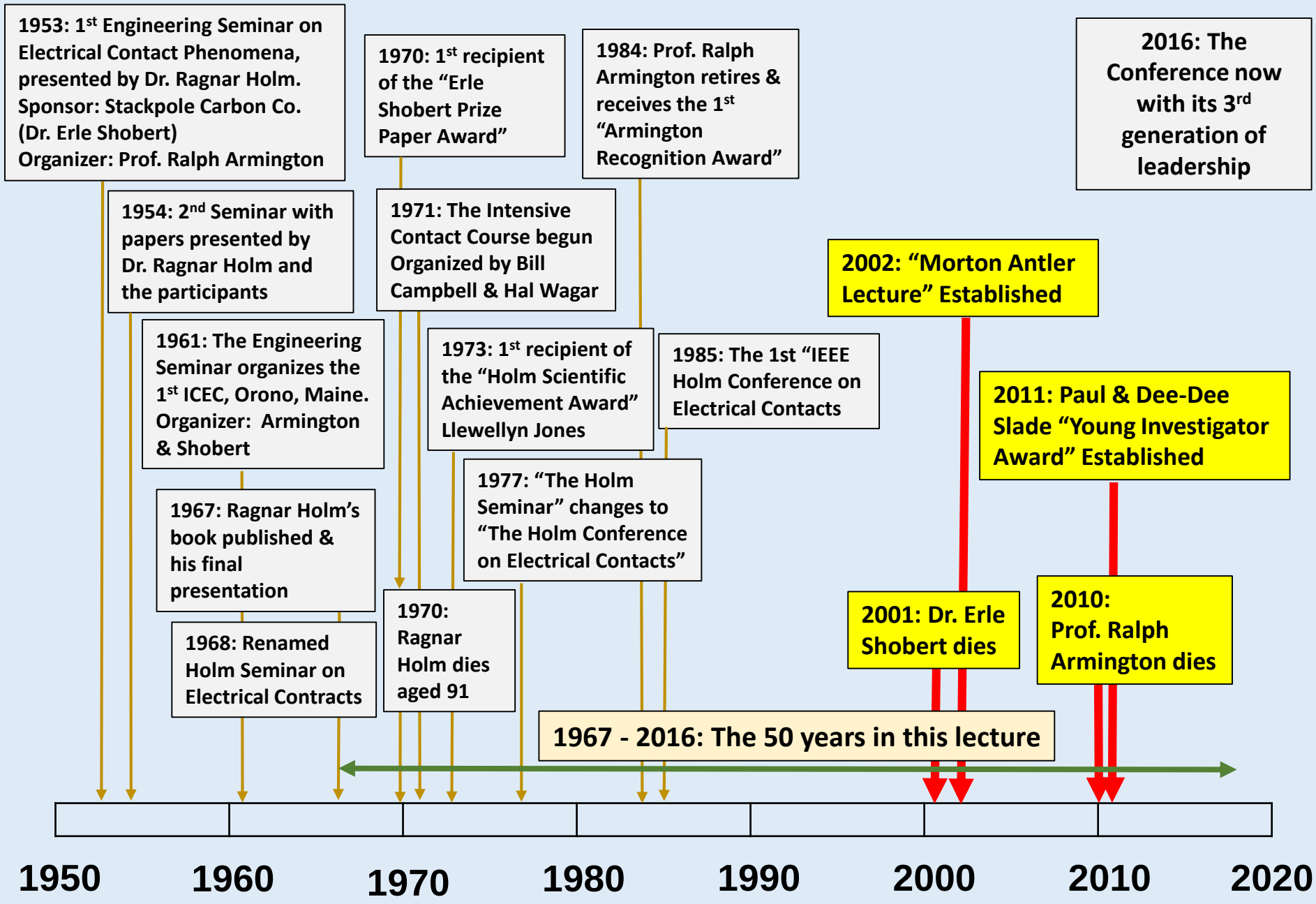
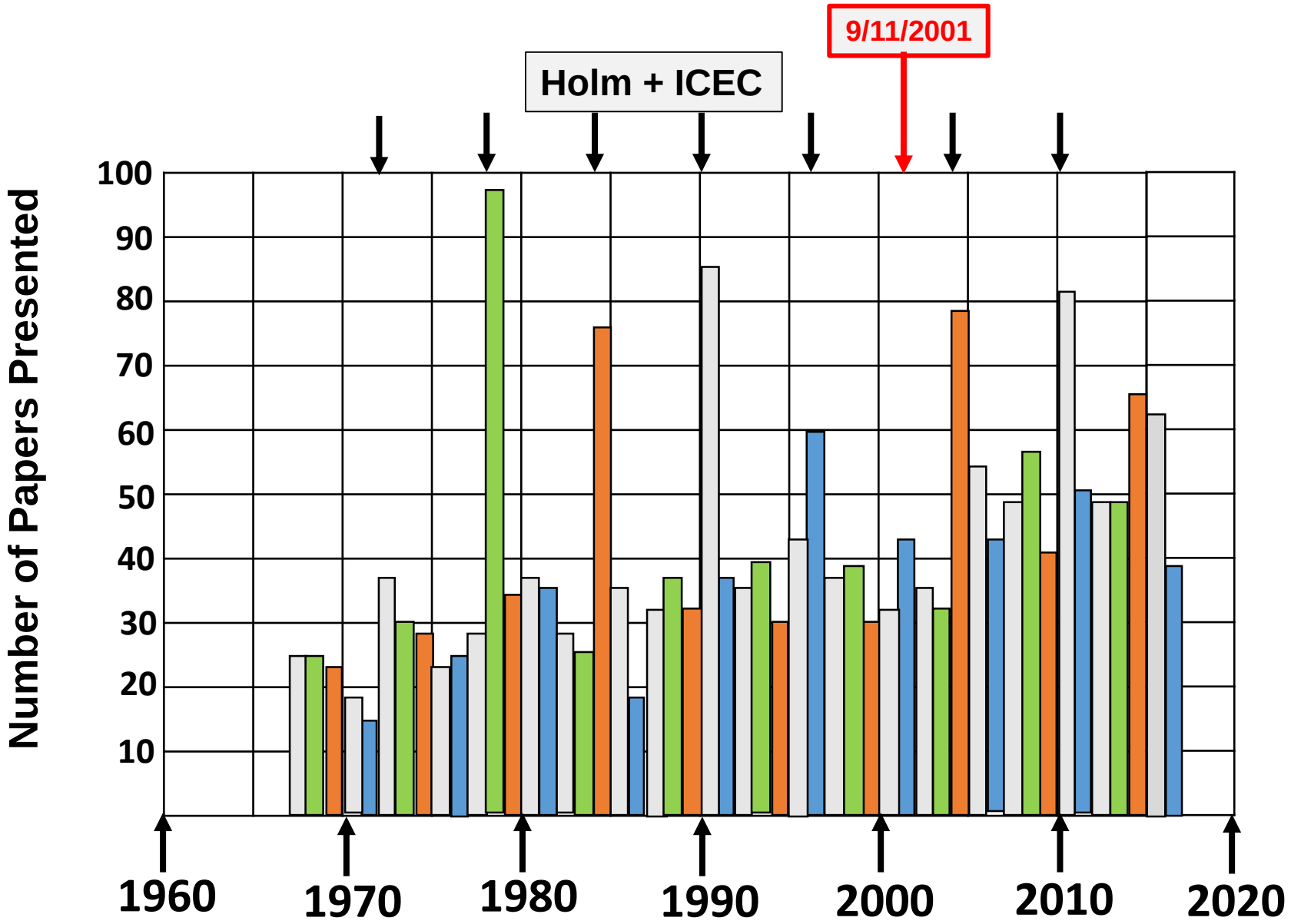
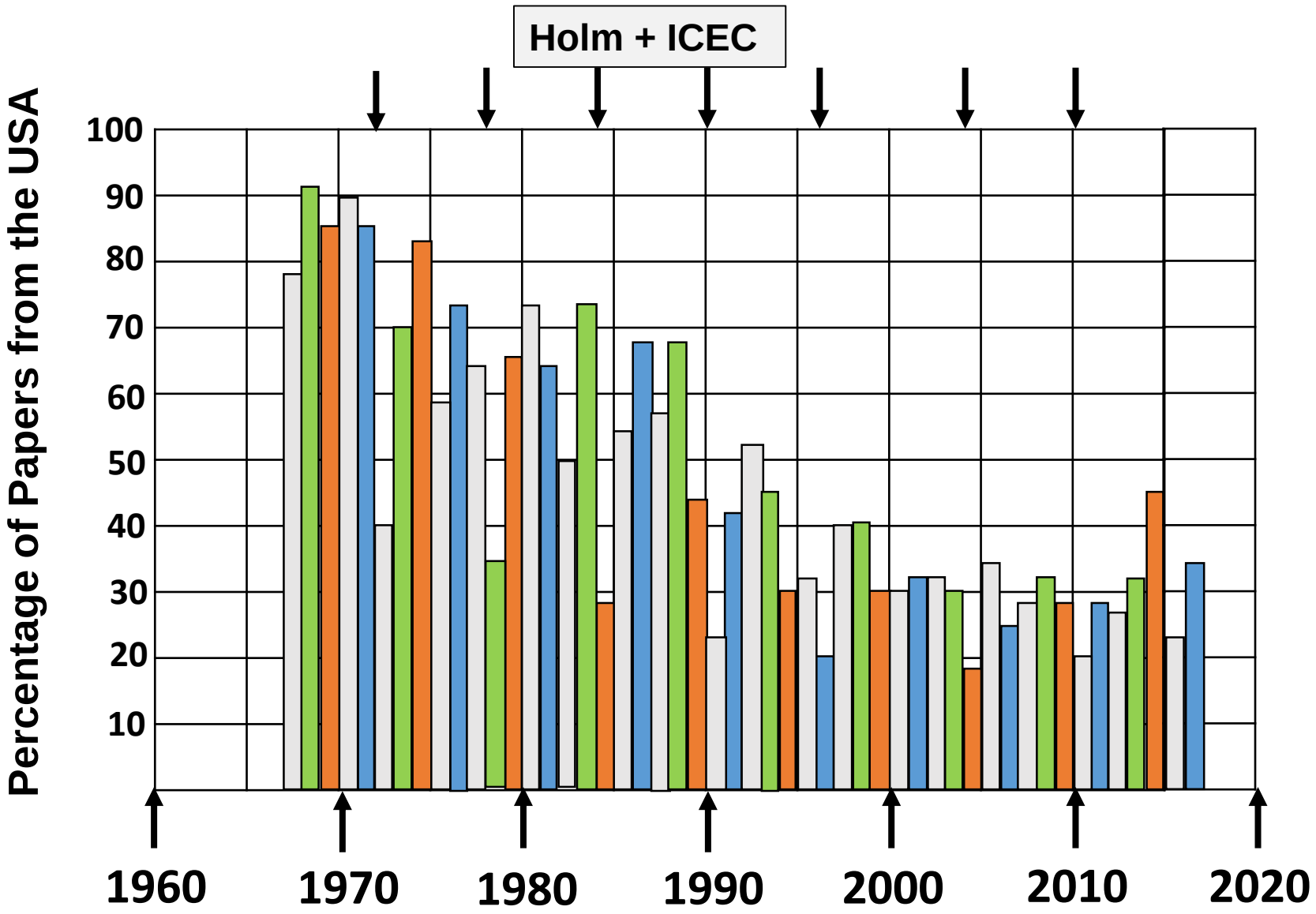


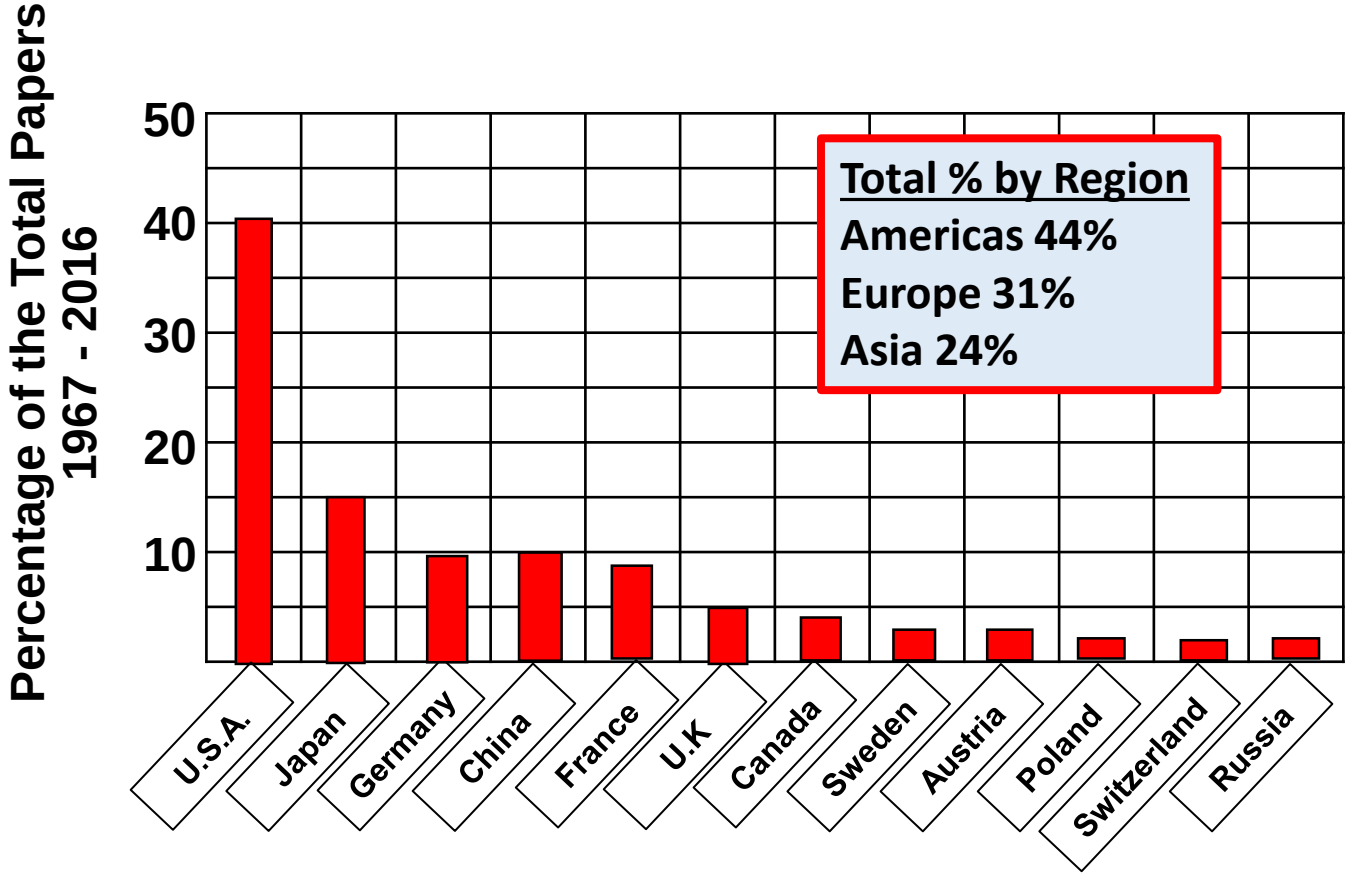
The Number of Papers Presented at the Holm Conferences



The Holm Conference has become increasingly International

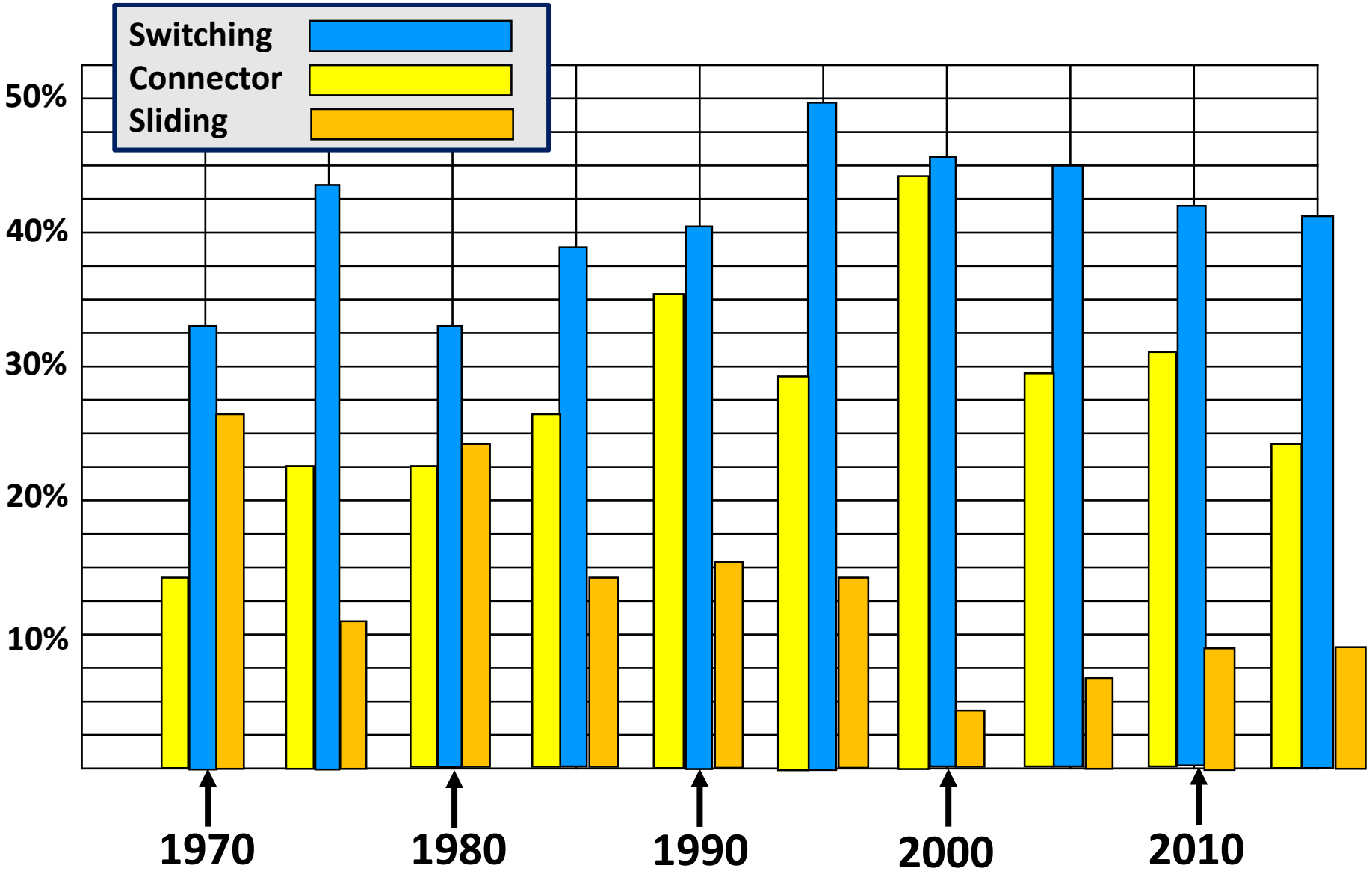


International Papers & Presentations at the Holm Conference 1967 to 2015



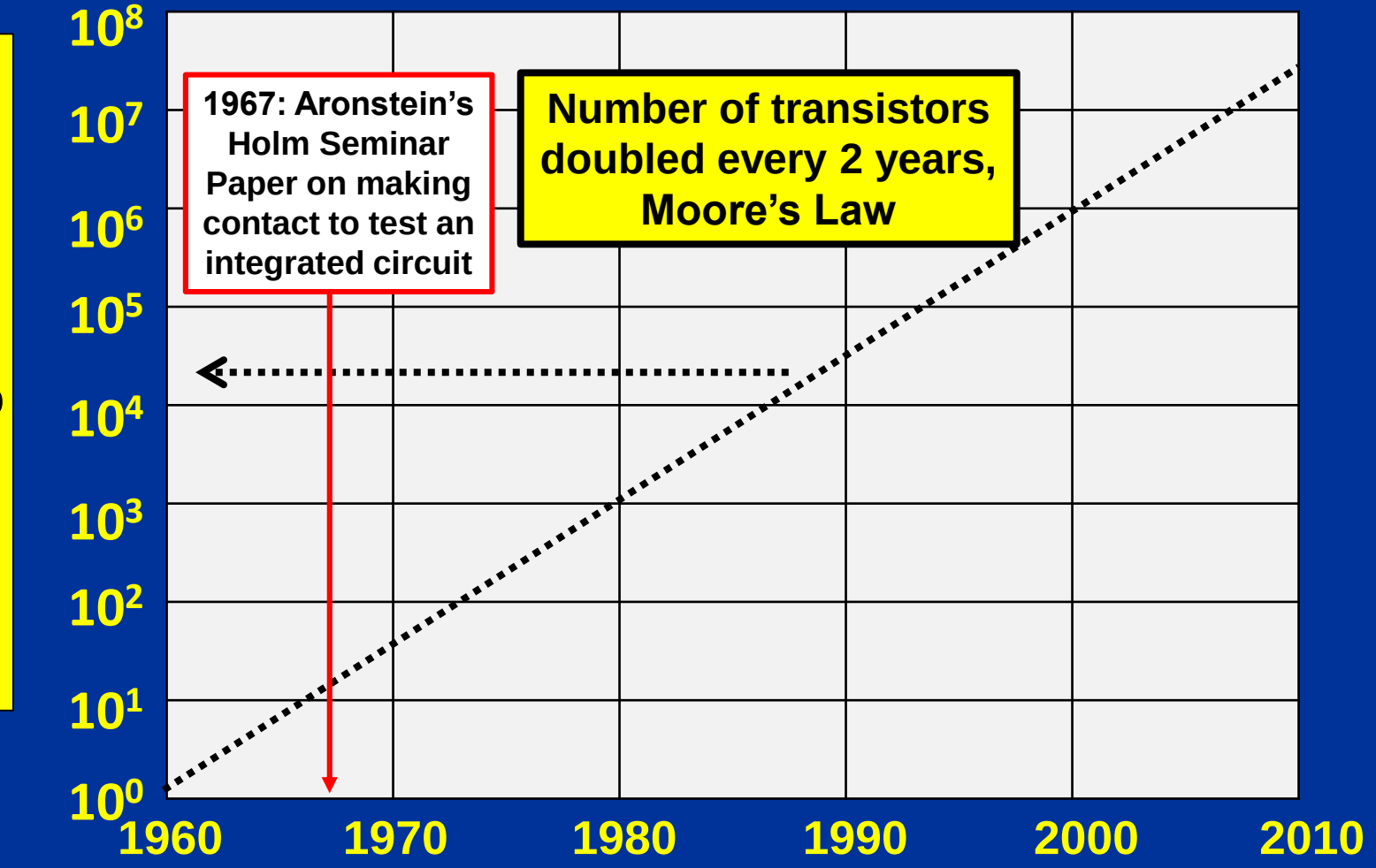
Less than 1%(i.e.1-8 papers)
Bulgaria
Czech Republic
Norway
Kazakhstan
South Korea
Hungary
Holland
Taiwan
Brazil
Australia
Denmark
Israel
Finland
India
Greece
Serbia
Turkey
Egypt
Pakistan

Percentage of Papers on Switching with Arcing, Connectors & Sliding



The Expansion of Information

1960



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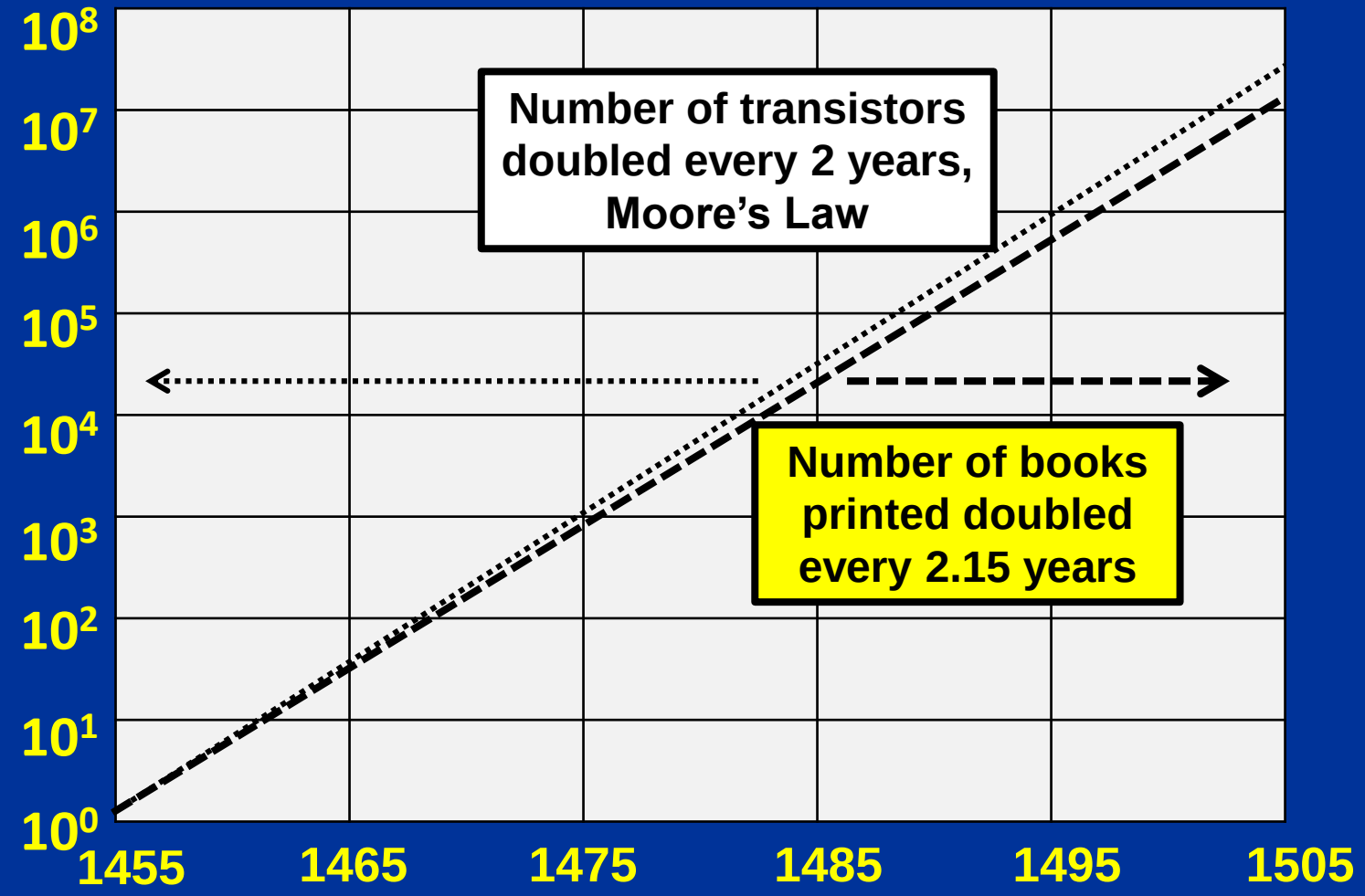
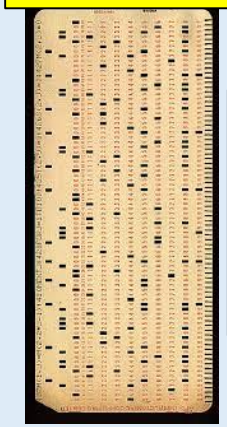


New Scientist, 16 March, 1972: ….. the optimists argue that if microelectronics can make small computers as inexpensive as telephones then people will buy them even though they are in use for a small fraction of the time. Once in the house, or small office, new uses will be found for them and eventually 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

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

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

IBM PC w. easy to use software 1981

1990: Microsoft Office

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

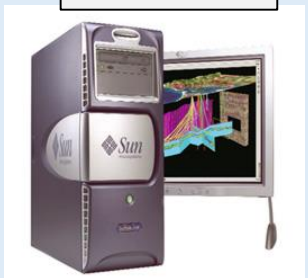
Ever increasing capability. Now used for computer graphics and high level computation

Slide Rule

Mini Computer 1969

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.

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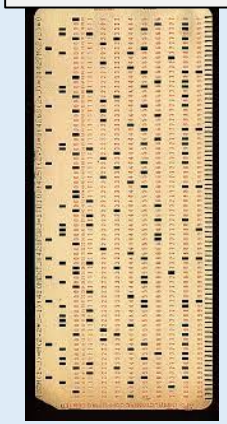

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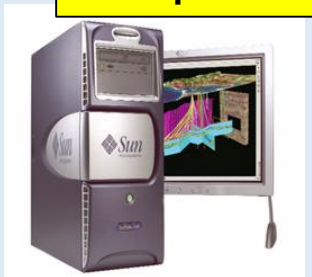

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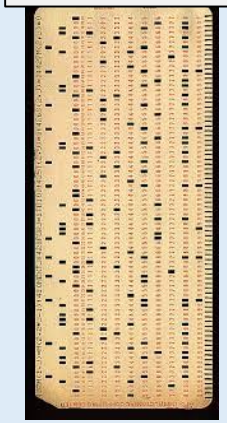

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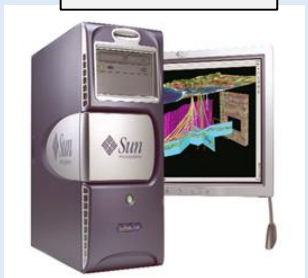

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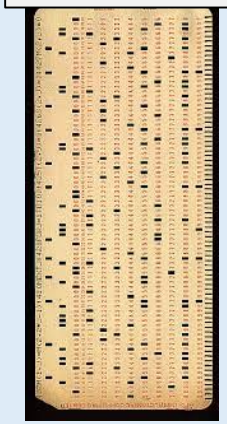

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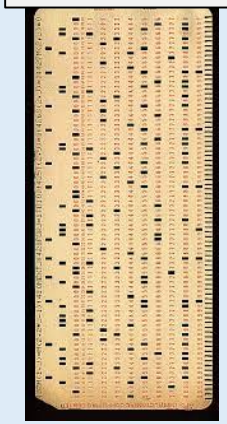

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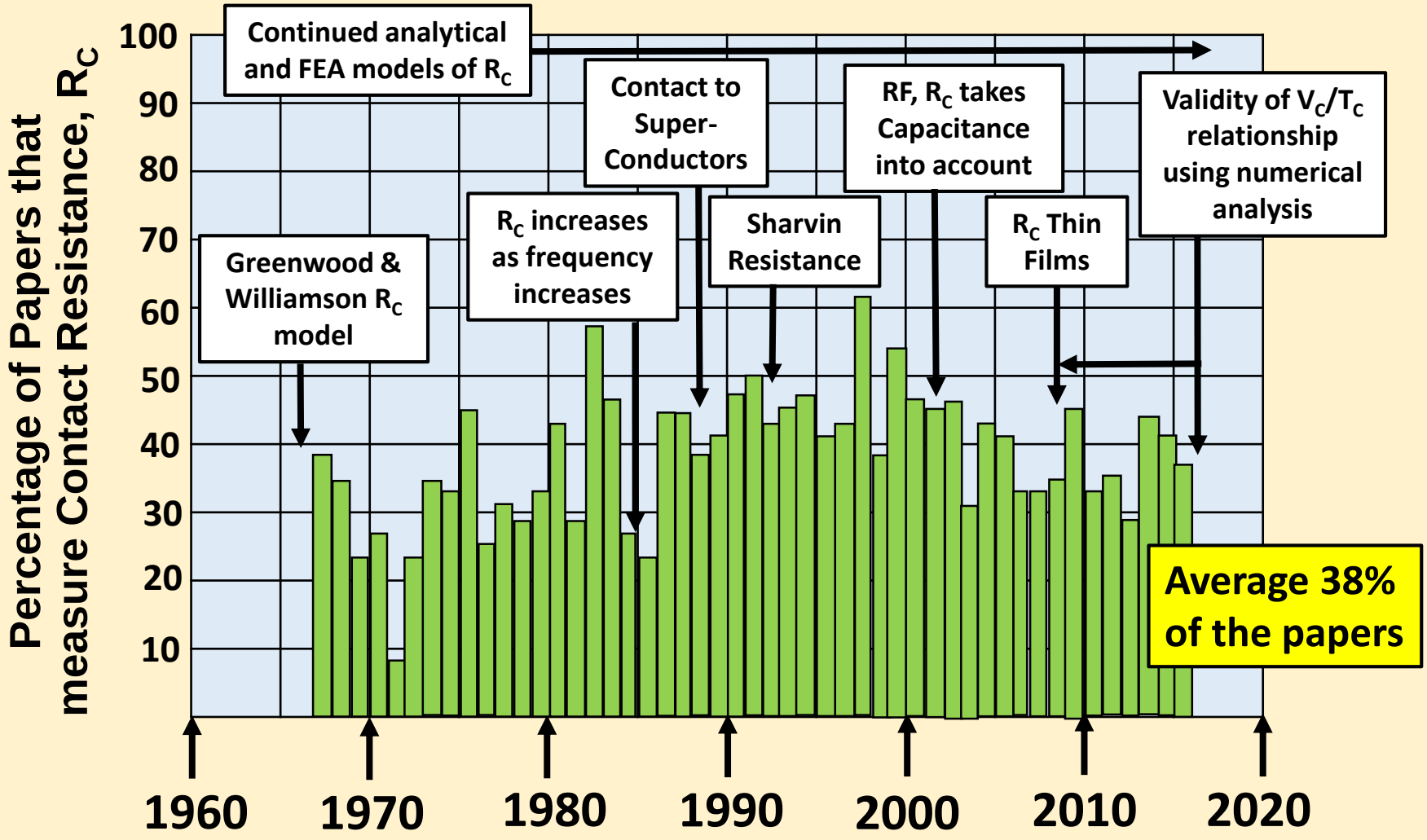
Contact Resistance

SEM & High Speed Oscilloscopes developed

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

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



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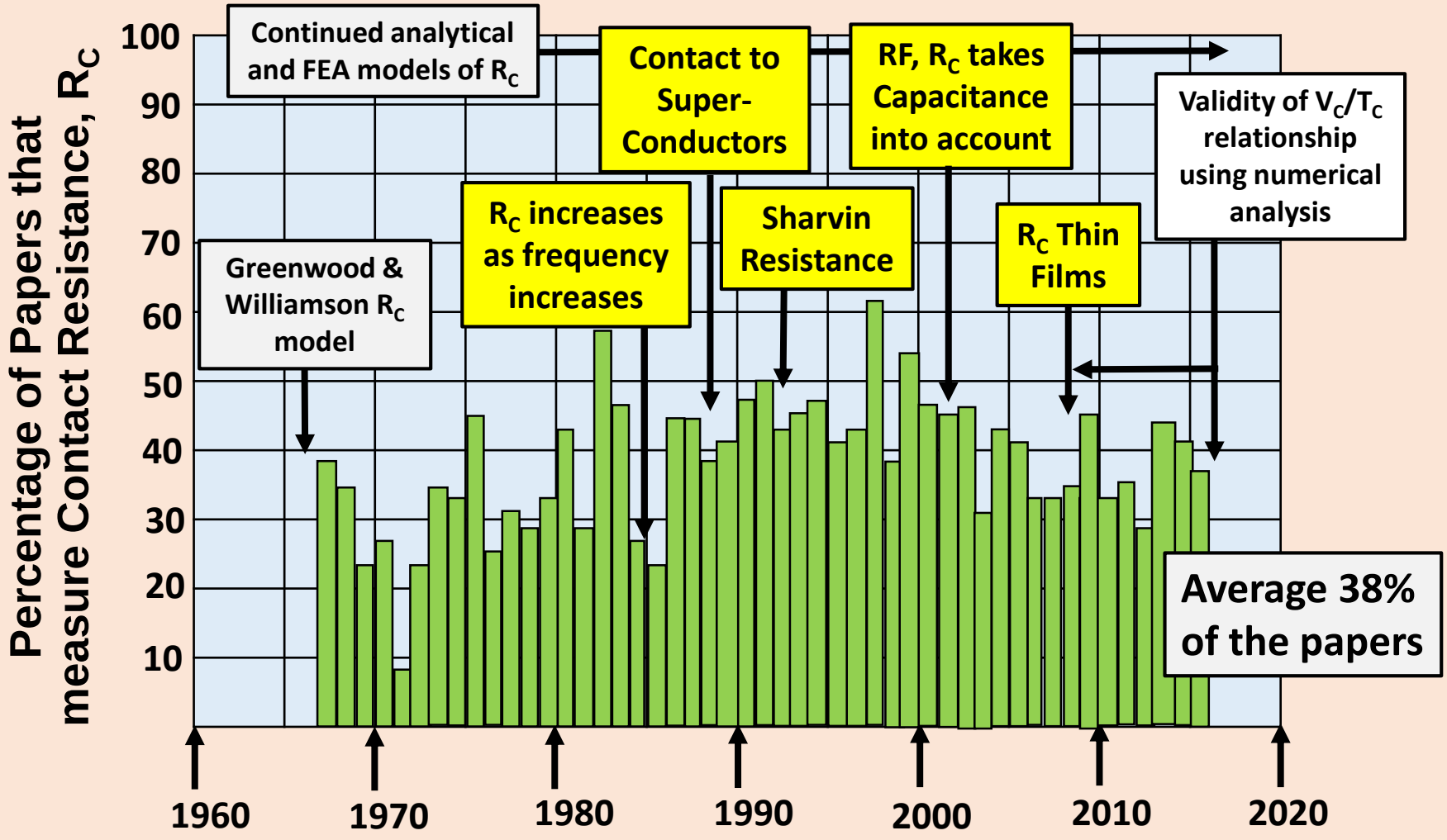

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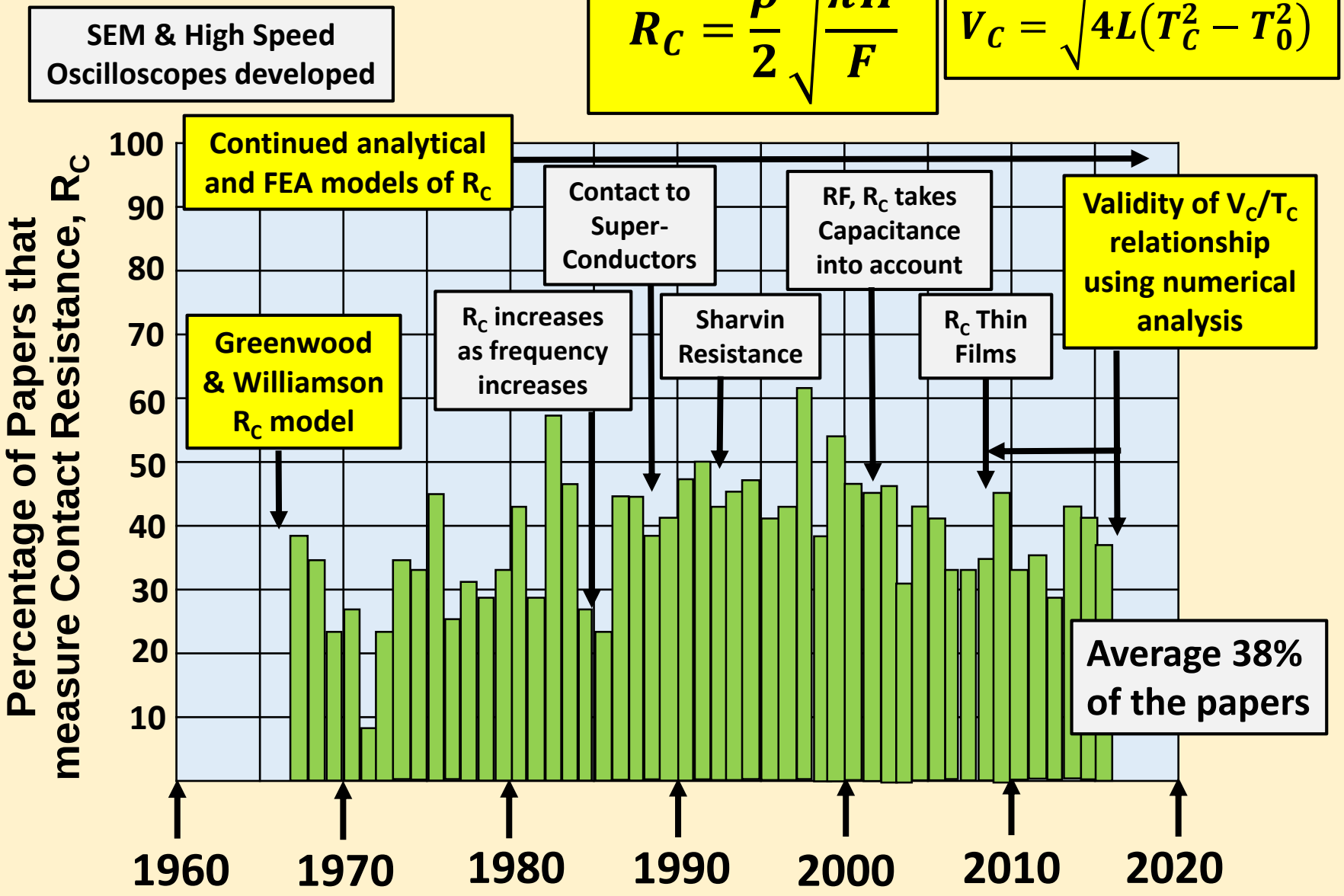
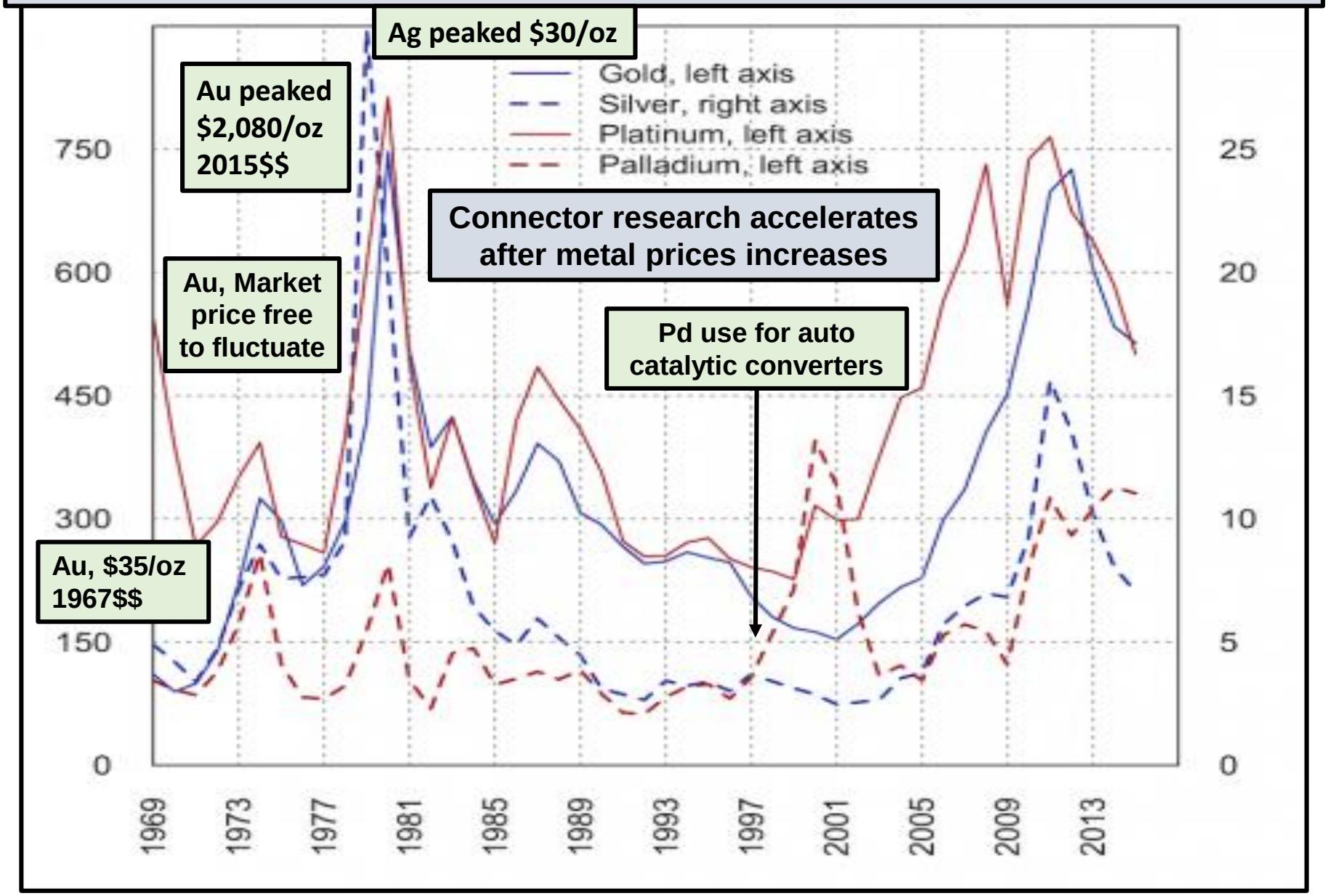


Connectors

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**

Precious metals prices in constant (1983) dollars



Minimum Contact Force for Stable Conduction

Metal	Minimum Contact Force, N
Au	0.05 – 0.1
Pt family (Pd)	0.1 – 0.5
Au plate	0.5 – 1.0
Ag	1.0 – 2.5
Au-Ag, Ag-Pd, Ag-Cu, Ag-CdO	1.0 – 3.0
Ag-SnO_2	2.5 – 4.0
Cu family (Cu-Be, Brass, Cupro-Nickels, Phosphor Bronze)	10 – 300
Ni, W, Al, & Sn	10 (with wipe) – 200
Ag-W	10 – 100

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Corrosion & Tarnishing

Arbitrary tests often produce arbitrary results

Mated connections resistant to surface corrosion and maintain R_C

Coupons in tarnishing ambients

Flash Au with Ni & other underplate

Studies of industrial environs

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

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

Determining gases & environs for corrosion studies

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

Ag plate + inhibitor to replace flash Au

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

Dust effects

Au price spiked

Mixed flowing gas testing established

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

1966 1976 1986 1996 2006 2016

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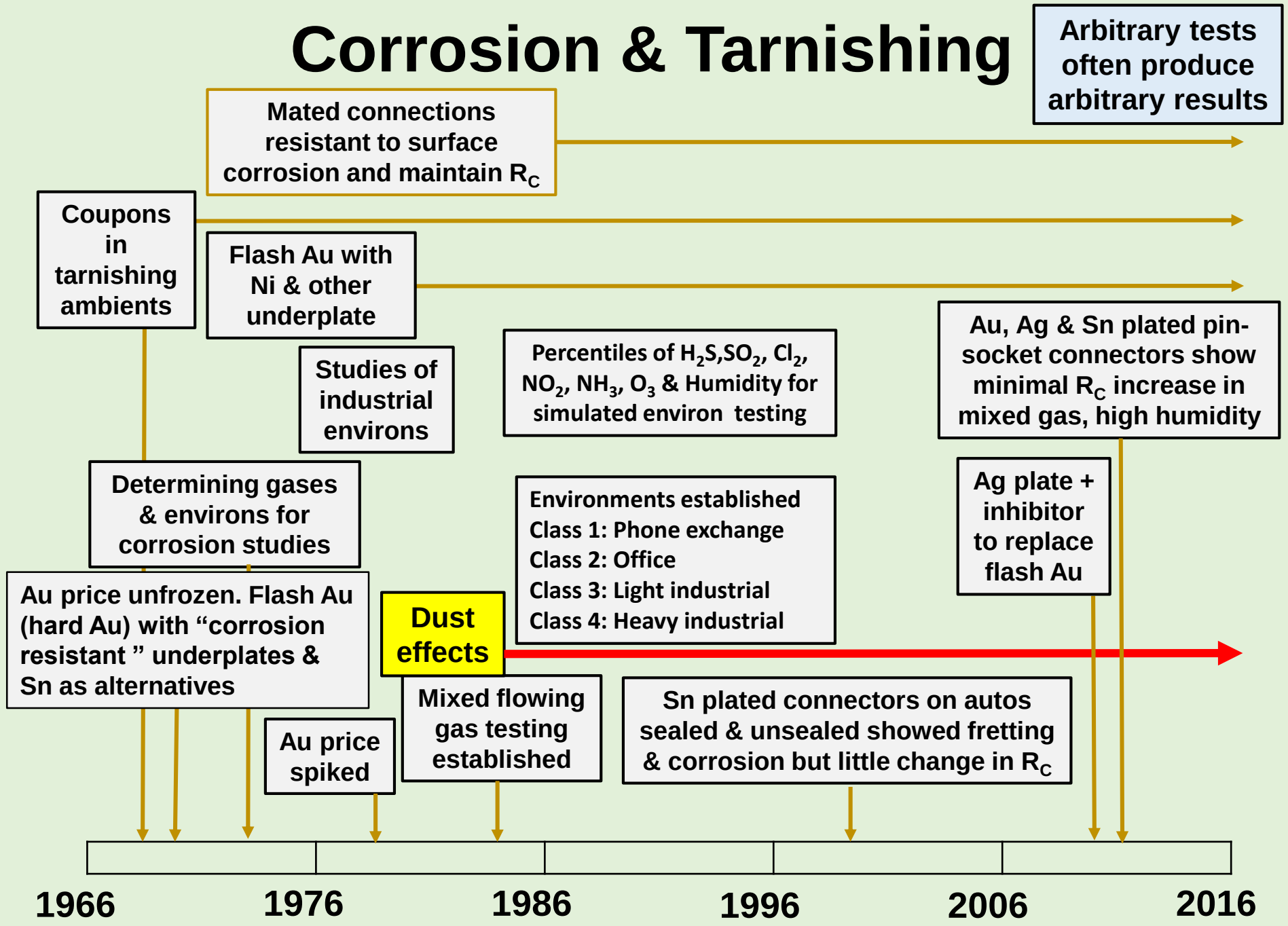

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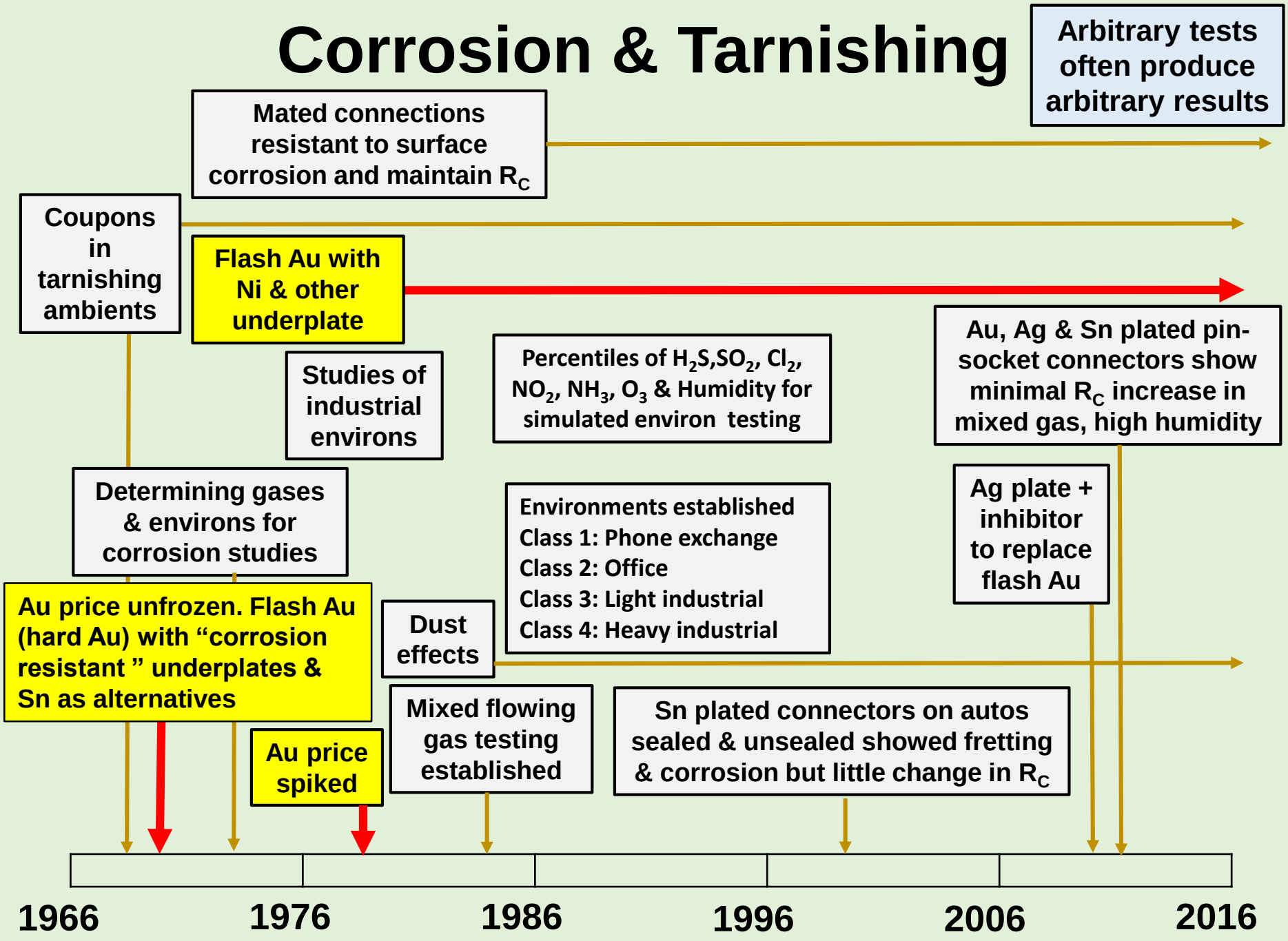

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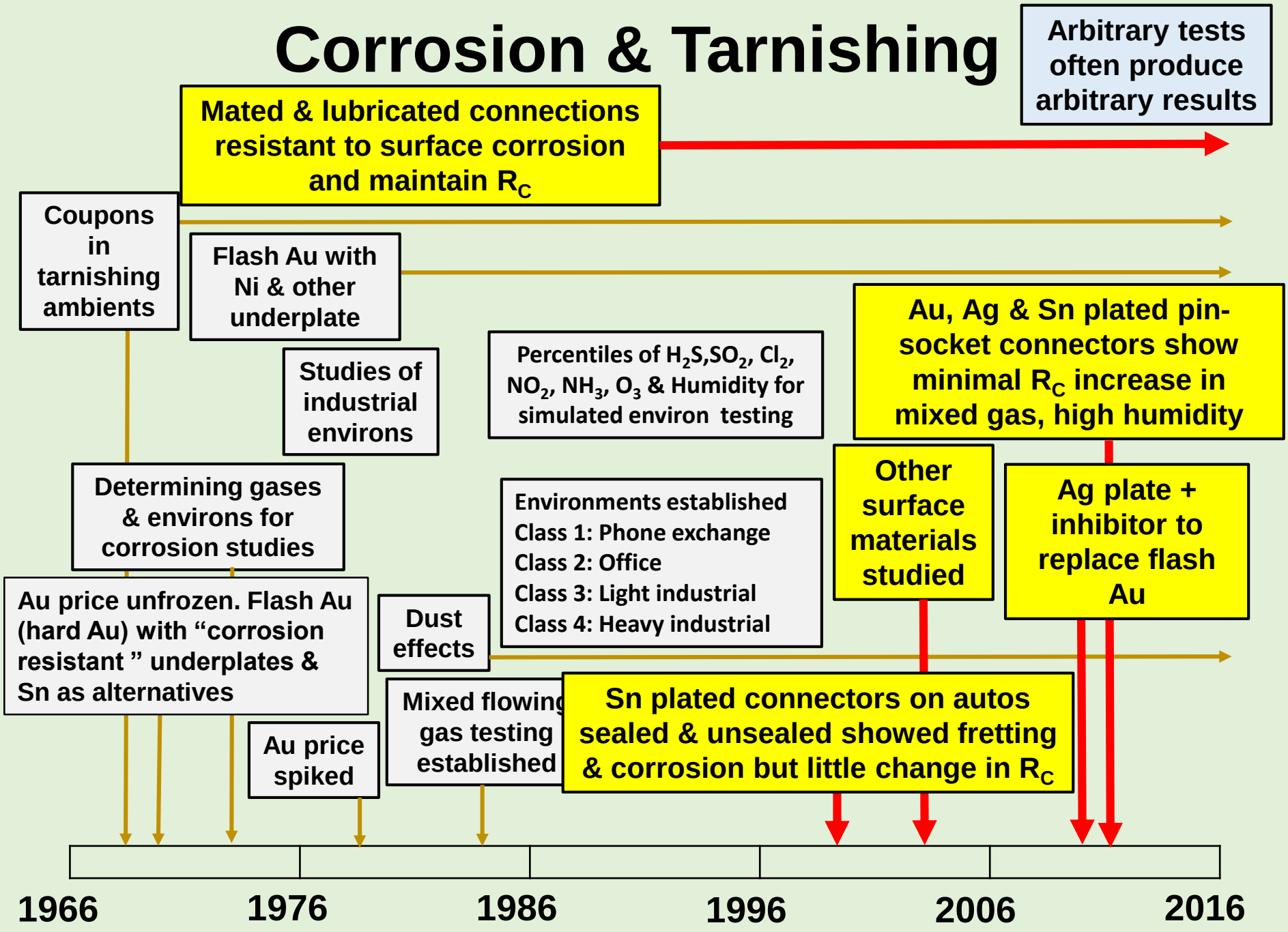
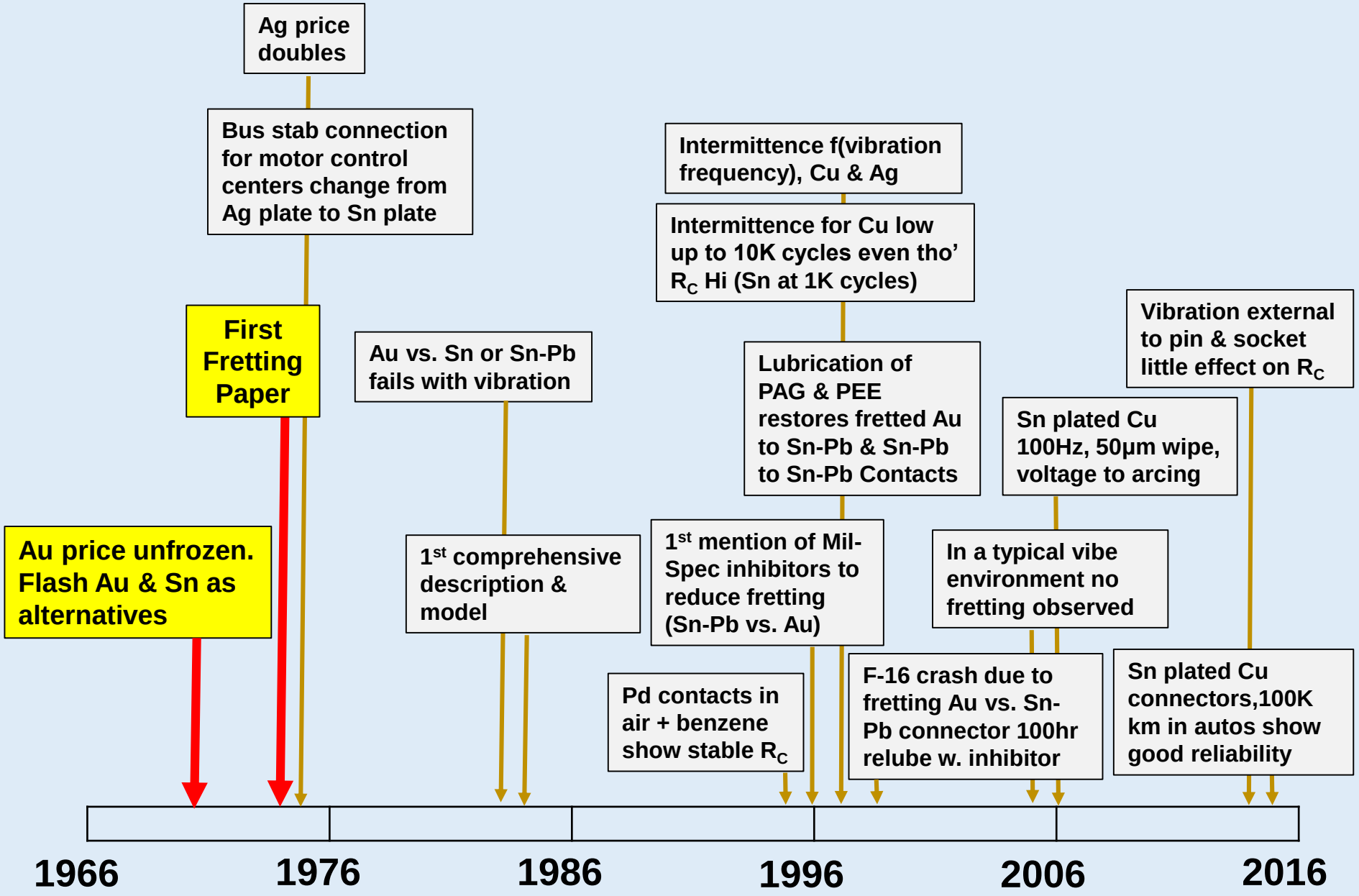


Fretting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Bus stab connection for motor control centers change from Ag plate to Sn plate
First Fretting Paper
Au price unfrozen. Flash Au & Sn as alternatives
Au vs. Sn or Sn-Pb fails with vibration
1st comprehensive description & model
Intermittence f(vibration frequency), Cu & Ag
Intermittence for Cu low up to 10K cycles even tho' RC 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)
Pd contacts in air + benzene show stable RC
Vibration external to pin & socket little effect on RC
Sn plated Cu 100Hz, 50µm wipe, voltage to arcing
In a typical vibe environment no fretting observed
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
1966
1976
1986
1996
2006
2016

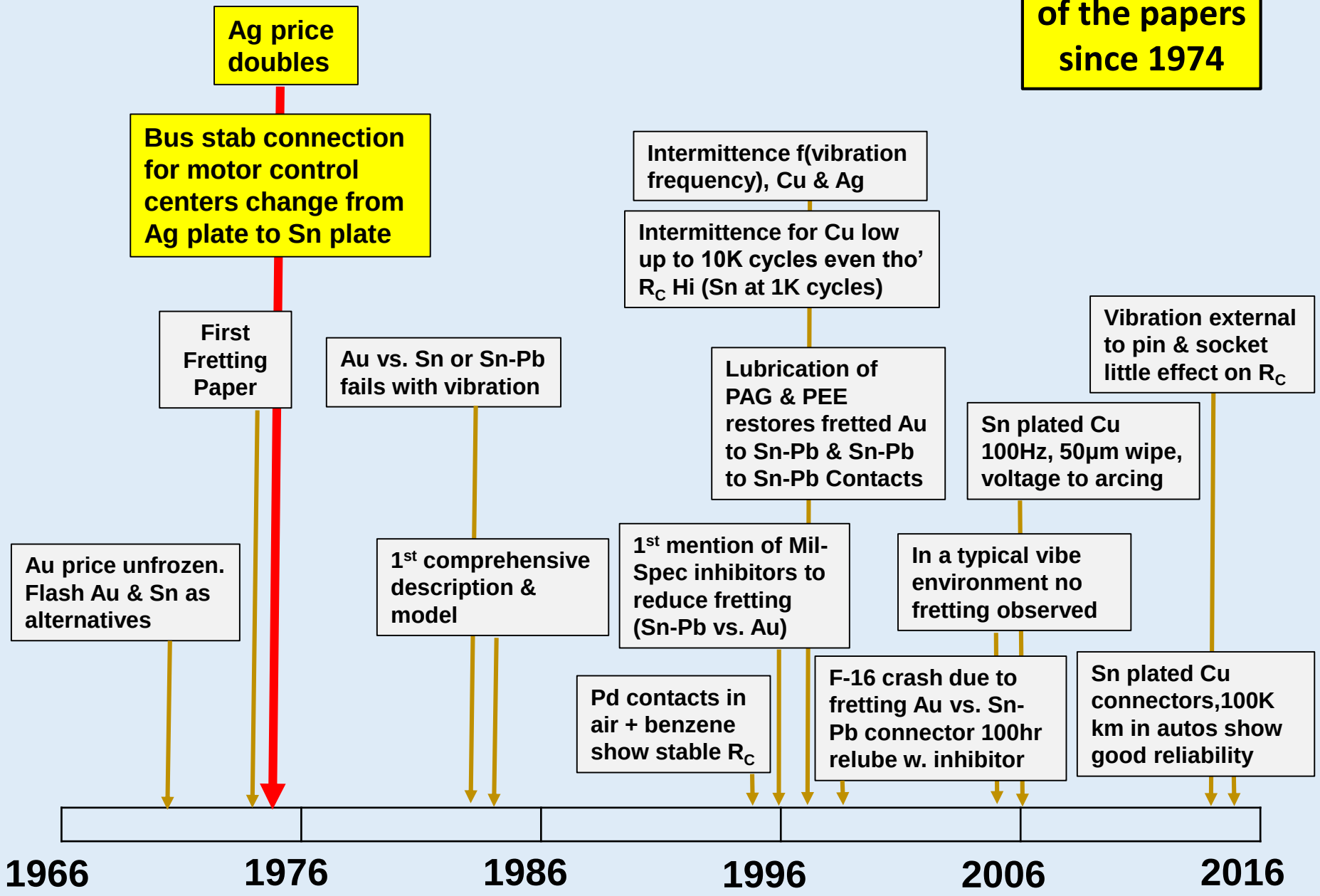
Fretting

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

Average 12% of the papers since 1974



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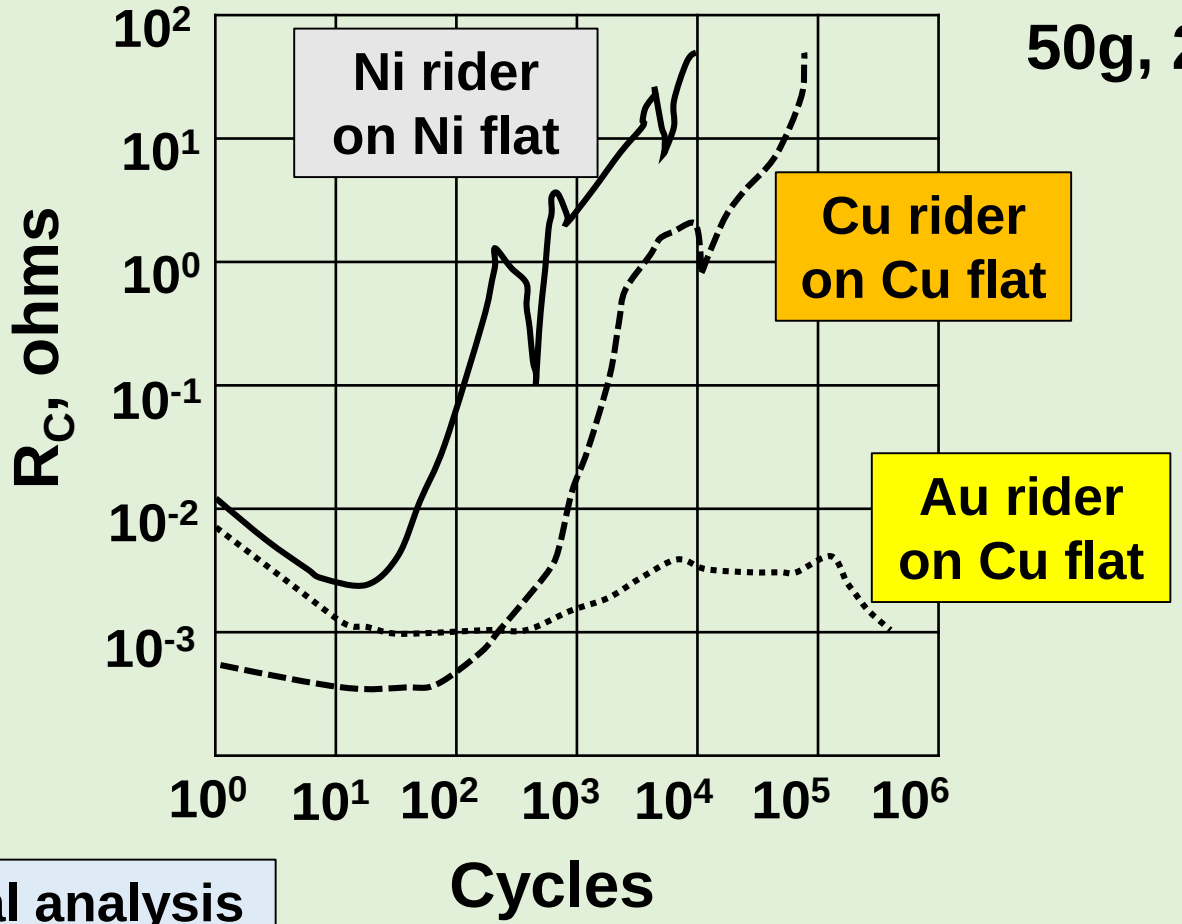

Experimental analysis from plated rider on a plated flat plane

Antler, Holm 1984

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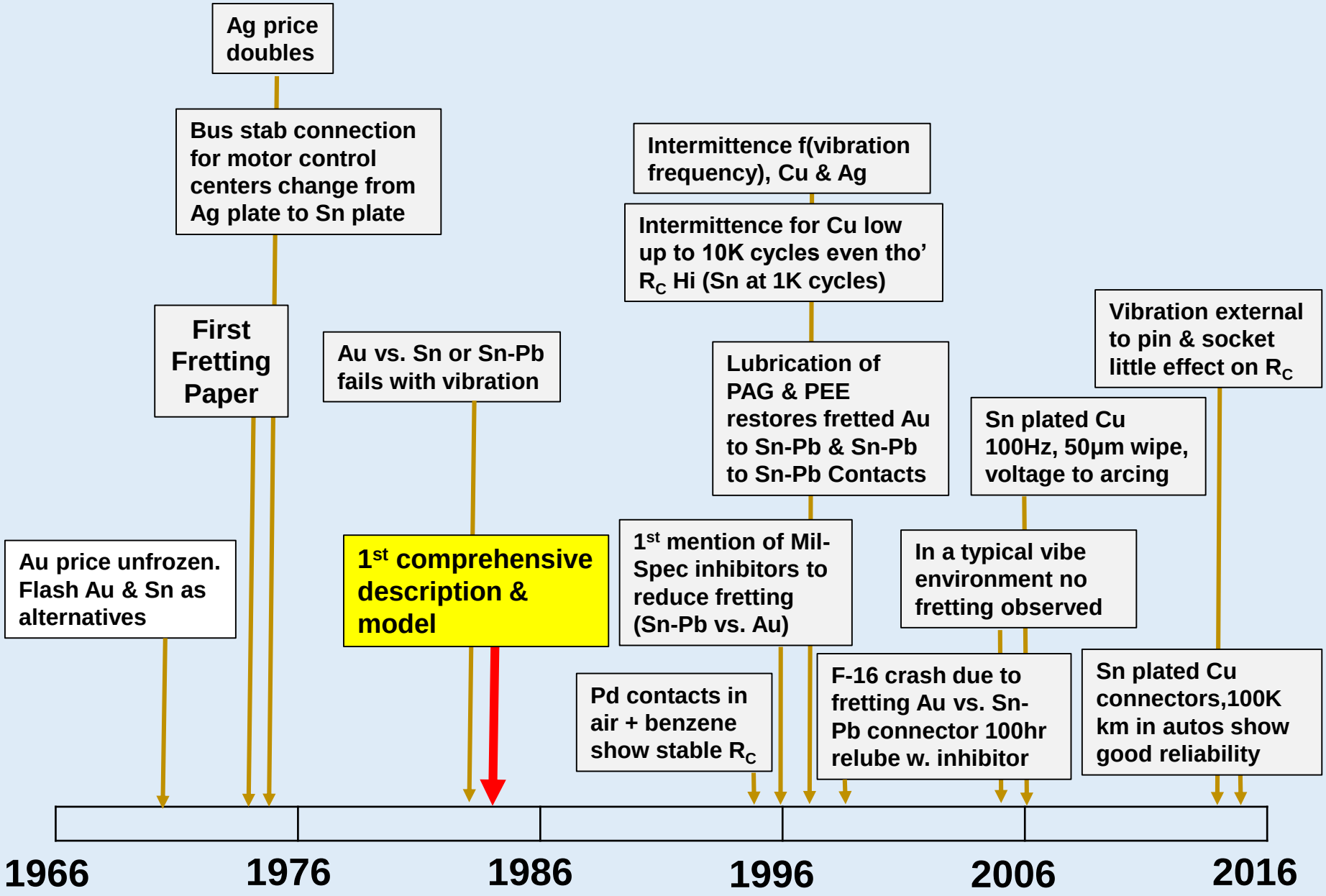
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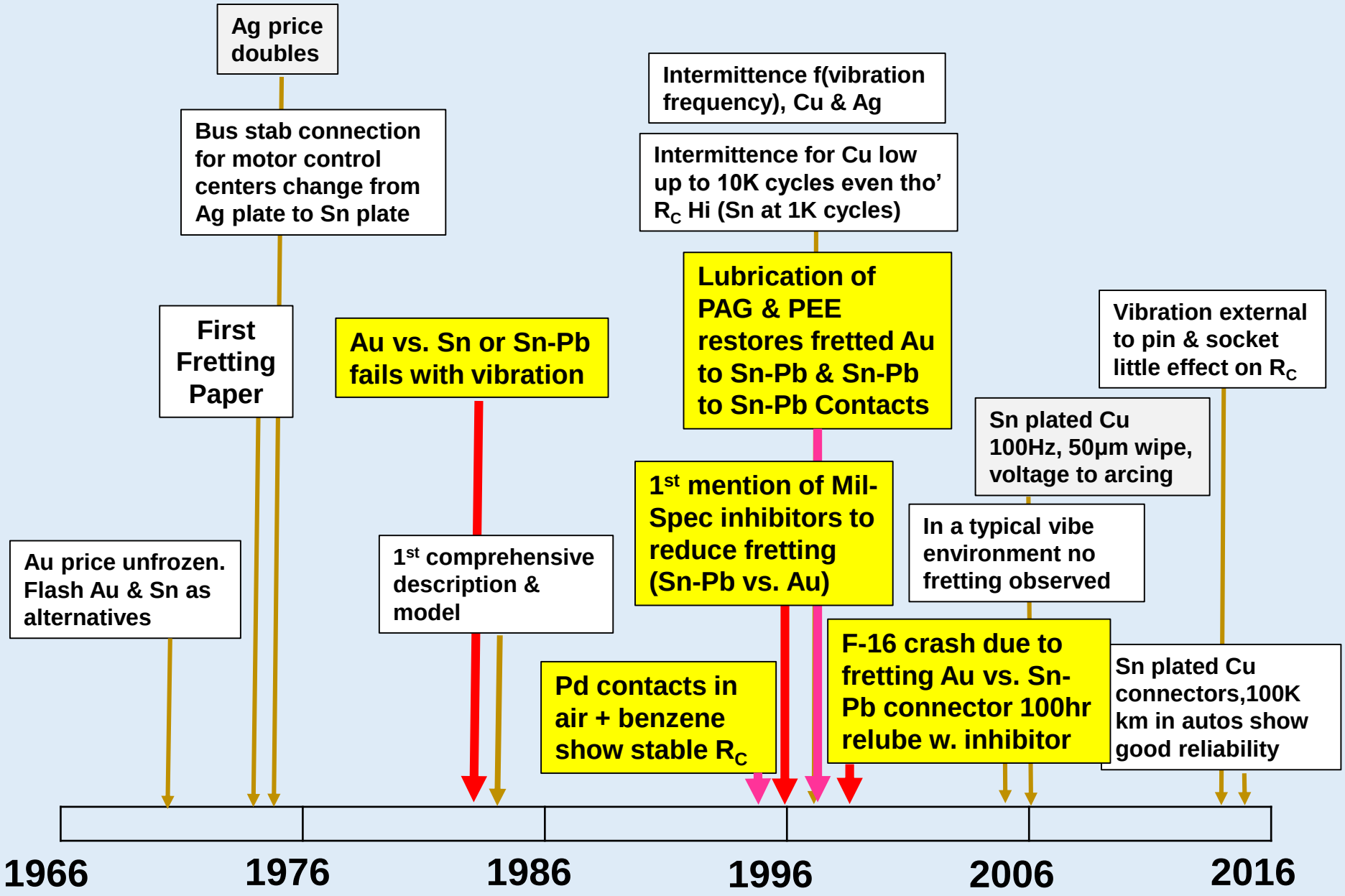
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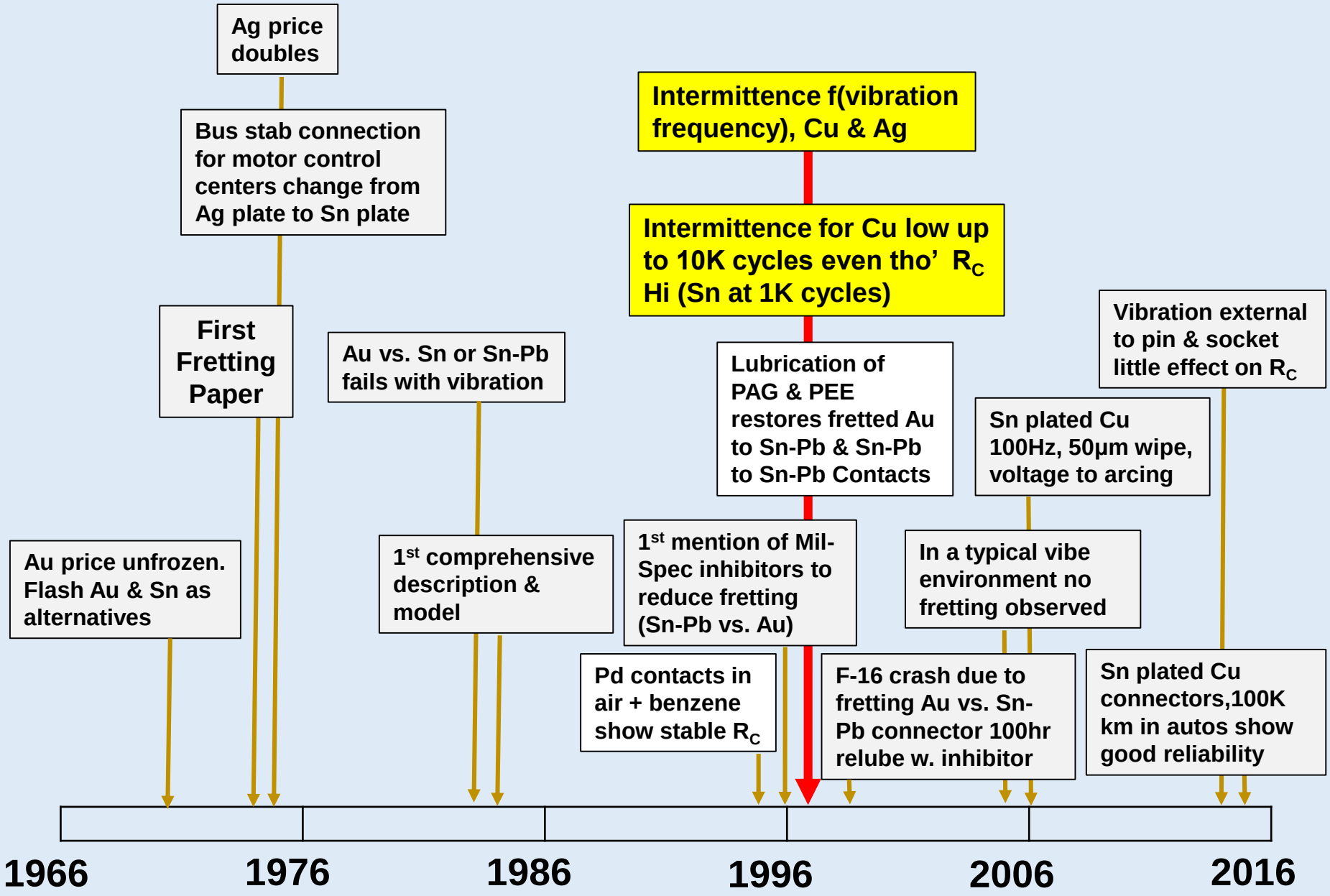
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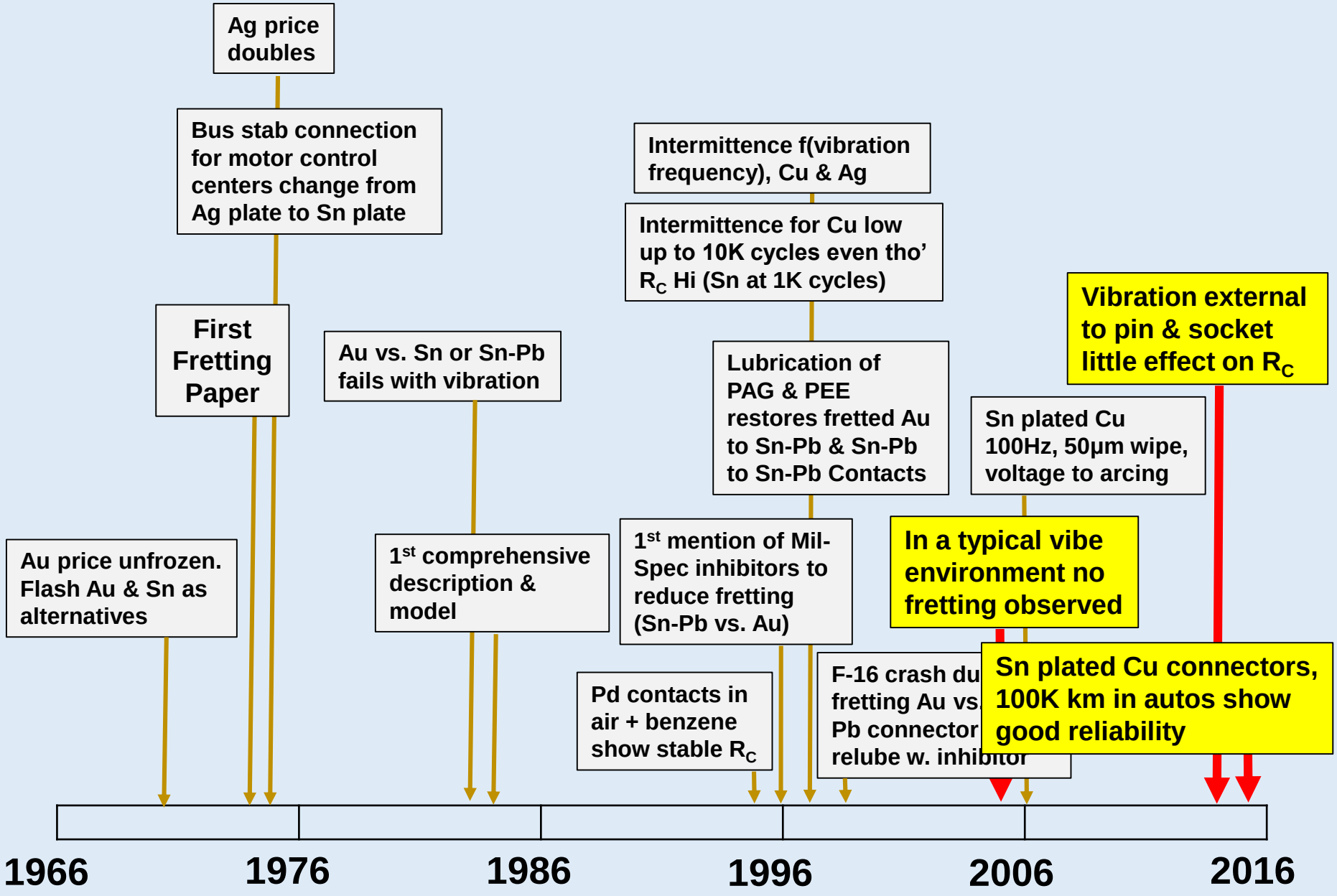
Ag price doubles
Bus stab connection for motor control centers change from Ag plate to Sn plate
First Fretting Paper
Au price unfrozen. Flash Au & Sn as alternatives
Au vs. Sn or Sn-Pb fails with vibration
1st comprehensive description & model
Intermittence f(vibration frequency), Cu & Ag
Intermittence for Cu low up to 10K cycles even tho' RC 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)
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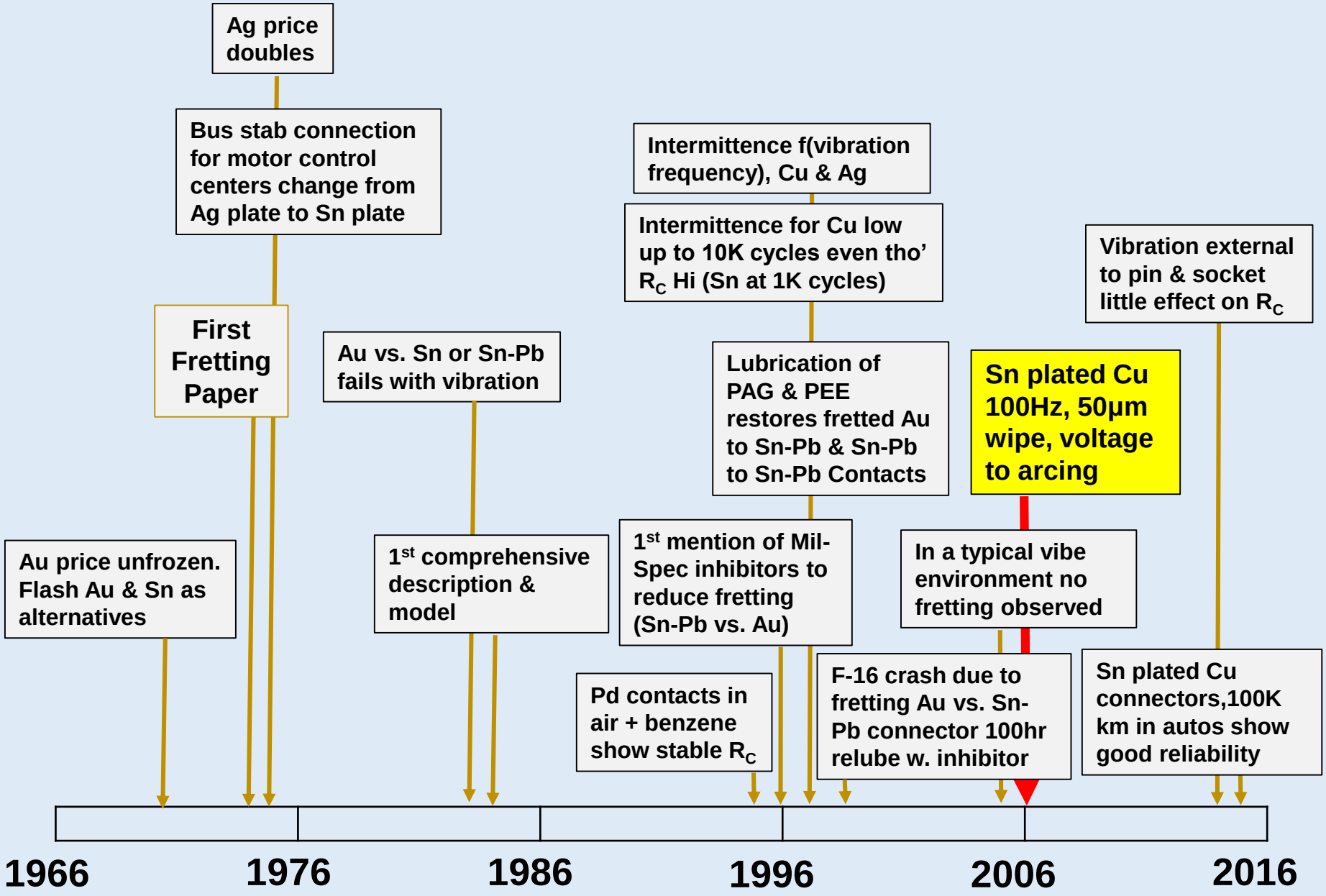
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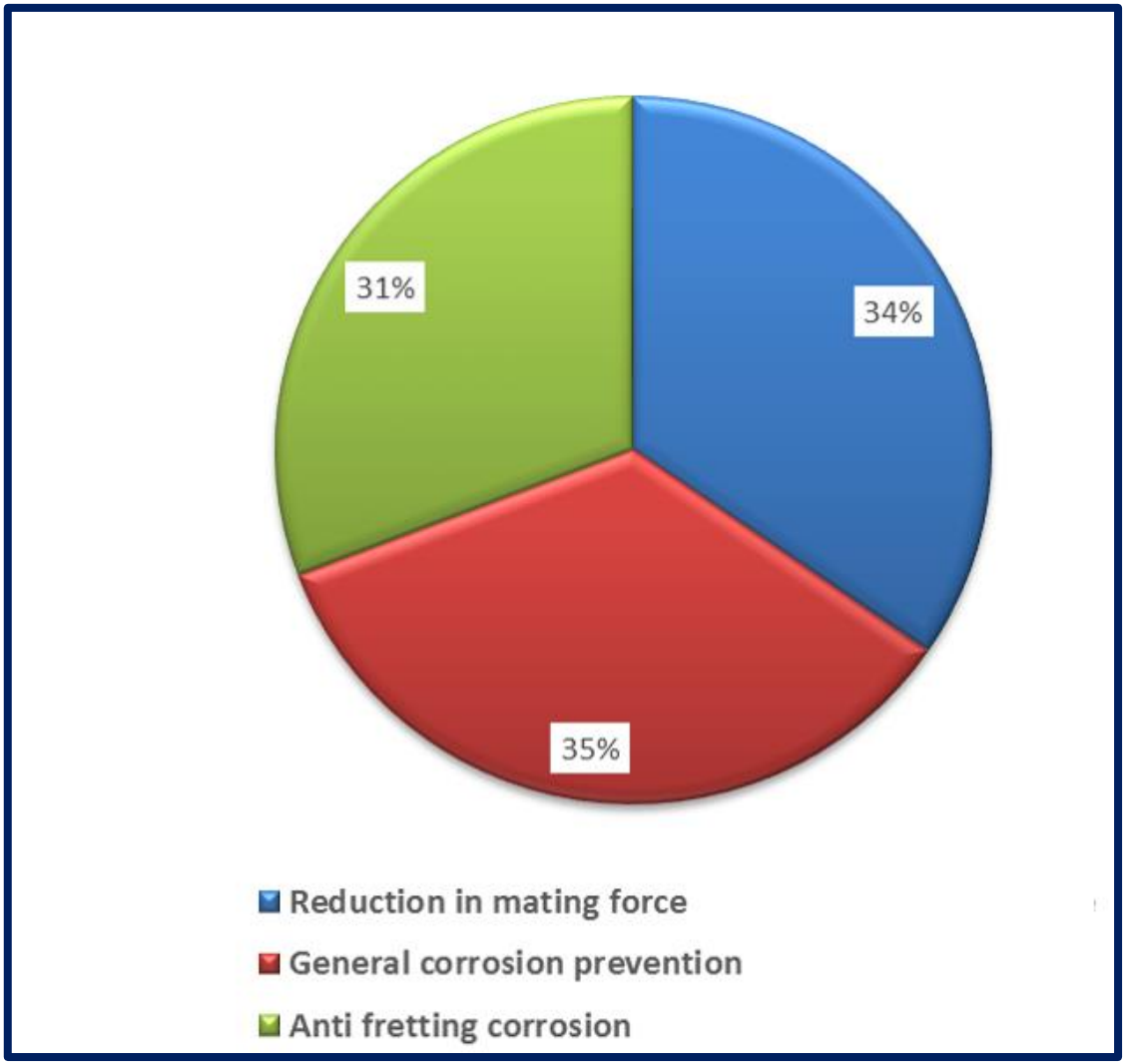
Connector Lubrication

- 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 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_5Al_2 (white plague)
- **Au & Cu:** AuCu, $AuCu_3$: **Au & Sn:** $AuSn_4$
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- **Ag & Al:** Ag_2Al, Ag_3Al: **Ag & Sn:** Ag_3Sn

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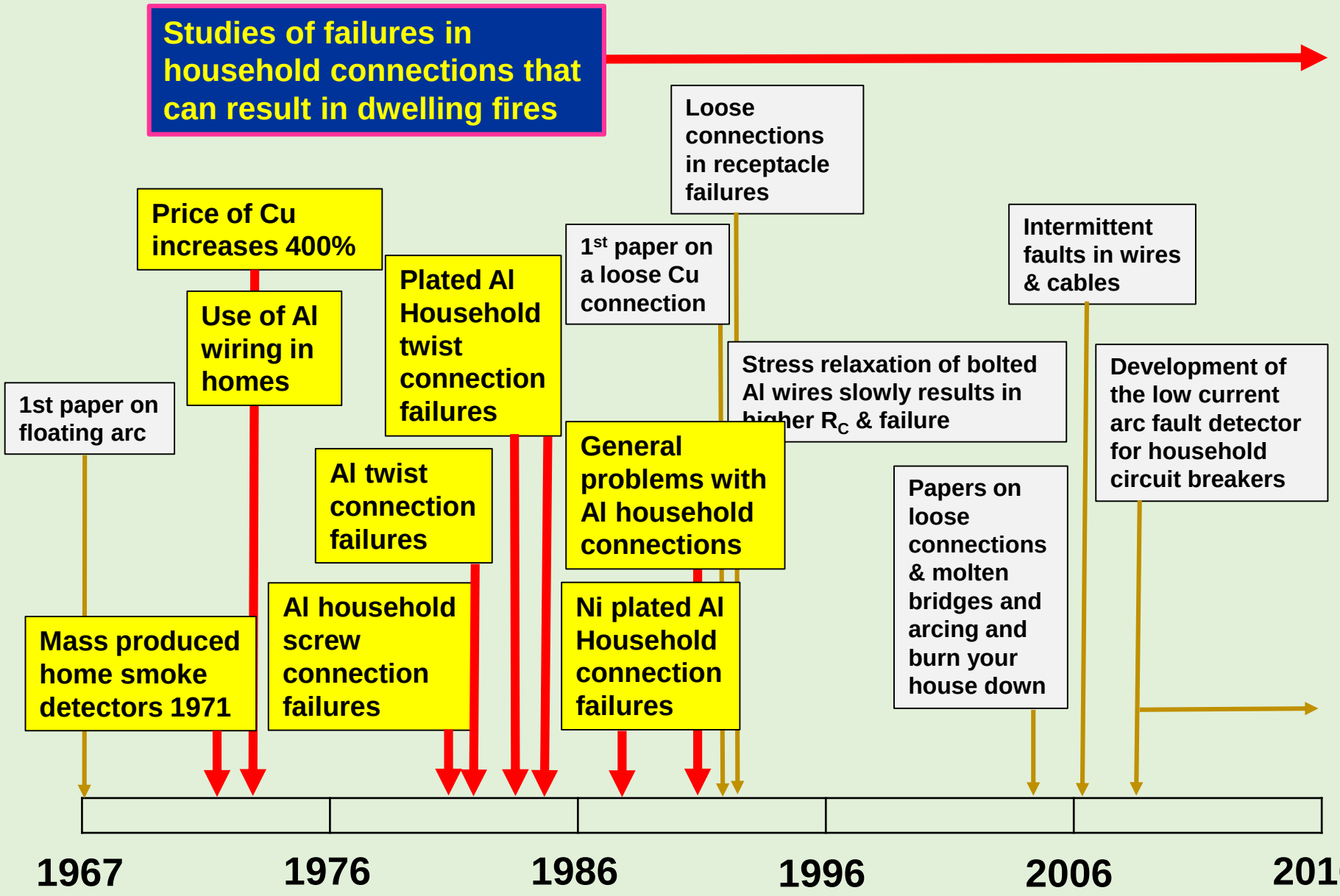
Whiskers

- Sn plate with a small percentage of Pb did not form whiskers
- After the ban on Pb starting ~ 2001, stressed Sn coatings formed whiskers Auto accelerator problem, caused by Sn whiskers shorting the Accelerator Position Sensor
- 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



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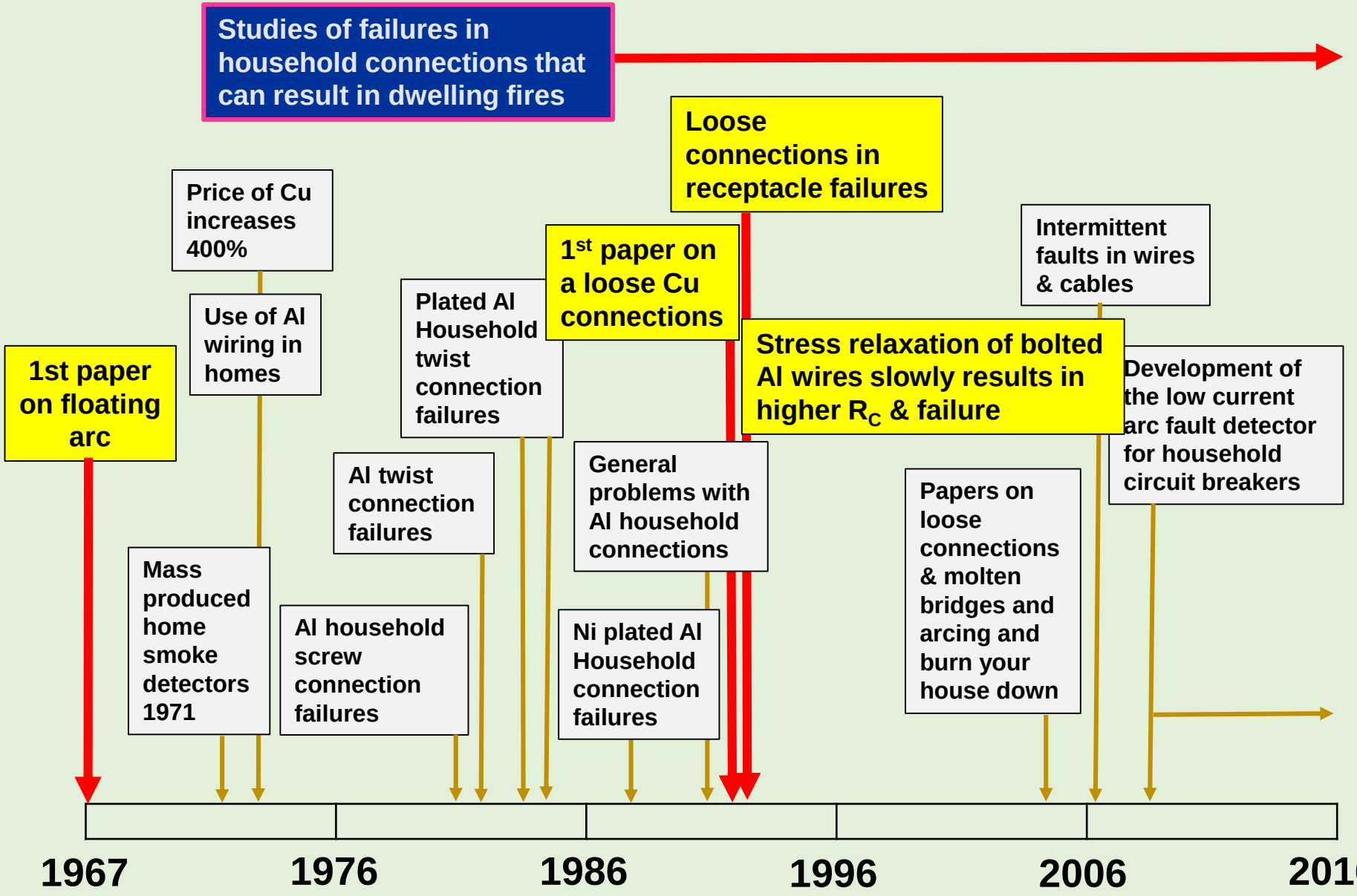

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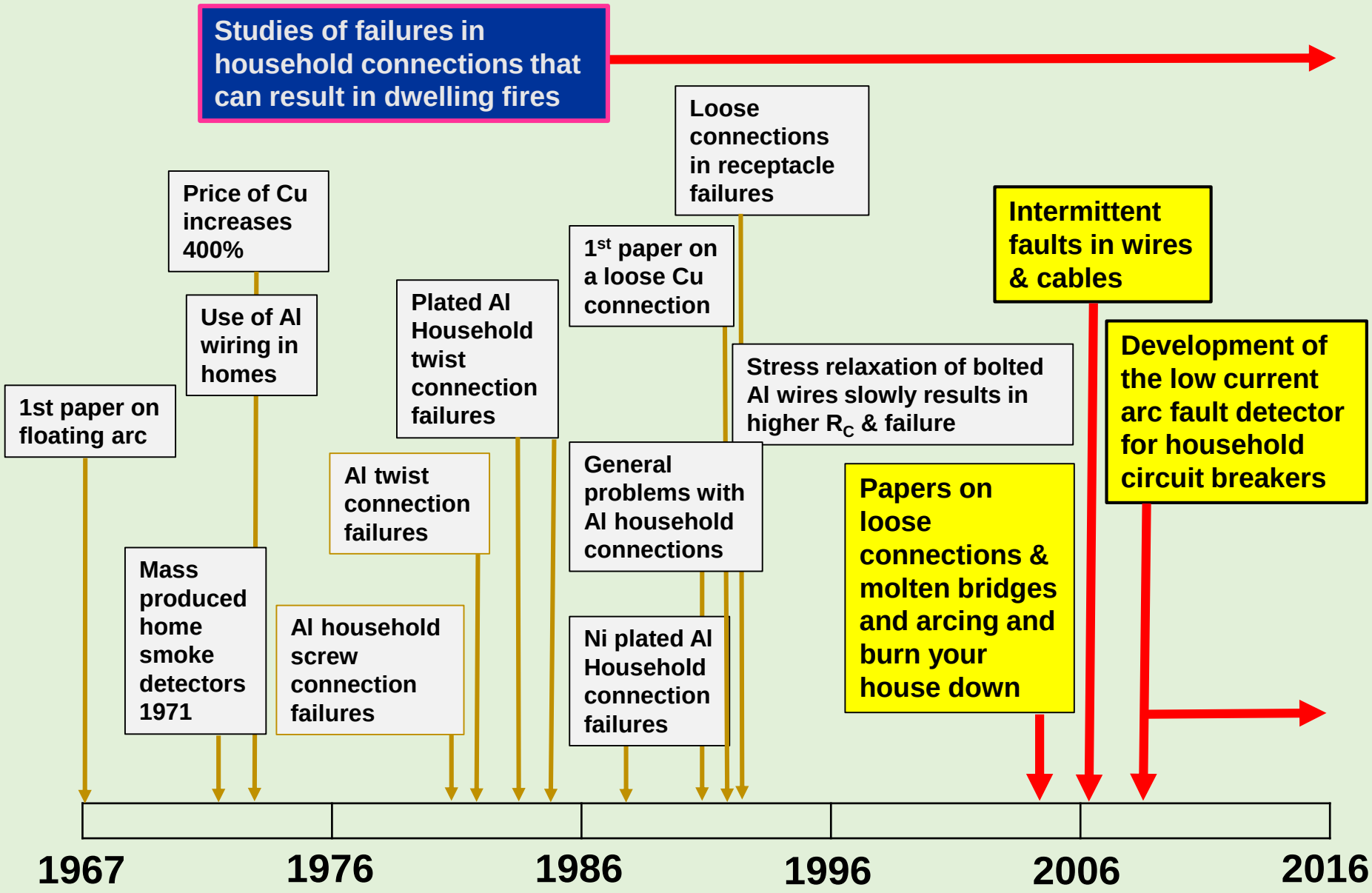


Switching with Arcing

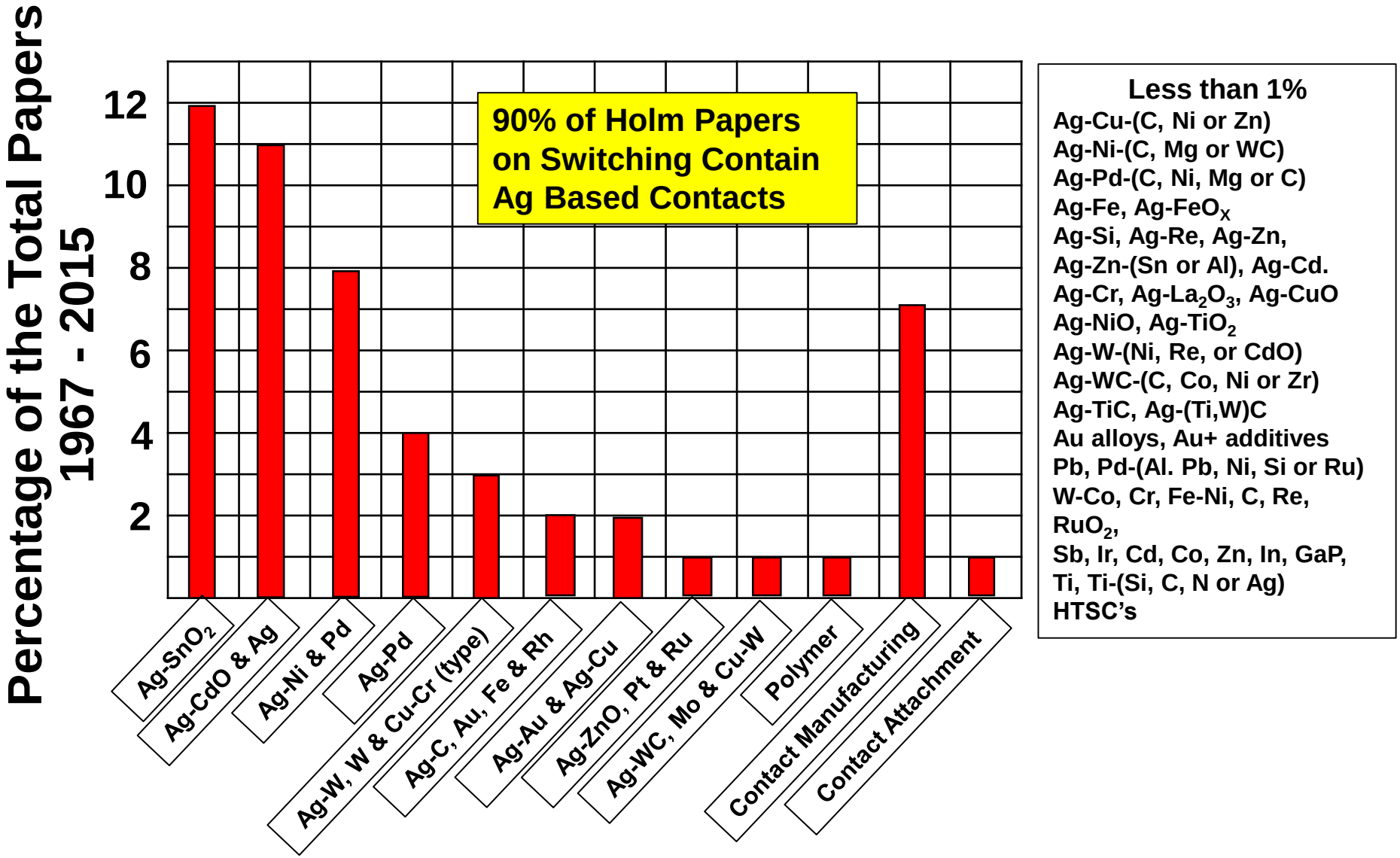
Circuit switching using electrical contacts has not been superseded by electronic switching except for specialty operations. Electrical contacts plus electronic detection, sensing and tripping will be the partnership for the future.

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

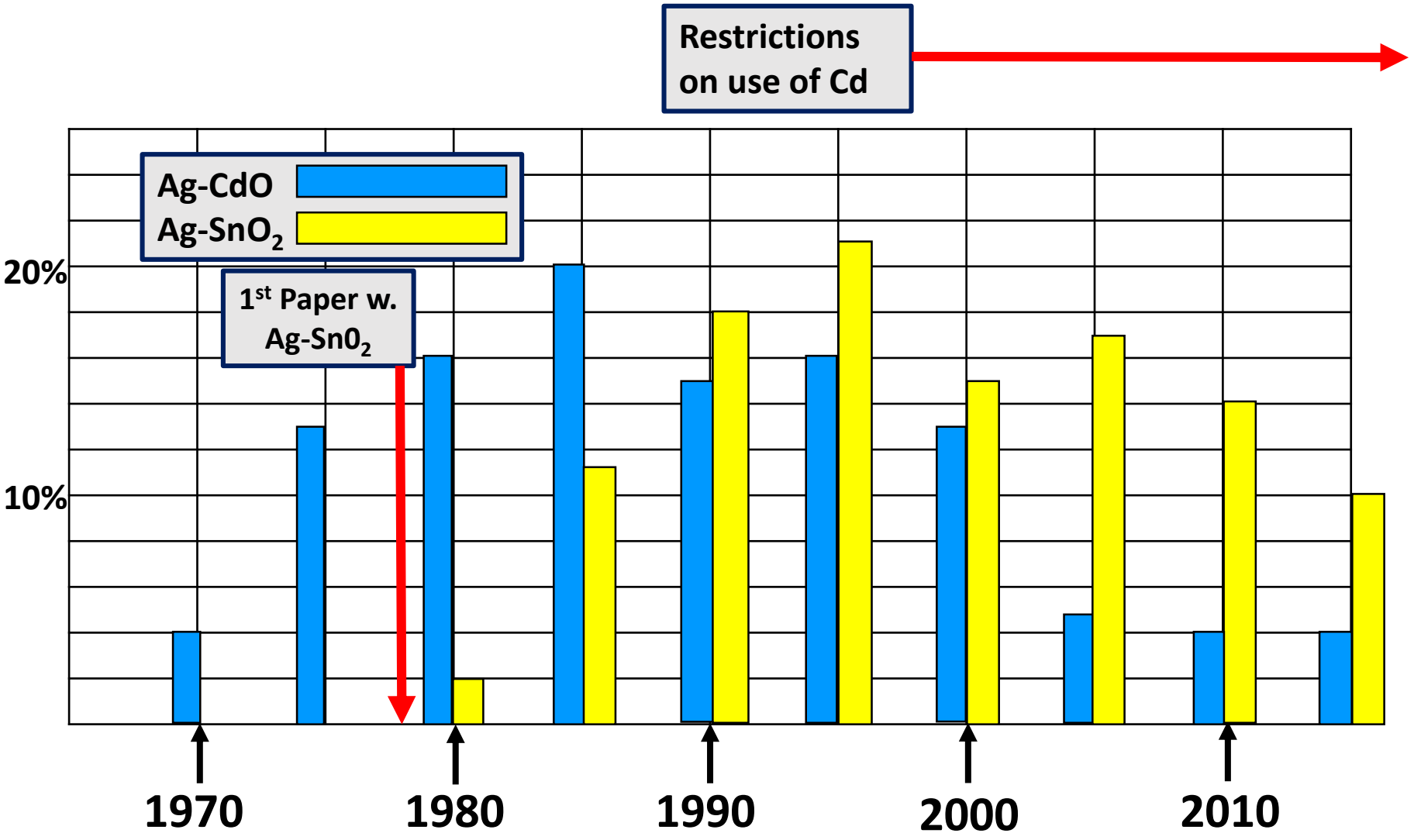
"If nature had not given us the electric arc we would have had to invent one"

Slepian. 1930's

Contact Materials for Switching Contacts



Percentage of Papers Ag-CdO and Ag-SnO_2 Contact Type of Materials



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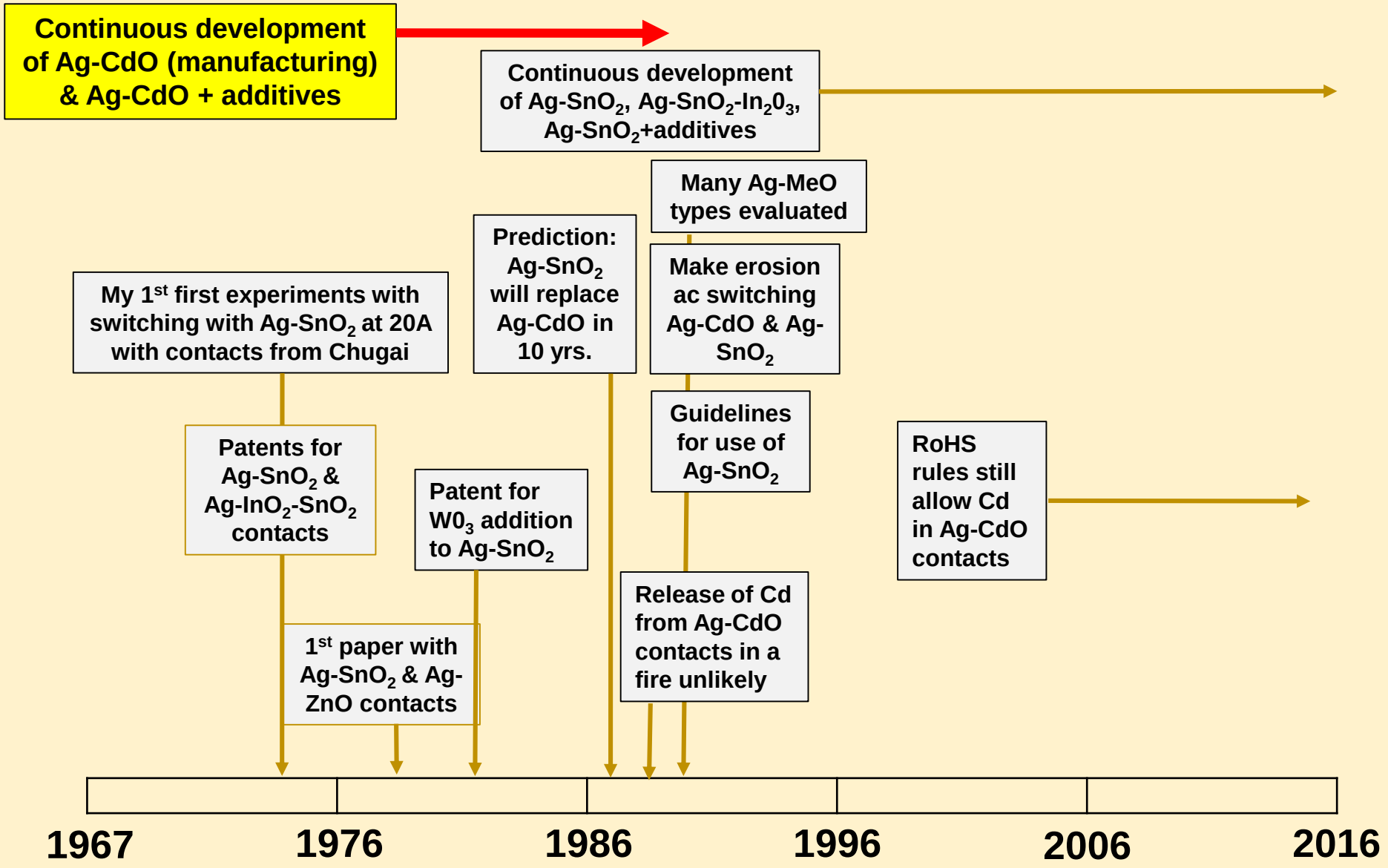

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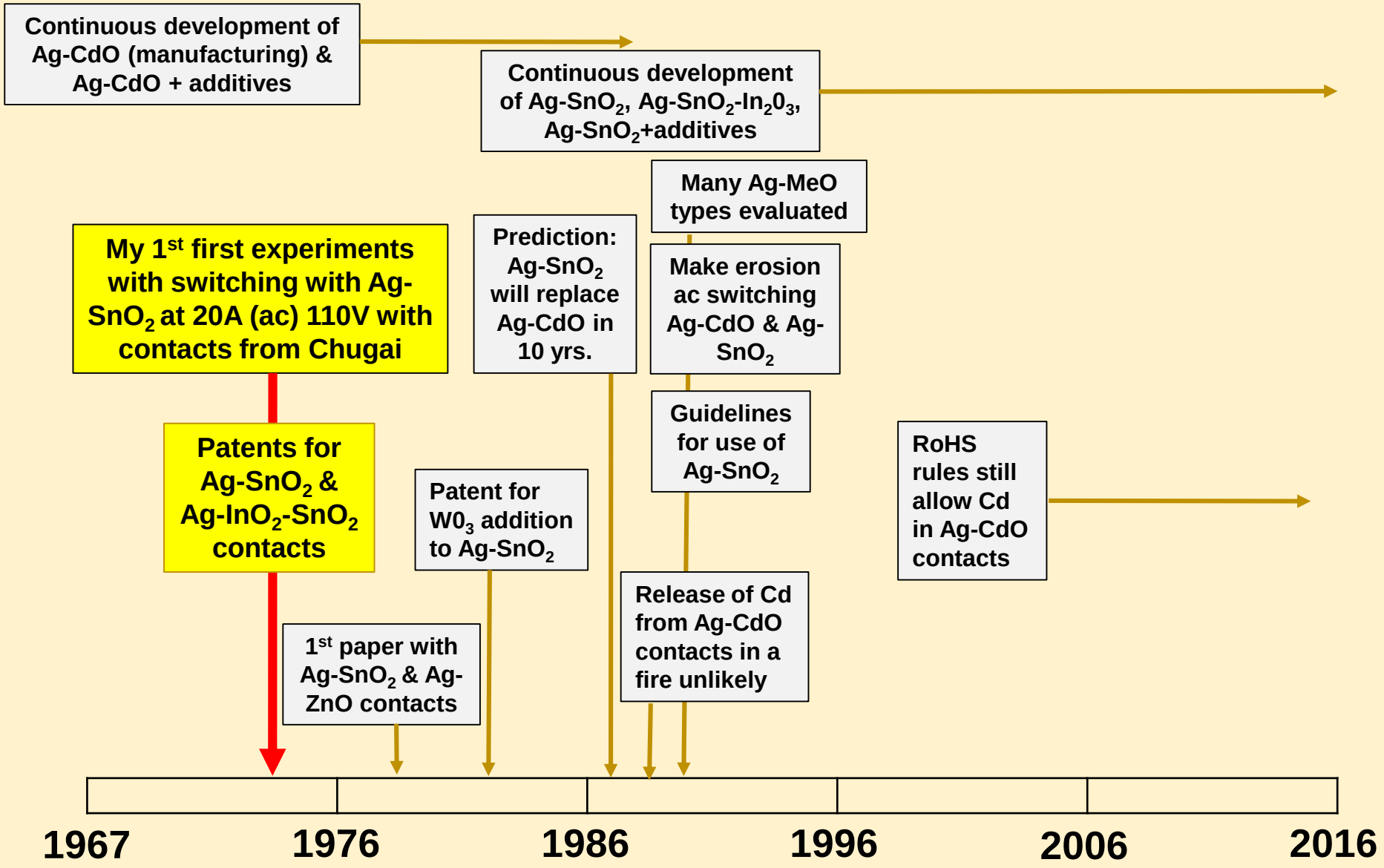

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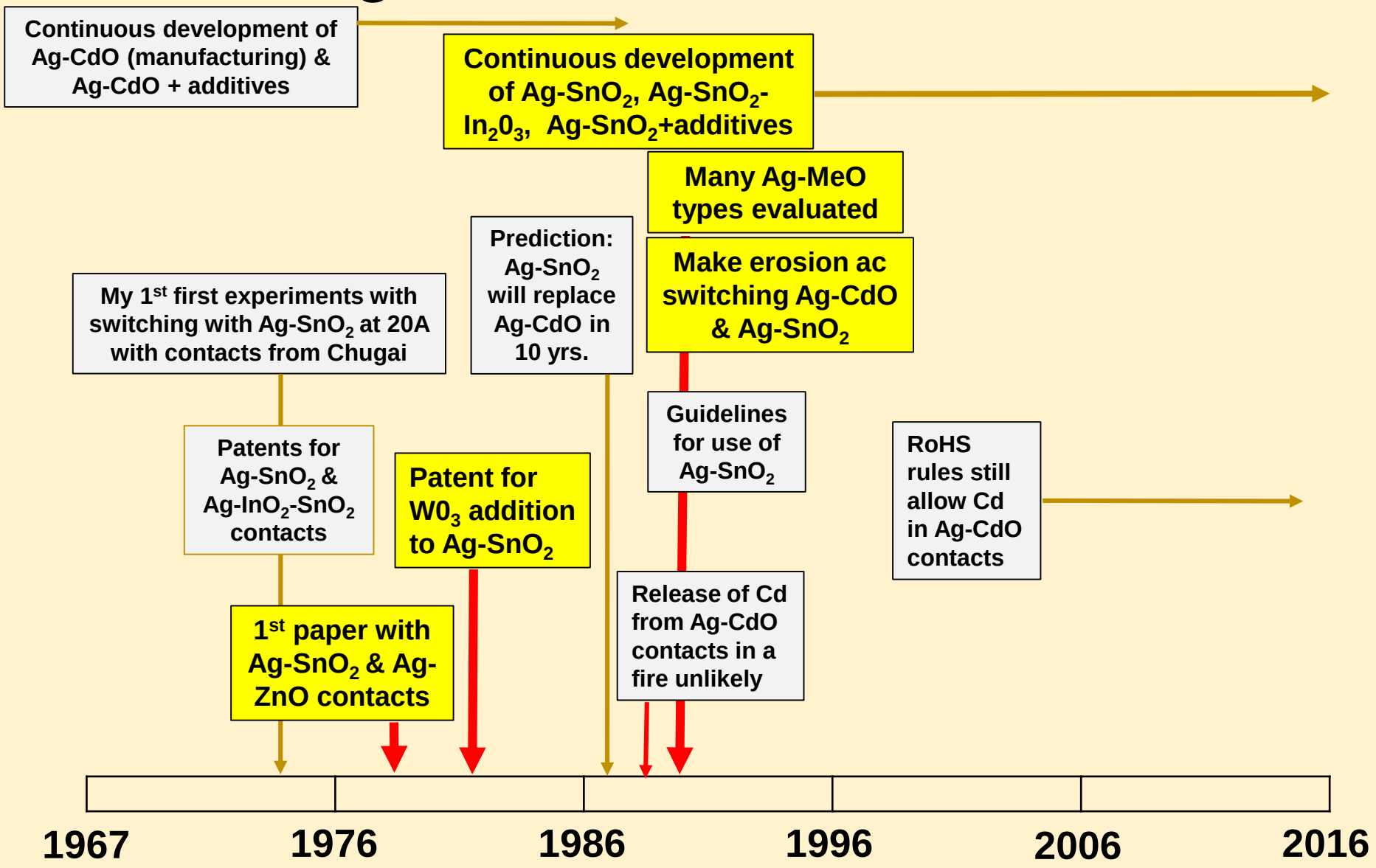

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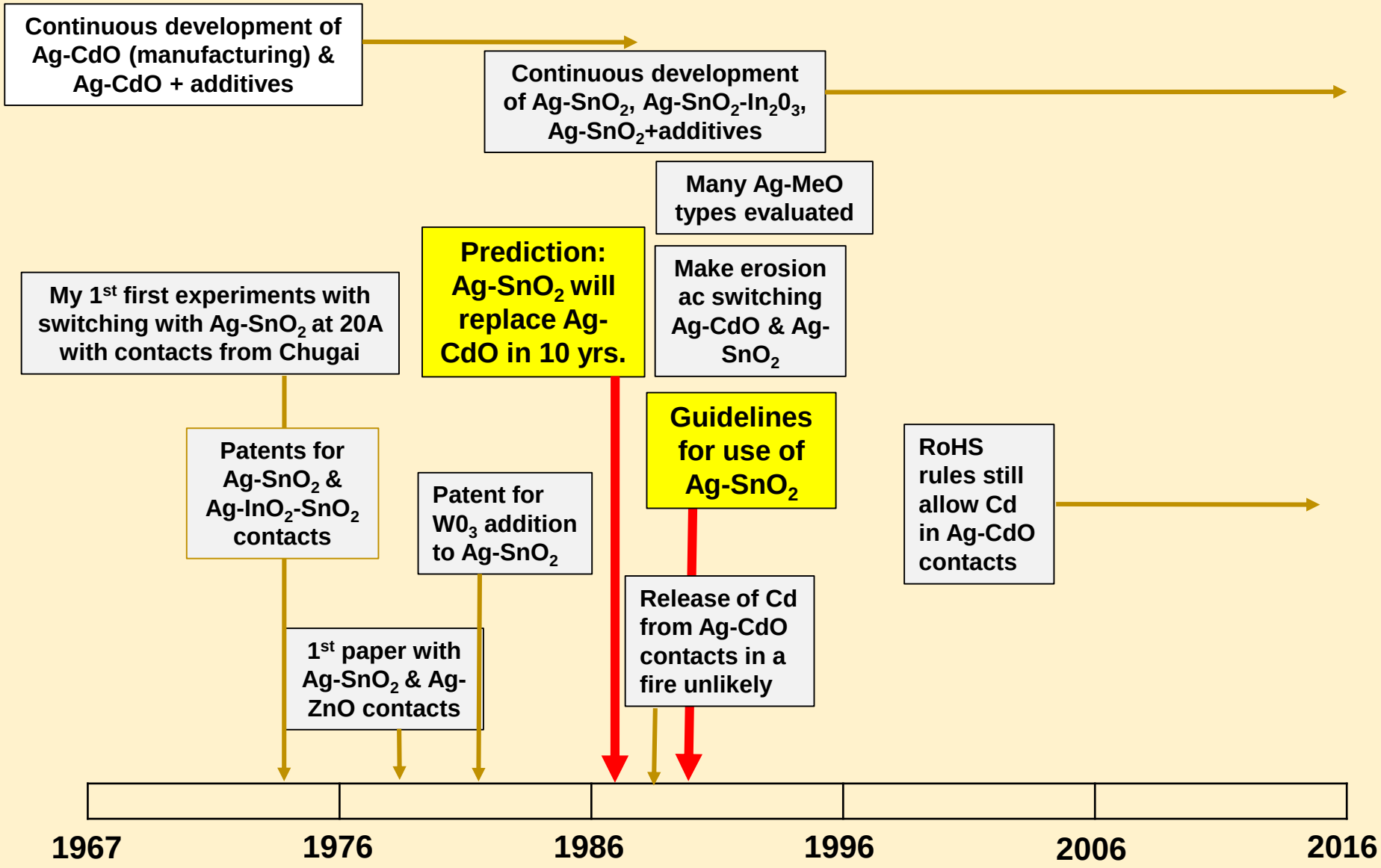

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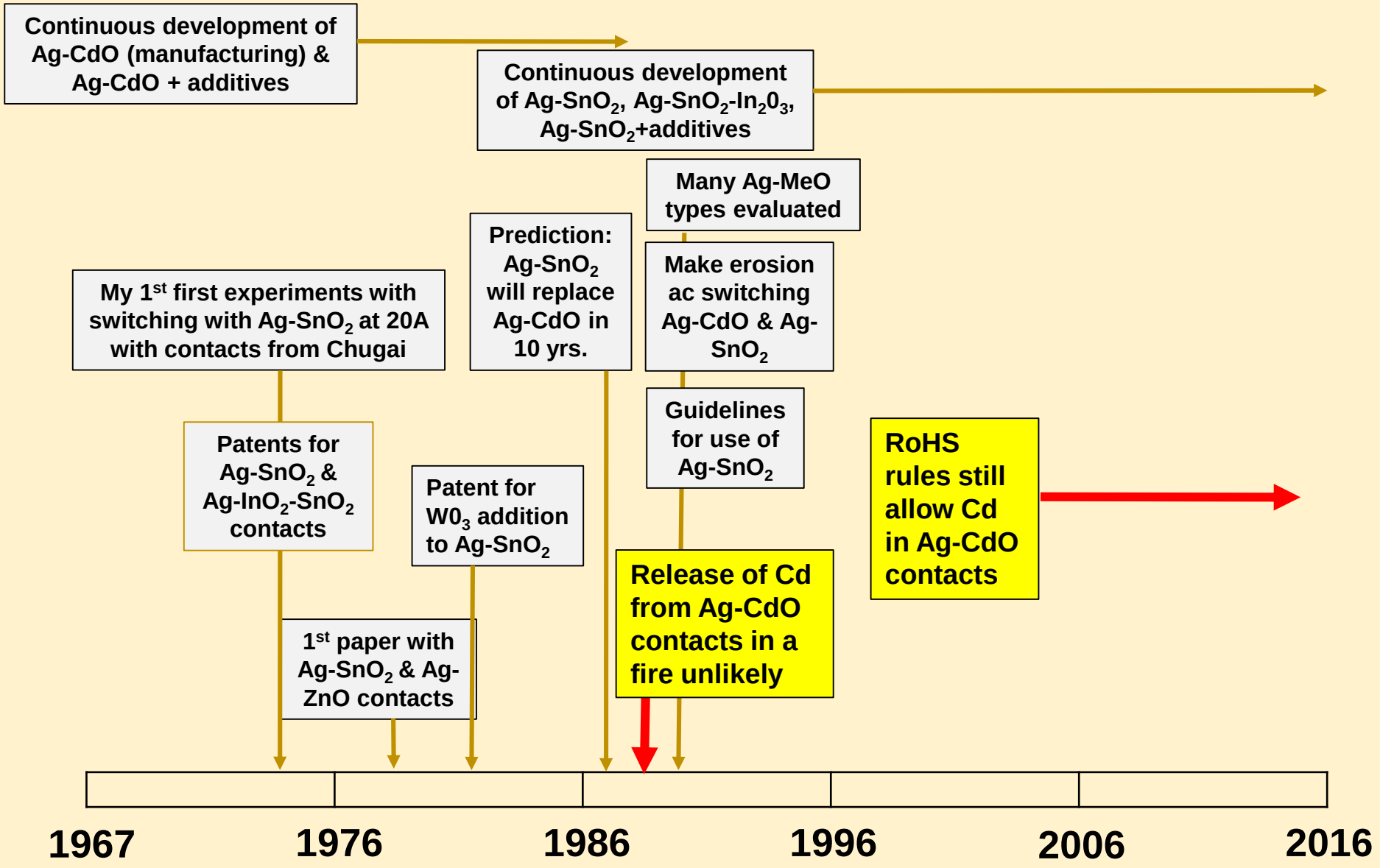

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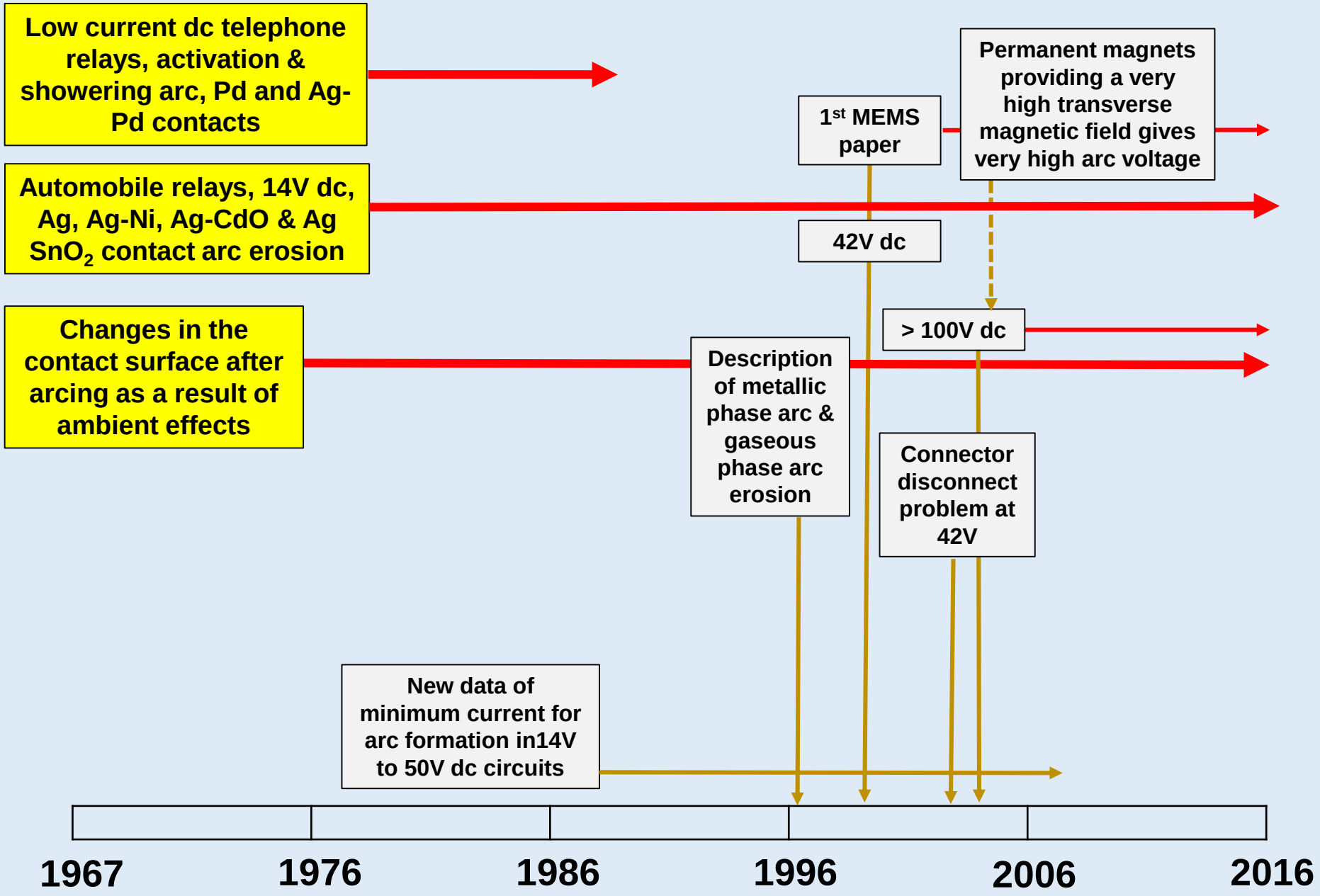

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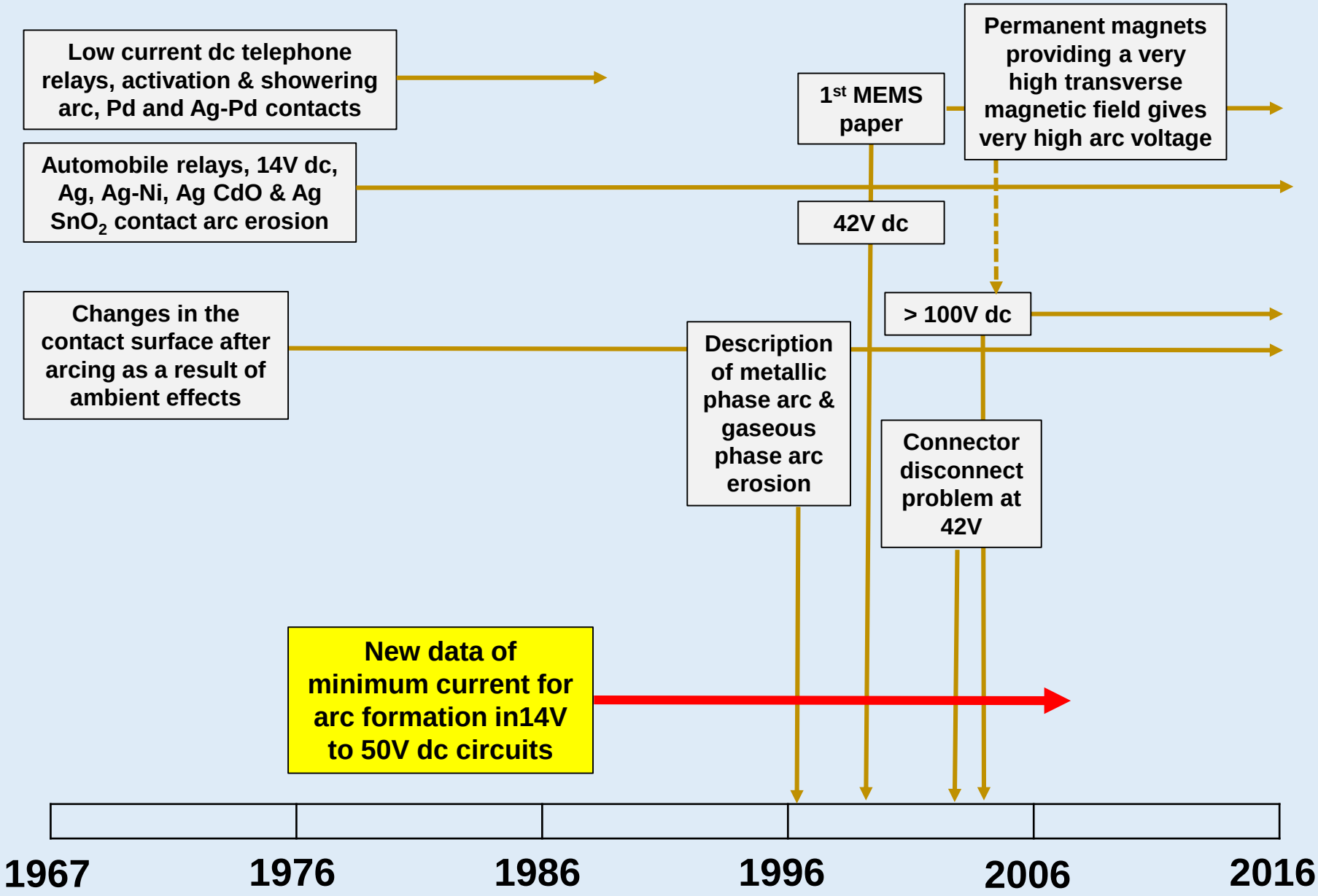

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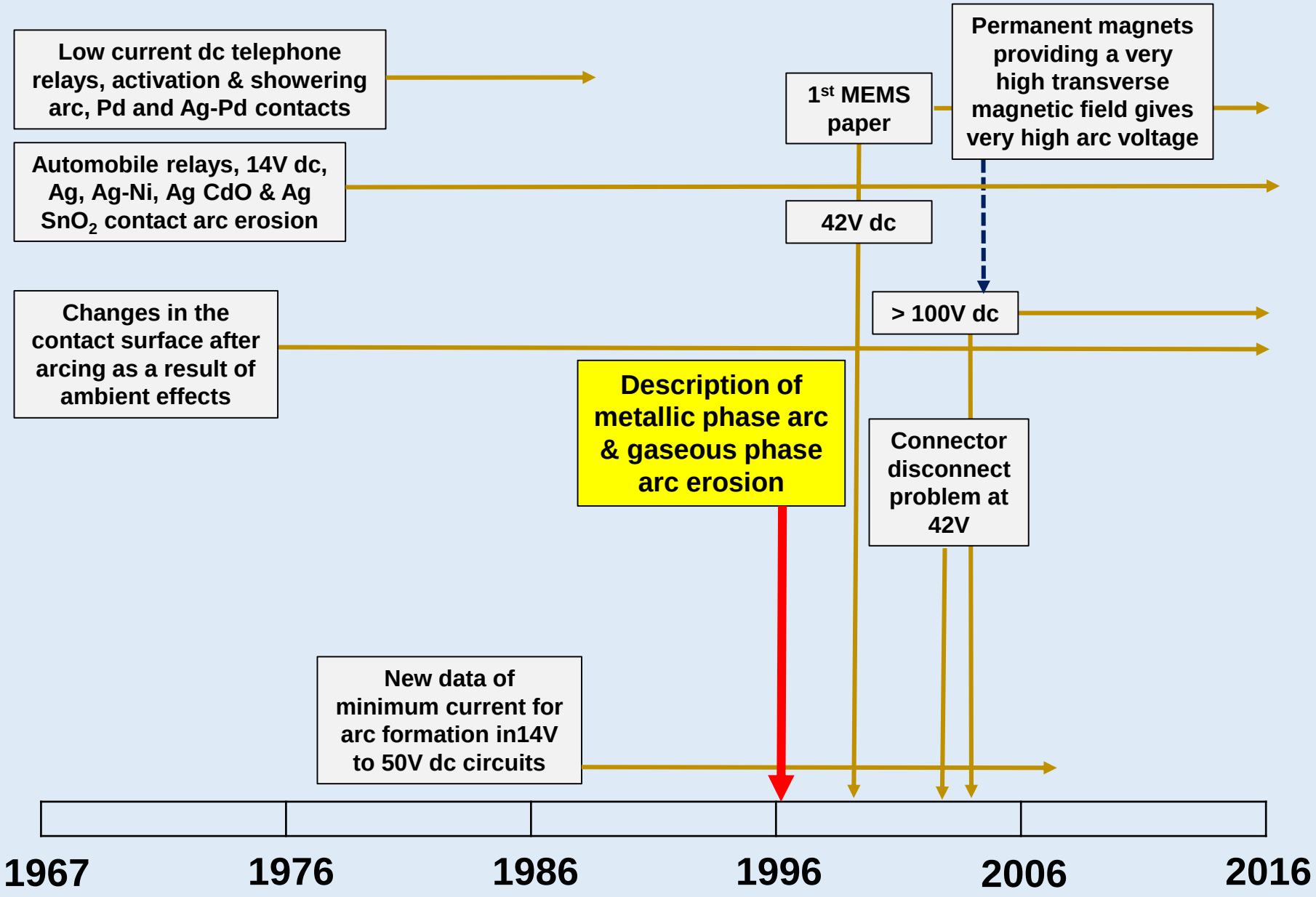

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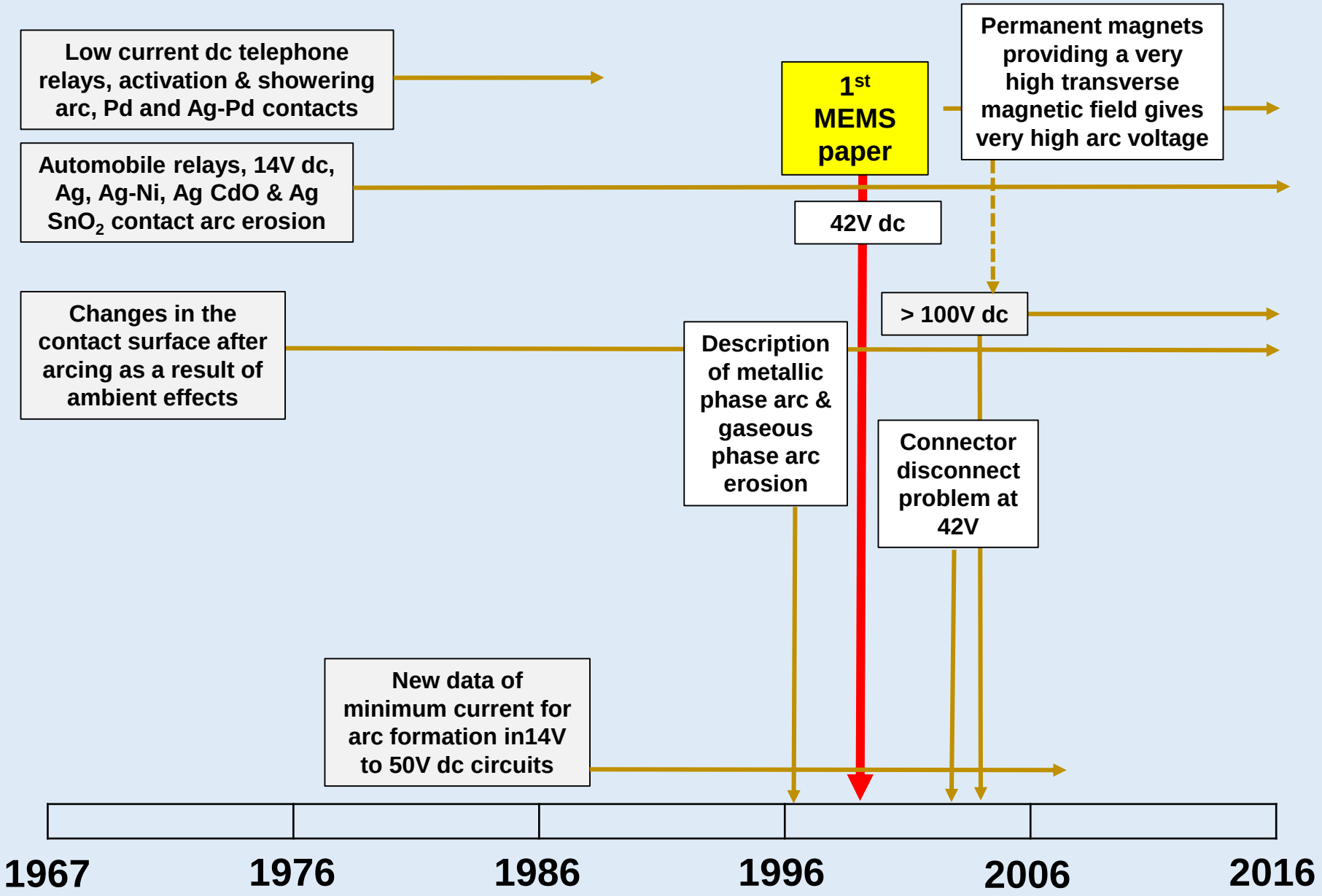

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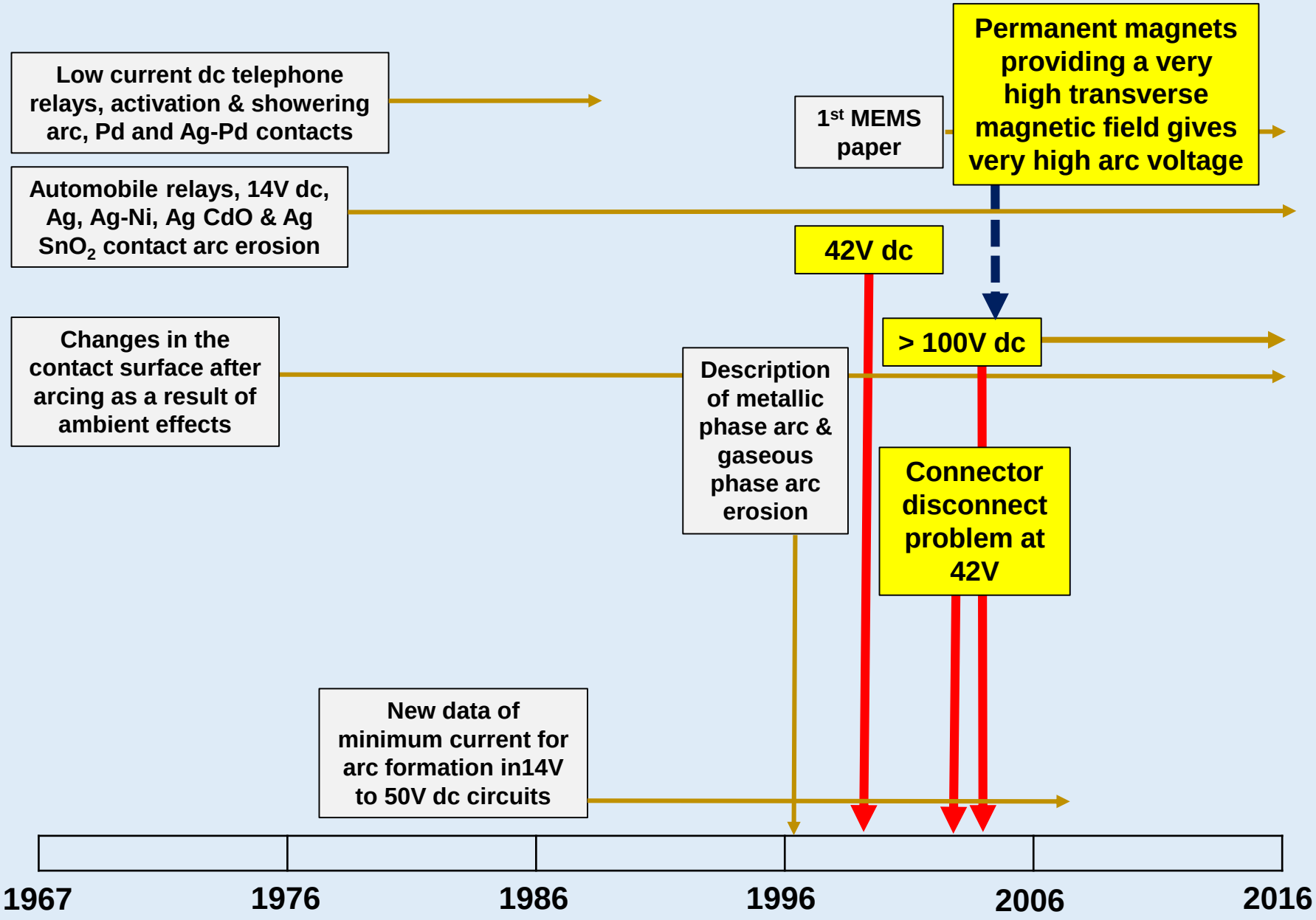
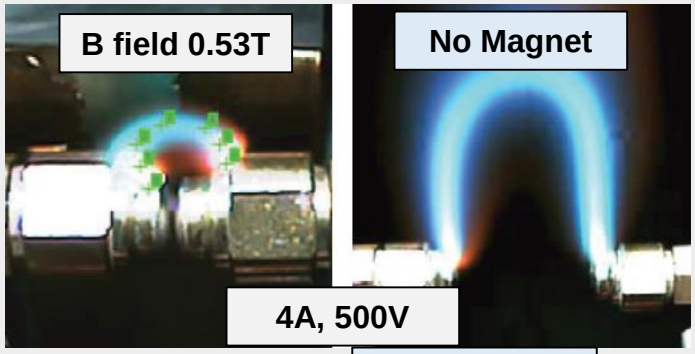


The most significant development in dc switching

Automobile relays, 14V & 42V dc, open contacts when arc voltage = circuit voltage currant 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 across open bridging contacts to interrupt dc circuits up to 700V results in compact dc relay deign 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

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 !

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2008 2001 2010 2011 2012 2013 2014 2015

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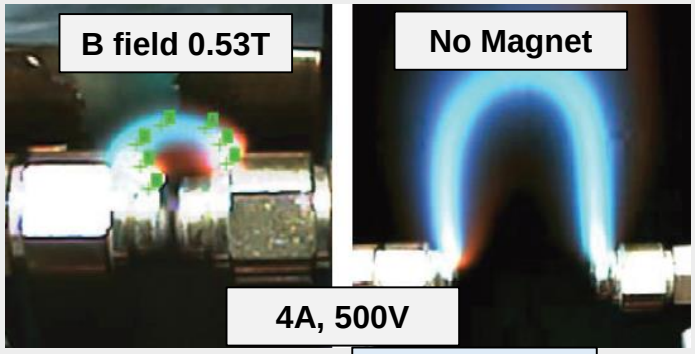

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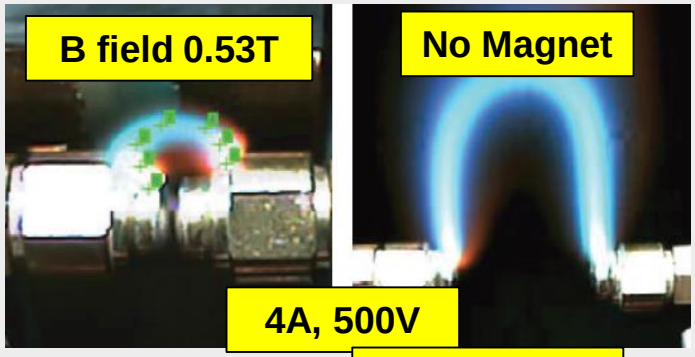

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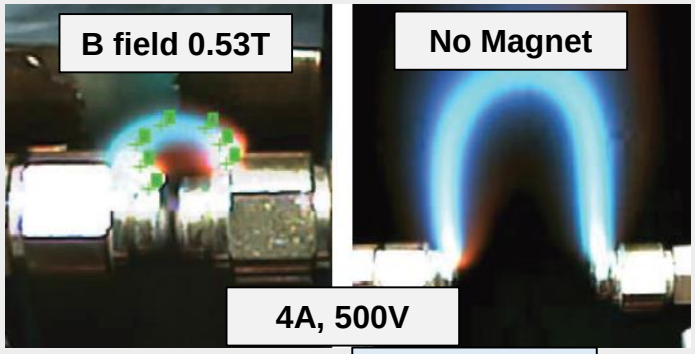

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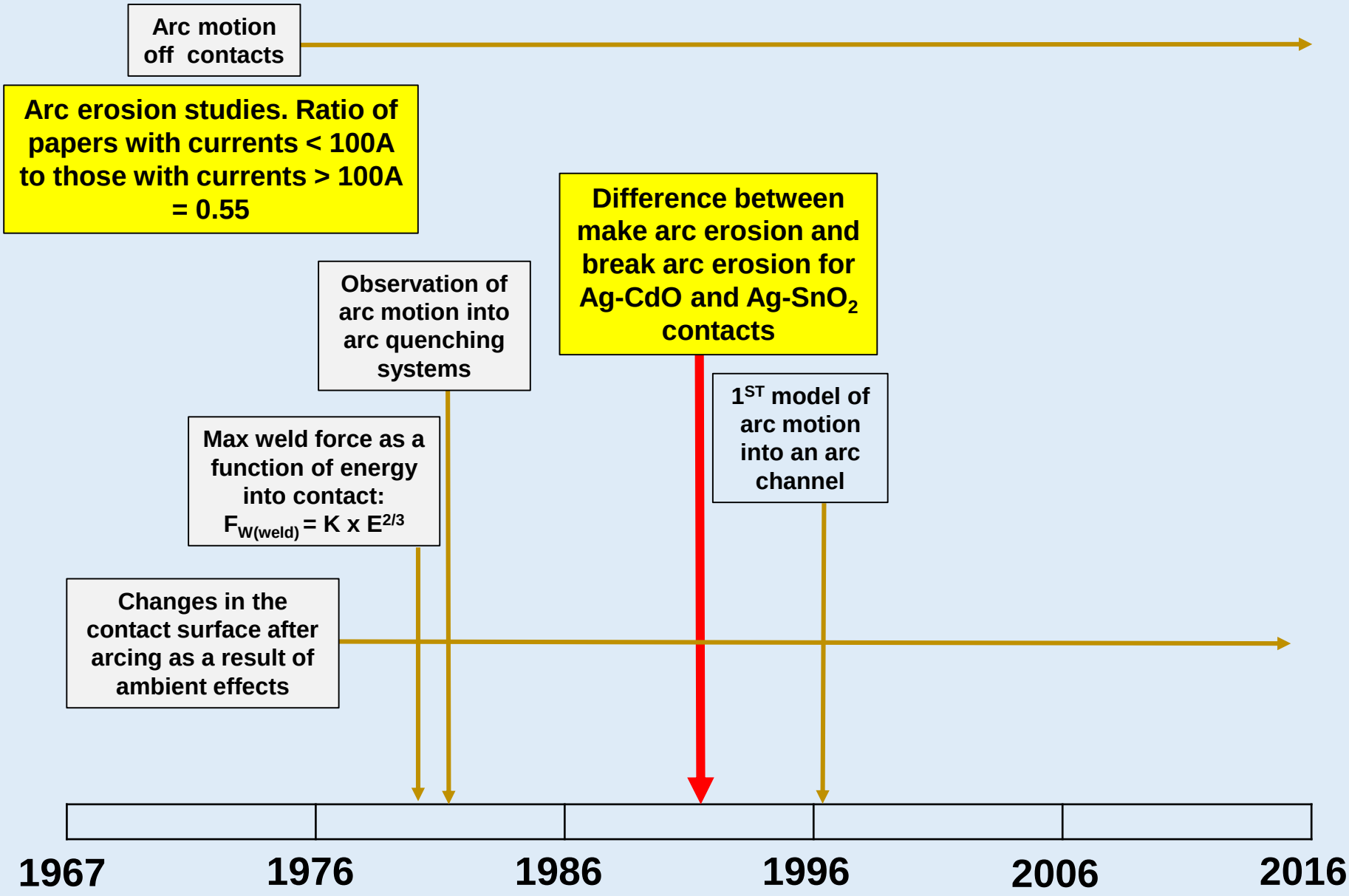

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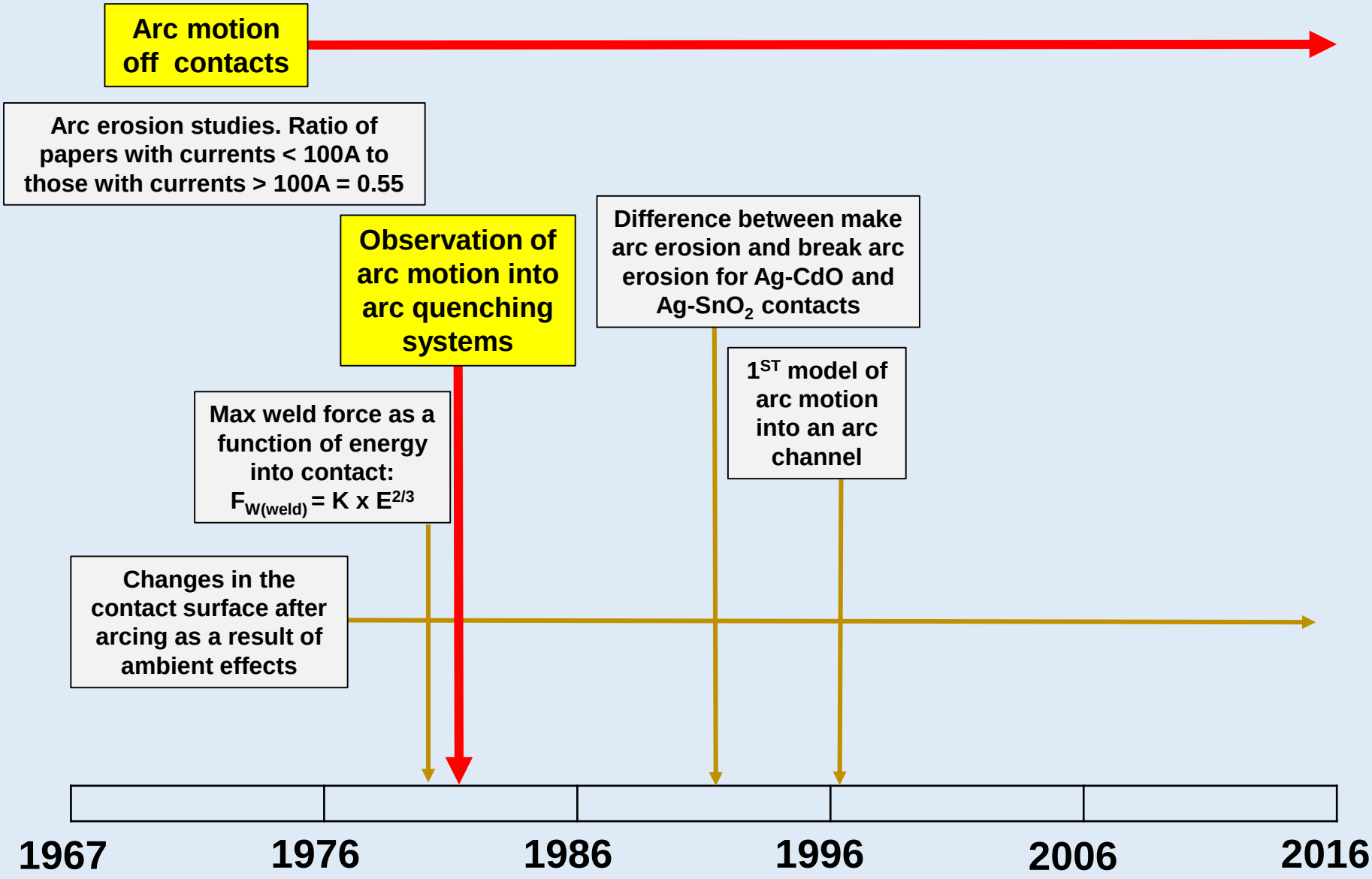

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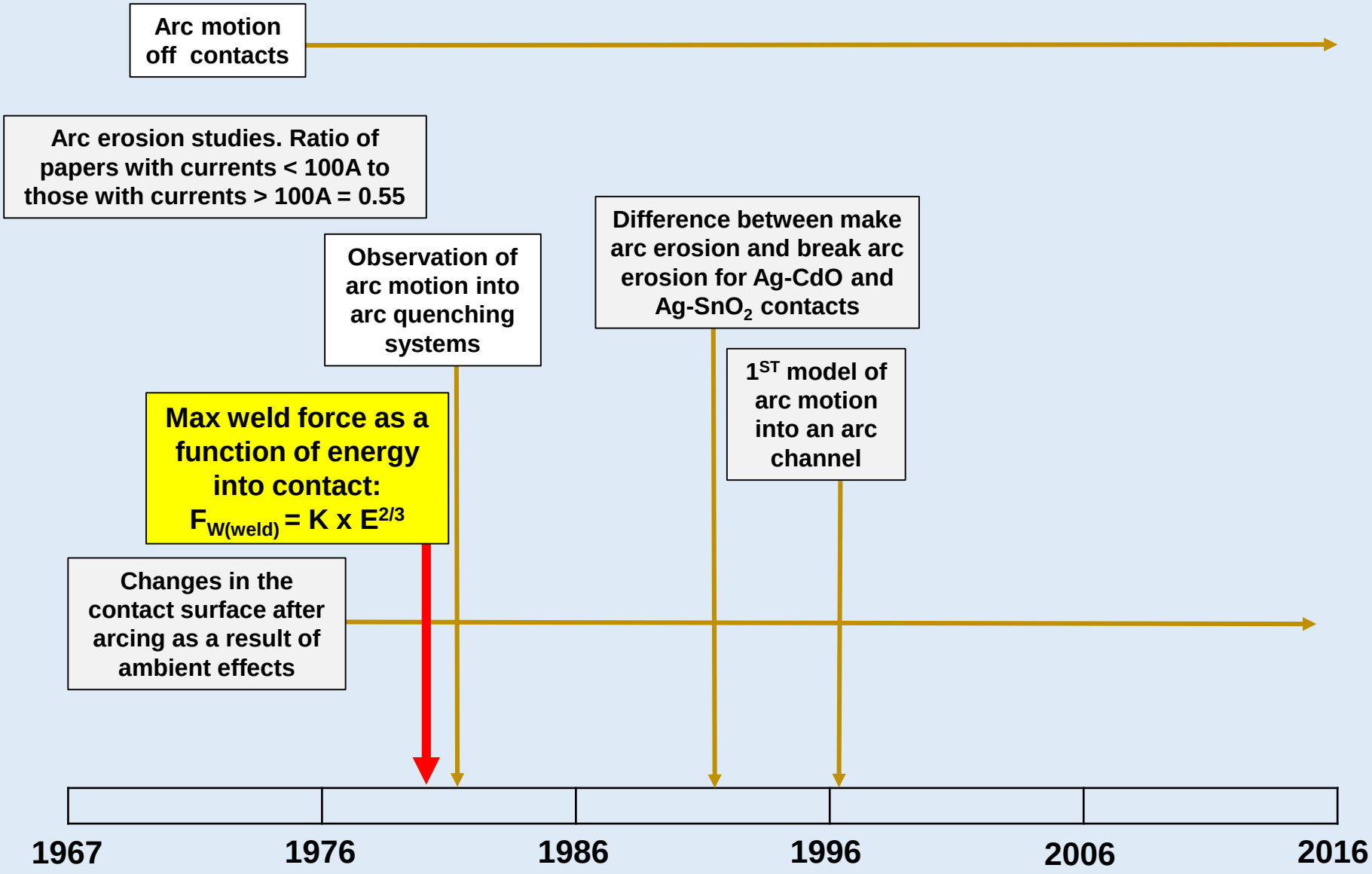

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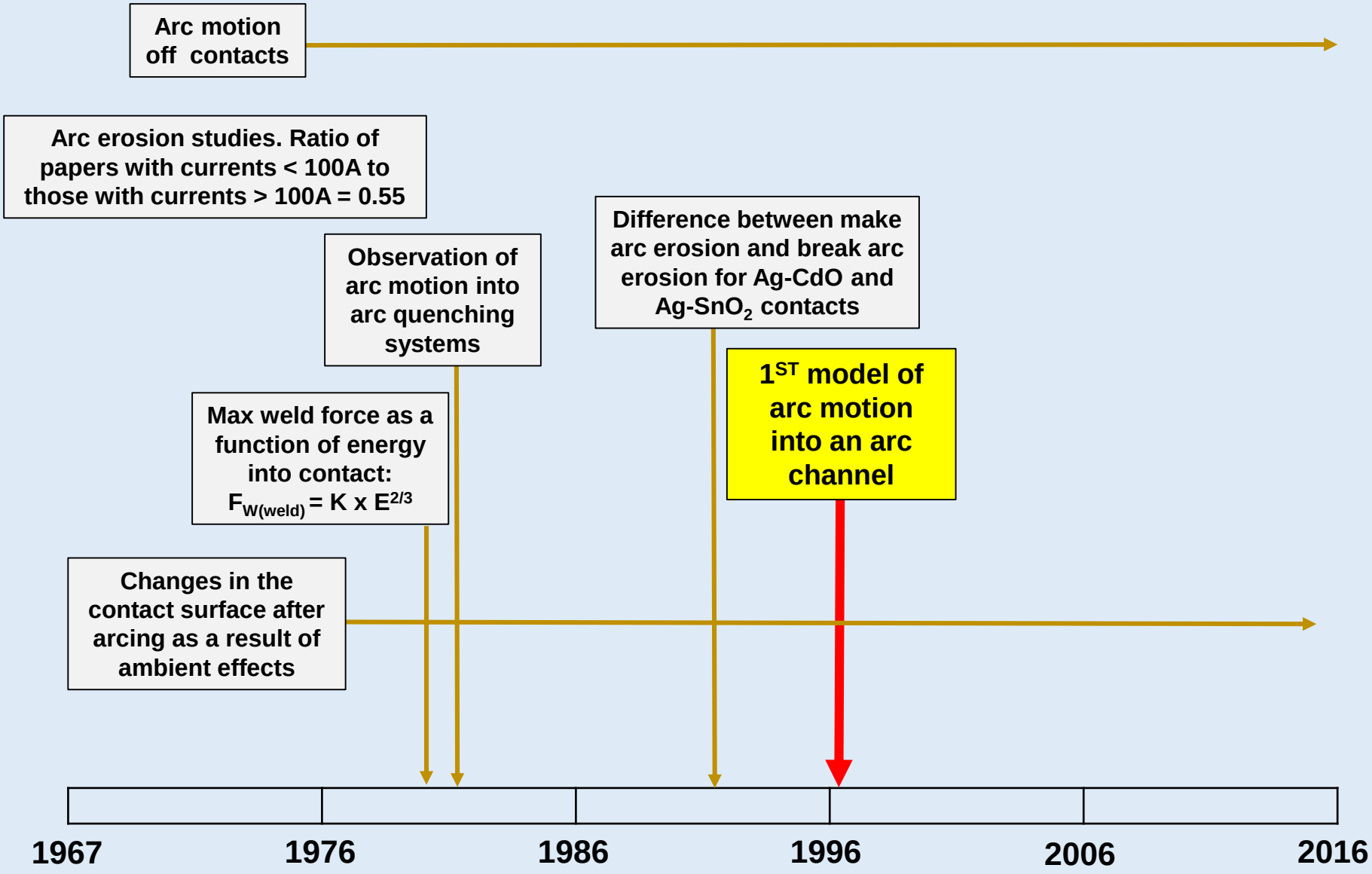

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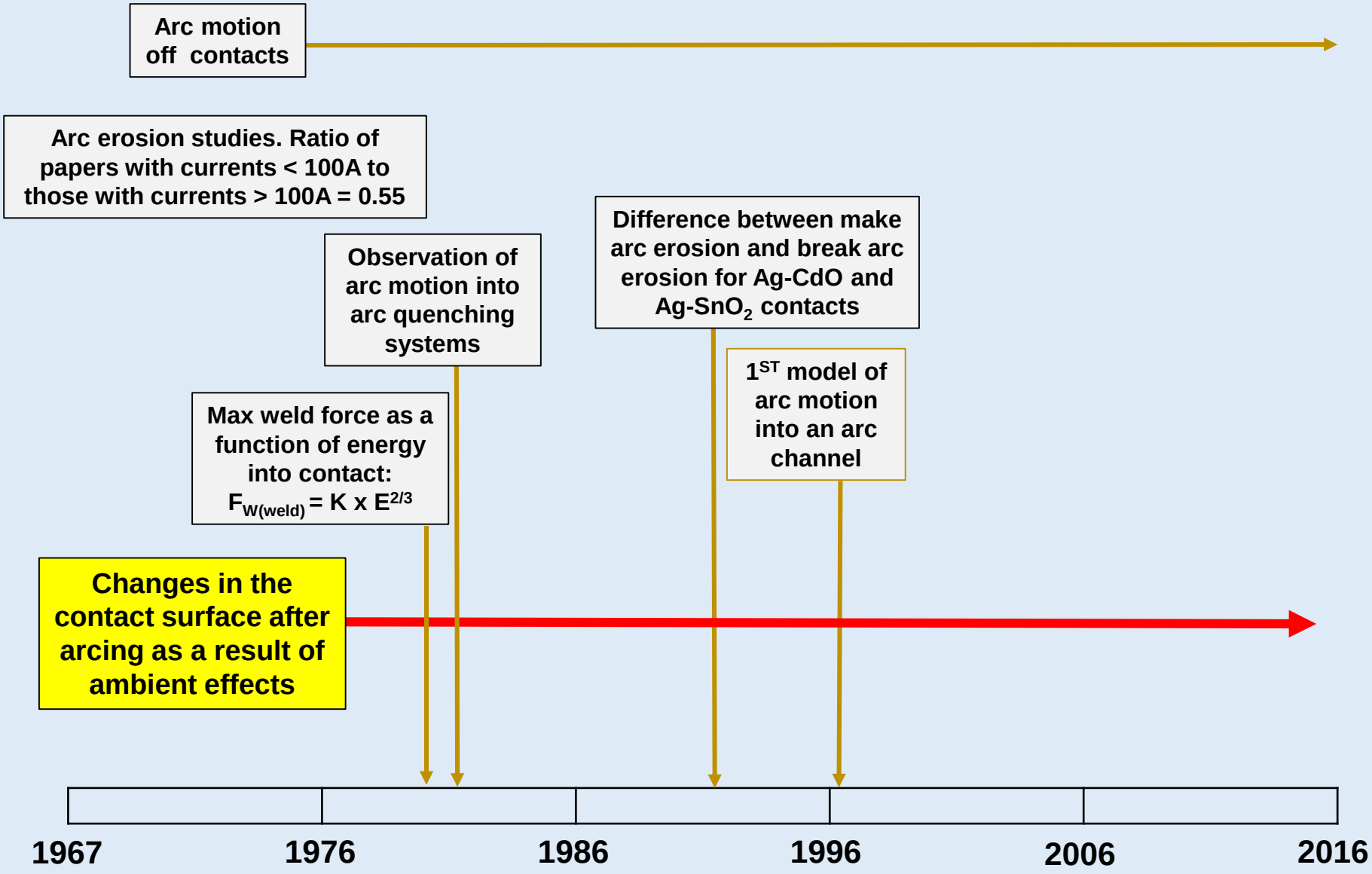

Effect of Silicone Lubricants, Sealants and Potting Compounds on Arcing Contacts

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

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Dimethyl Silicones: Dn

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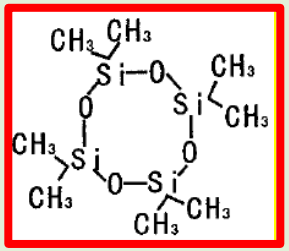

D4

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

Effect of silicone vapor concentration and 120mA dc switching frequency

Acrylic based polymeric materials show promise as silicone free encapsulants

Effect of 100mA switching frequency

High R_C after 300 operations at 150A ac

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

1966 1976 1986 1996 2006 2016

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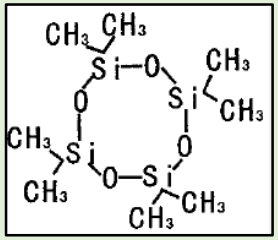

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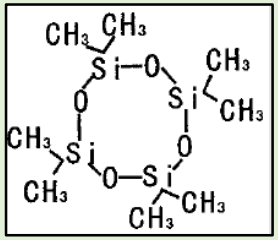

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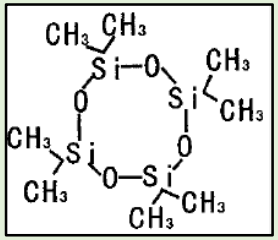
R_C increases linearly switching 0.5 to 500mA in presence of Silicone rubber

Dimethyl Silicones: Dn

(CH3)2SiO]n



D4

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

Silicone vapor formation rate on contact surfaces

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

1966 1976 1986 1996 2006 2016

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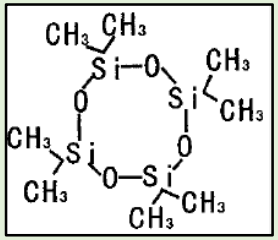

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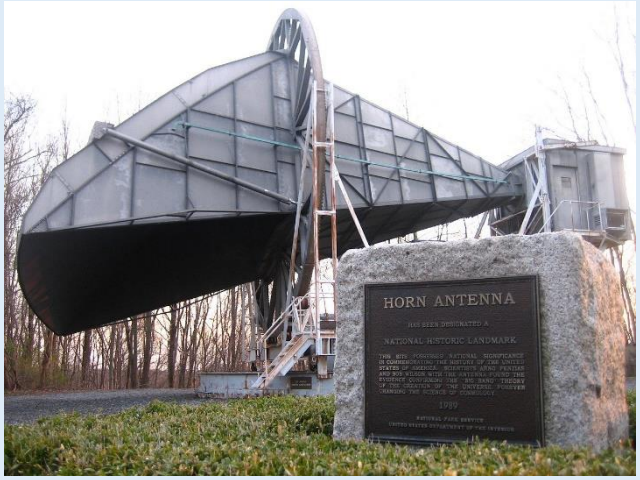
The Nobel Prize

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



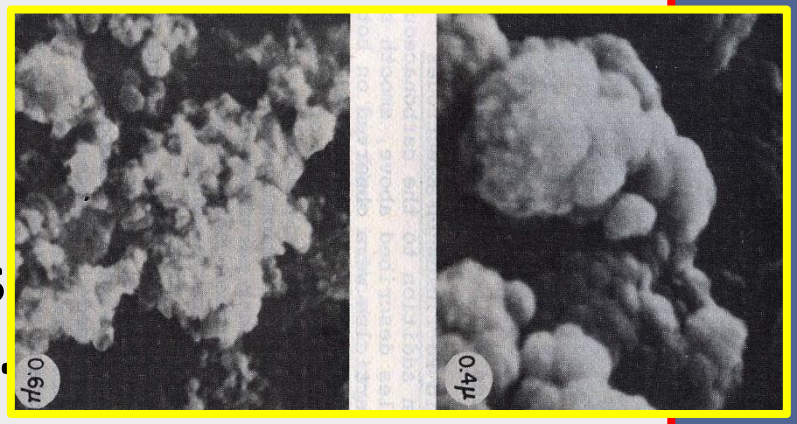
In 1964 They had some irritating interference in their supersensitive 6m horn antenna

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.

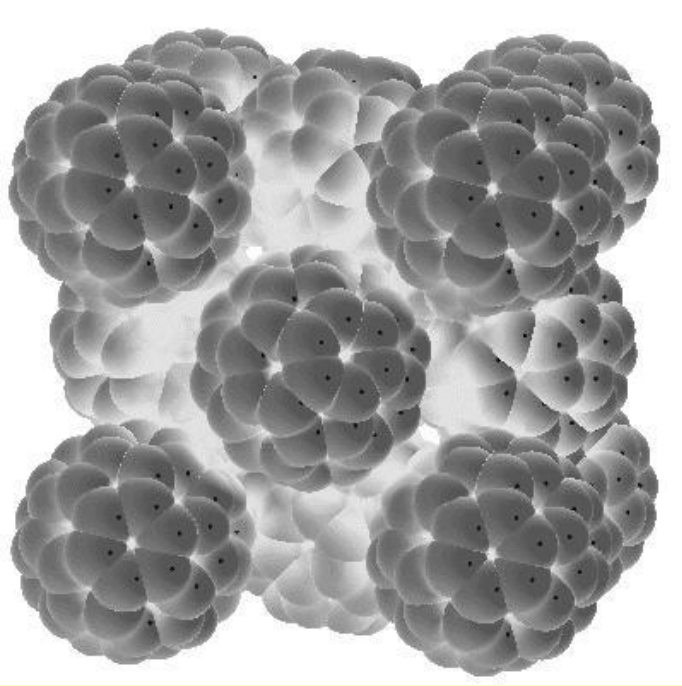


Buckminsterfullerenes (Bucky-Balls)

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

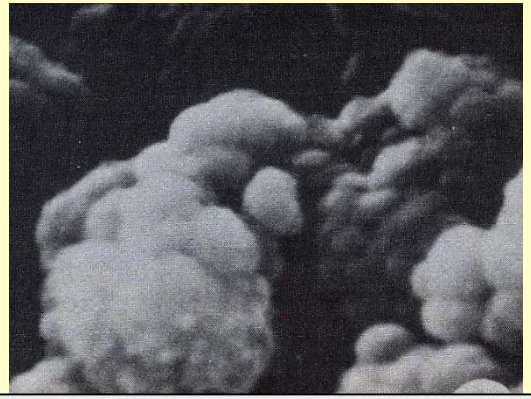
First claimed generation of C_{60} by Kroto, Heath, O'Brian, Curl, & Smalley (Rice University) in 1985 firing a laser beam into a block of C

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

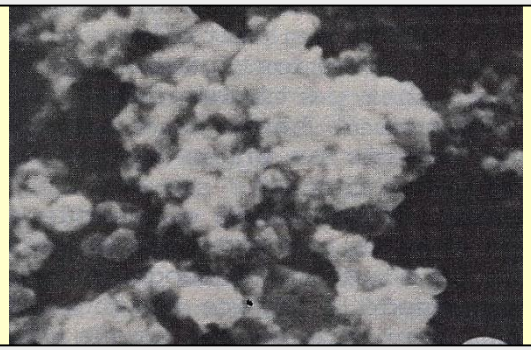


My own team of plasma researchers manufactured Bucky-Balls in the late 1980's using an arc discharge in air containing a hydro-carbon gas. Did the contact scientists in Bell Columbus organization miss out on a Nobel prize?

Bucky-Ball creation by an arc in a hydrocarbon ambient

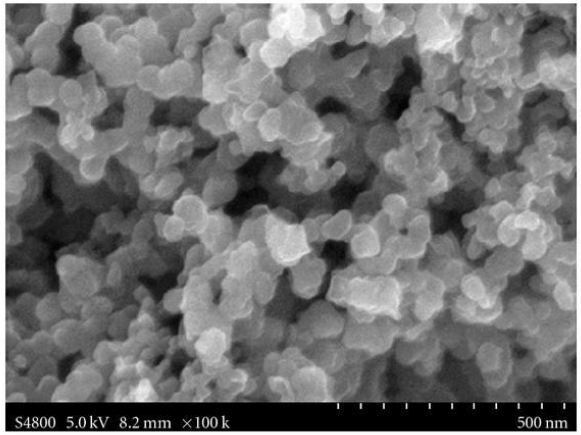


Gray: Holm Conference 1975. A low current (0.5A) arc in air plus toluene.



Analysis showed balls of carbon material 45nm in diameter

Zhao et al: J. Nano-materials 2011
An 8A arc in benzene plus argon



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

10 years before Kroto et als Bucky-Ball announcement Gray had produced them. A missed opportunity?

Key Rules of Thumb

1) Contact Resistance

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

2) Temperature of the contact spot

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

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 is f(contact material)]

$$F_w = K E_C^{2/3}$$

5) Threshold closed contact welding current for 'n' regions of contact

$$i_W = \frac{2U_m\left(\sqrt{n}\right)\sqrt{F}}{\left[\left\{\rho_0\left[1+\frac{2}{3}\alpha\left(T_1 - T_0\right)\right]\right\}^2 \pi\left(0.1H_0\right) + 4U_m^2(\beta)\right]^{1/2}}$$

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**

Future Trends

- 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