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Rethinking Contact Current Arcing ...

New Insights on an Old, Chronic Problem

Prepared and
Presented by: ARC SUPPRESSION
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**Rethinking
Contact Current Arcing ...**
New Insights on an Old, Chronic Problem



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September 27, 2012

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Thank you very much for allowing me to share my area of expertise with you.

A Brief Look at the Workhorses of Power Switching:

RELAYS AND CONTACTORS

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“Sometimes we have to close our eyes in order to see more clearly!” -rh

Relays & Contactors

- The most common form of electrically operated switch
- For consumer, commercial, industrial, automotive, medical and military applications



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Some sources of unintentional but predictable contact current arcing.

Contact Current Arcing



Arcing Causes

- Short contact life
- Product failures
- Significant EMI
- Air pollution (Ozone, fine dust, and other undesirable particulate matter)

Arcing Requires

- Preventive maintenance
- Costly repairs
- Shielding
- Venting



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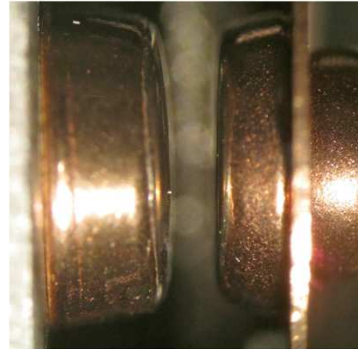
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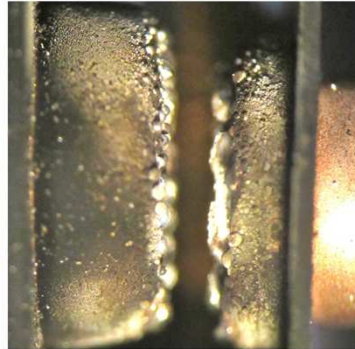
Some not so well known basic relay, contactor and switch contact information...

Contact Degradation

Unused Contacts



100K Cycles
Unsuppressed



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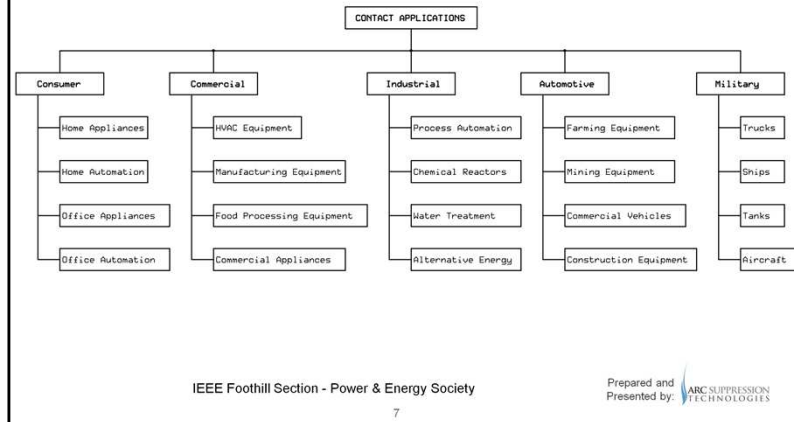
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This slide shows T9A style relay contact electrodes in comparison under a 20x inspection microscope magnification:

More on this later

A General Example of Contact Applications



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This slide outlines a general example of five primary industry classifications for electromechanical switching applications, along with some representative examples from each class:

Consumer applications are those that typically operate at lower power, and under relatively benign operating temperature conditions of 0°C to 70°C.

These include, but are not limited to home and office applications.

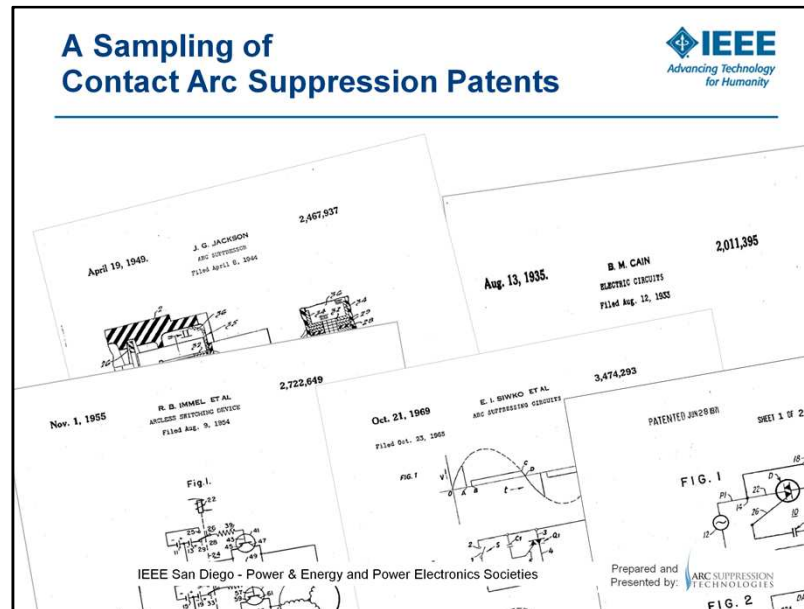
Commercial applications are those that operate at higher power and under operating temperature conditions of -40°C to 85°C.

These include, but are not limited to commercial appliances and HVAC, as well as various manufacturing equipment.

Industrial applications are those that typically use high power and operate under the even more operating temperature conditions of -40°C to 100°C.

Automotive applications are typically associated with vehicles. These applications may be relatively low power through higher power, operating under a wide range of operating temperature conditions from -40°C to 125°C. These applications include consumer vehicles and industrial vehicles such as agricultural, mining, and construction equipment.

Military applications include those, regardless of power, operating under the most arduous of operating temperature conditions of -55°C to 150°C.



This slide shows a few examples of significant contact arc suppression patents of the past:

Thomas Edison, George Westinghouse and Nikola Tesla who were some of the pioneers who started to commercialize electrical power had to put up with contact arcing but I am sure they wished they could have gotten rid of it.

To date, the author has reviewed over 340 US and International, granted and pending patents in the contact arc suppression space some dating back to the days of Nikola Tesla.

For example: US Patent 1,368,325 filed August 13, 1916 and granted February 15, 1921 by Chrichton, assigned to Westinghouse, teaches the reduction to practice of an “Arc Extinguishing Device”.

Another more modern example: US Patent 7,782,578 filed March 5, 2007 and granted August 24, 2010 by Tao, assigned to Delta Electronics, Inc., teaches the reduction to practice of a “Relay Protection Circuit and Controlling Method thereof Having Relatively Better Effectiveness for Suppressing DC Arc”.

Companies with Patents in the Contact Arc Suppression Space



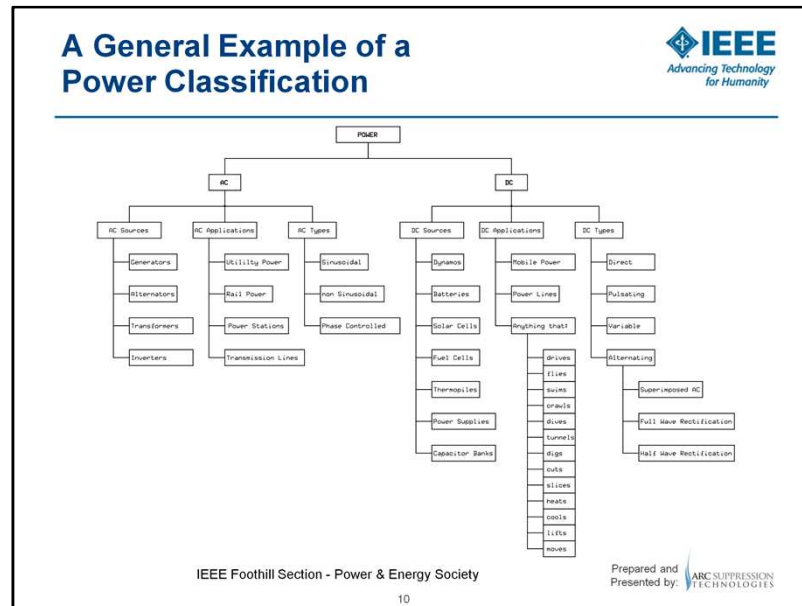
- Government Agencies and Industrial Concerns
- Most Manufacturers on the Fortune 500 List
- Many Other World-known Companies
- Electro-mechanical Manufacturers
- Specialty Controls Manufacturers
- Semiconductor Companies
- Relay Manufacturers
- Private Individuals
- Et cetera, etc.

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This slide indicates the significance of the continuous needs and attempts by the industry to come up with better contact arc suppression solutions.



This slide presents a general example of a Power Classification:

Sources for AC power include generators, alternators, transformers, etc.

AC power is typically sinusoidal, however, it may also be non-sinusoidal, or phase controlled.

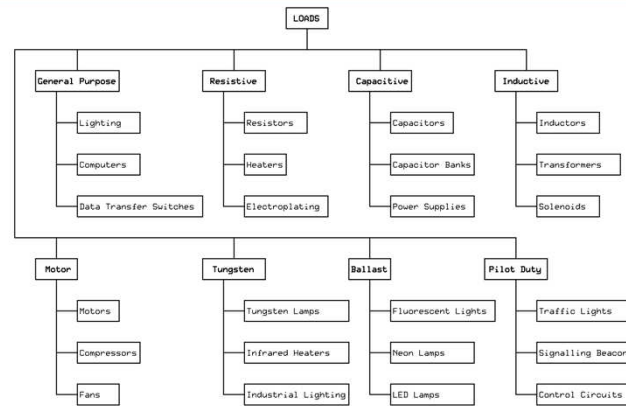
Applications for AC power include the power grid (utility power, power stations, transmission lines, etc.) as well as off the grid uses such as rail power.

Sources for DC power include various types of battery-like storage, such as batteries, solar cells, fuel cells, capacitor banks and thermopiles, as well as dynamos, power supplies.

DC power types include direct, pulsating, variable, and alternating (which includes superimposed AC, full wave rectification and half wave rectification).

DC power is mostly associated with self-propelled applications, i.e., anything that drives, flies, swims, crawls, dives, tunnels, digs, cuts, slices, heats, cools, lifts, moves, etc.

A General Example of a Load Classification



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This slide outlines a general example of the eight main load classes (as per UL), with representative examples of each class:

1. **General purpose** loads include consumer lighting, computers, data transfer switches, etc.
2. **Resistive** loads include resistors, heaters, electroplating, etc.
3. **Capacitive** loads include capacitors, capacitor banks, power supplies, etc.
4. **Inductive** loads include inductors, transformers, solenoids, etc.
5. **Motor** loads include motors, compressors, fans, etc.
6. **Tungsten** loads include Tungsten lamps, infrared heaters, industrial lighting, etc.
7. **Ballast** loads include fluorescent lights, neon lights, LED lights, etc.
8. **Pilot duty** loads include traffic lights, signal beacons, control circuits, etc.

Relay, Contactor and Switch Contact State Tables



Relay and Contactor State Table		CONTACT STATE (NO)	
		OFF	ON
COIL STATE	Energized	Make → Bounce ← MAKE ↔ CLOSED	
	De-energized	↑ OPEN → Break ← Bounce ↓ BREAK	

Switch (SPST) State Table		CONTACT STATE	
		OFF	ON
LEVER STATE	ON	Make → Bounce ← MAKE ↔ CLOSED	
	OFF	↑ OPEN → Break ← Bounce ↓ BREAK	

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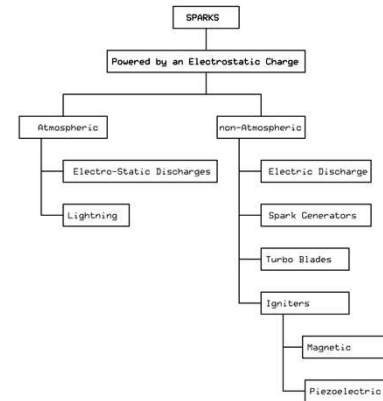
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This slide shows the contact cycle of a relay or contactor and the contact cycle of a switch (respectively):

A contact cycles through four distinct states: OPEN, MAKE, CLOSED and BREAK. The make and break states are generally transitional and are of generally short duration. The open and closed states are generally non-transitional and are of generally longer duration. A general switch cycle may start with the OPEN state. As part of the MAKE state, the contact may bounce multiple times until it achieves the CLOSED state. A general switch cycle may remain a certain amount of time in the CLOSED state. As part of the BREAK state, the contact may bounce multiple times until it re-enters the OPEN state.

A General Example of a Spark Classification



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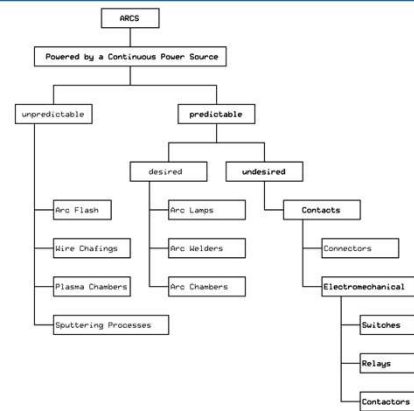
This slide outlines a general example of a Spark Classification:

Atmospheric sparks include electrostatic discharge and lightning.

Non-atmospheric sparks include electric discharge, spark generators, turbo blades, and both magnetic and piezoelectric igniters.

The various classes of sparks are powered by an electrostatic charge.

A General Example of an Arc Classification



This slide outlines a general example of an Arc Classification:

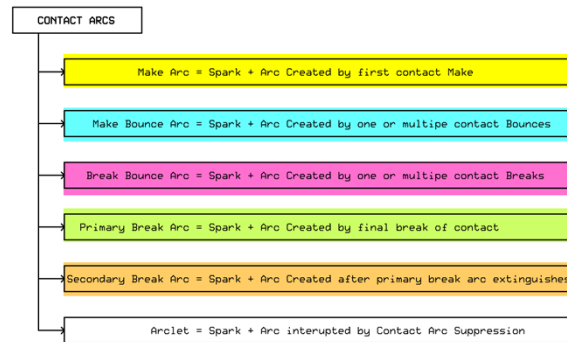
Unpredictable arcs include arc flash, chafing, plasma chambers, sputtering processes, etc., and are typically both dangerous and undesired.

Predictable and desired arcs include both desired and undesired arcing. Arc lamps, arc welders, and arc chambers are examples of desired, predictable arcing.

Predictable but undesired arcs include arcing in connectors and the contact current arcing that occurs within switches, relays and contactors.

The various classes of electrical arcs are powered by a continuous power source.

Contact Arc Classification



This slide outlines a Contact Arc Classification:

1. The **Make Arc** is the combination of a spark plus the arc created by the first contact make.
2. The **Make Bounce Arc** is the combination of a spark plus the arc created by the one or more contact bounces.
3. The **Break Bounce Arc** is the combination of a spark plus the arc created by one or multiple contact breaks.
4. The **Primary Break Arc** is the combination of a spark plus the arc created by the final contact break.
5. The **Secondary Break Arc** is the combination of a spark plus the arc created after the primary break arc extinguishes.
6. The **Arclet** is an arc interrupted by contact arc suppression.

Each arc has a life of its own (ignition, burning, extinguish).

Contact Cycle Sequence



CONTACT CYCLE SEQUENCE									
Time is generally moving in this direction ----> (Note: not to scale)									
Open State	Make Transition			Closed State	Break Transition			Open State	
Gap Widest	Gap Narrowing			No Gap	Gap Widening			Gap Widest	
Voltage Across Contact		Current Through Contact				Current Through Contact		Voltage Across Contact	
No Arcing	Make Arc	Make Bounce Arc	No Arcing		Break Bounce Arc	Primary Break Arc	Secondary Break Arc	No Arcing	
Broken Microwelds		Make New Microweld	New Microweld	Break Microweld		Broken Microwelds			
Metal Cooling or Cold		Metal Softening, Melting & Boiling		Metal Cooling or Cold		Metal Softening, Melting & Boiling		Metal Cooling or Cold	

- 1. Make Arc
- 2. Make Bounce Arc

- 3. Break Bounce Arc
- 4. Primary Break Arc
- 5. Secondary Break Arc

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This slide is a table showing the Contact Cycle Sequence:

Top row: CONTACT CYCLE SEQUENCE

Second row: Contact travel time line (generally moving in direction indicated, however, neither necessarily linearly nor to scale)

Third row: Contact States

Fourth row: Contact Air Gap condition

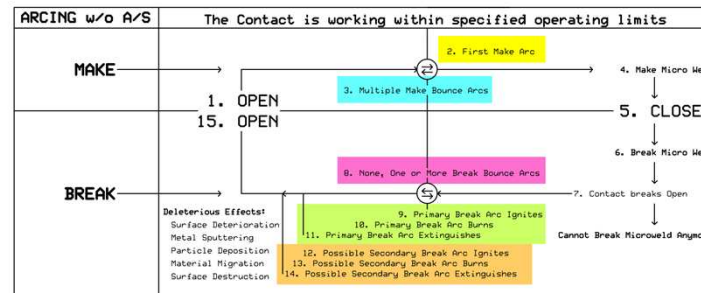
Fifth row: Contact voltage or current condition

Sixth row: Arcing condition

Seventh row: Micro weld condition

Eighth row: Contact metal condition

Contact Cycle Details



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This slide is a chart illustrating an example of a contact arc cycle at greater than a 1A load current without arc suppression:

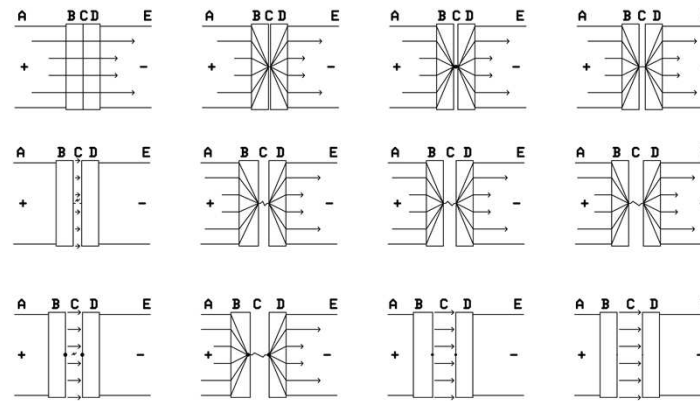
It is assumed that the contact of a switch, relay or contactor is working within specified operating limits. A contact cycles through four distinct states: Open, make, closed and break. The make and break states are generally transitional and are of generally short duration. The open and closed states are generally non-transitional and are of generally longer duration. Each state generally has specific phases associated with them that the contact has to travel through. A general switch cycle may start with the:

1. OPEN state. After entering the make state the contact cycles through phase
2. First Make Arc, followed generally by phase
3. Multiple make bounce arcs, followed generally by phase
4. Make Micro Weld and coming to rest at the generally non-transitional state
5. CLOSED. A general switch cycle may remain a certain amount of time in the state CLOSED state. After entering the break state the contact cycles through phase
6. Break Micro Weld, followed by phase
7. Contact Breaks Open, followed by phase

8. None or more break bounce arcs, followed by phase
9. Primary Break Arc Ignites, followed by phase
10. Primary Break Arc Burns, followed by phase
11. Primary Break Arc Extinguishes, followed by phase
12. Possible Secondary Break Arc Ignites, followed by phase
13. Possible Secondary Break Arc Burns, followed by
14. Possible Secondary Break Arc Extinguishes, and coming to rest at the generally non-transitional state
15. OPEN

Phases 9 through 14 are the direct cause of the noted deleterious effects of contact surface deterioration, including metal sputtering, particle deposition, material migration and surface destruction.

Contact Breaking Event



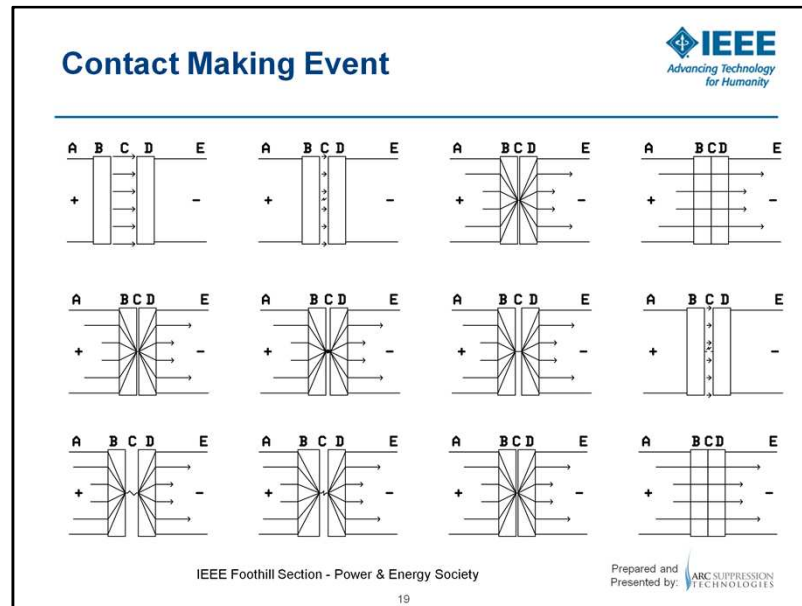
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This slide represents examples of a contact breaking event without contact arc suppression. Showing in the following sequence:

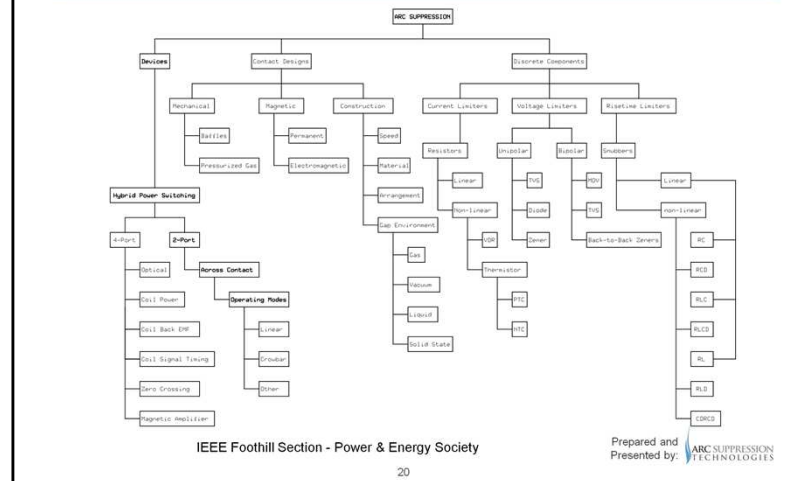
Current flowing, current constricting and contact heating, metal melting and pooling, molten wire bridge forming, wire bridge ripping followed by a first dielectric (low voltage) breakdown (spark), ignition of the primary break arc between 9 and 15V, primary break arc burning, primary break arc lengthening, primary break arc extinguishing followed by a secondary (high voltage) dielectric breakdown (spark), ignition of the secondary break arc via a high voltage spike, secondary break arc burning, secondary break arc extinguishing, contact travels to its open position.



This slide represents examples of a contact making event without contact arc suppression. Showing in the following sequence:

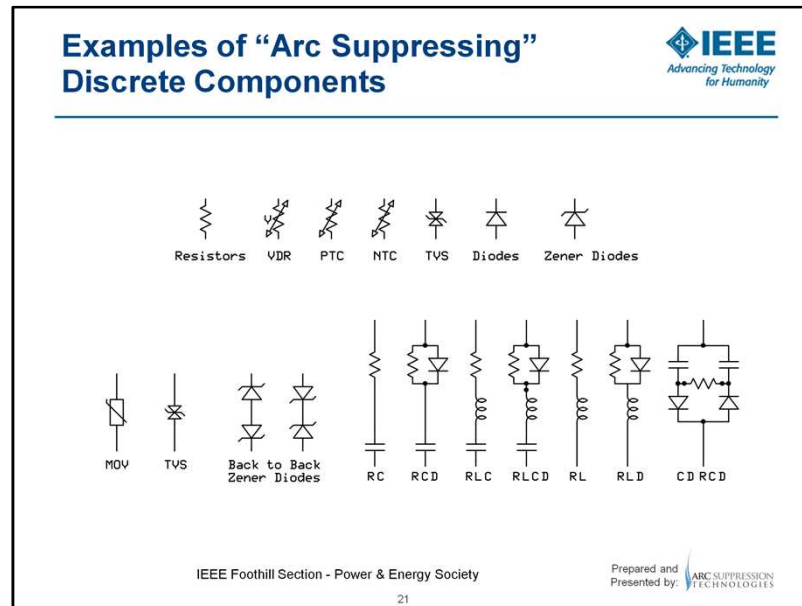
Contact open, contact closing and gap small enough for the first dielectric breakdown (spark) to occur, make arc igniting, current constricting, contact metal heating possibly melting, contact closing for the first time and current flowing for the first time, contact bouncing, current constricting and contact heating, metal melting and pooling, molten wire bridge forming, wire bridge ripping followed by a dielectric (low voltage) breakdown (spark), ignition of the bounce arc between 9 and 15V, bounce arc burning, bounce arc lengthening, bounce arc shortening, contact closing, bounce arc extinguishing, possibly followed by another contact bounce, with bounce arc and metal melting, making for a good quality micro weld, providing low contact resistance.

A General Example of a Contact Arc Suppression Classification



This slide outlines an example of a general classification contact arc suppression as currently available to industry:

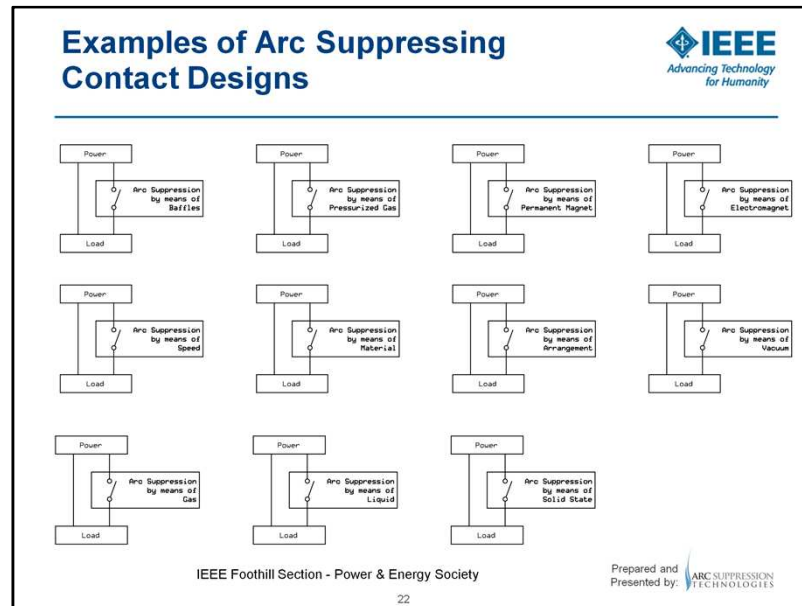
These contact arc suppression classes fall into three broad classes of devices, contact design, and discrete components. Contact devices are generally understood to be hybrid power devices, using both solid state and electromechanical components. Four-port devices typically use input outside of the contacts, including but not limited to optical, coil power, coil back EMF, coil signal timing, zero crossing, or magnetic amplifiers. Contact design includes both the contact construction and adjacent, environment conditions in which the contacts operate. Mechanical means include elements such as baffles and pressurized gas. Magnetic means include both permanent and electromagnets. Contact construction includes contact speed, contact material, contact arrangement, and gap environment. The gap environment may be gas, vacuum, liquid or solid state. Discrete components are broadly classified as current limiters, voltage limiters, and rise-time limiters. Current limiters include linear and non-linear resistors. Non-linear resistors are comprised of voltage dependent resistors (VDR's), positive temperature coefficient (PTC) Thermistors, and negative temperature coefficient (NTC) Thermistors. Voltage limiters are either unipolar or bipolar. Unipolar voltage limiters include transient voltage suppressors (TVS's), diodes, and zener diodes. Bipolar voltage limiters include metal oxide varistors (MOV's), TVS's, and back-to-back zeners. Risetime limiters are generally known as snubbers, and are either linear or non-linear. Non-linear snubbers are comprised of a combination of components such as resistors R, capacitors C, inductors L and diodes D but not limited to and thus including possible circuit configuration permutations such as RC, RCD, RLC, RLCD, RL, RLD, CDRCD



This slide shows the schematic symbols for the discrete components noted in the discrete class of the Contact Arc Suppression Classification slide:

Top row: The symbol for a resistor, the symbols for a VDR, a PTC, and an NTC, the symbols for a TVS, a diode, and a zener diode

Bottom row: The symbols for an MOV, a TVS, and back-to-back zener diodes, the symbols for an RC, an RCD, an RLC, an RLCD, an RL, an RLD, and a CDRCD Snubber.



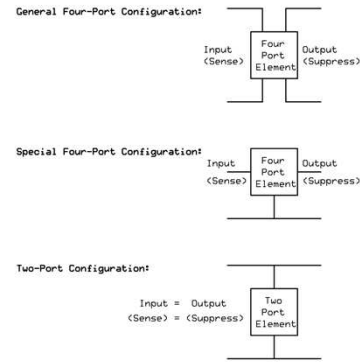
This slide shows example schematic diagrams for contact arc suppression noted in the contact design class of the Contact Arc Suppression Classification slide:

Top row: A diagram for contact arc suppression by means of baffles, a diagram for contact arc suppression by means of pressurized gas, a diagram of contact arc suppression by means of permanent magnet, a diagram of contact arc suppression by means of electromagnet.

Middle row: A diagram for contact arc suppression by means of contact speed, a diagram of contact arc suppression by means of contact material, a diagram of contact arc suppression by means of contact arrangement, a diagram of contact arc suppression by means of contact operating in a vacuum.

Bottom row: A diagram of contact arc suppression by means of contact operating in a gas, a diagram of contact arc suppression by means of contact operating in a liquid, a diagram of contact arc suppression by means of a solid state device as part of the contact construction.

Academic Teaching of Two-Port and Four-Port Elements



This slide illustrates an example of an academic teaching of four-port network elements:

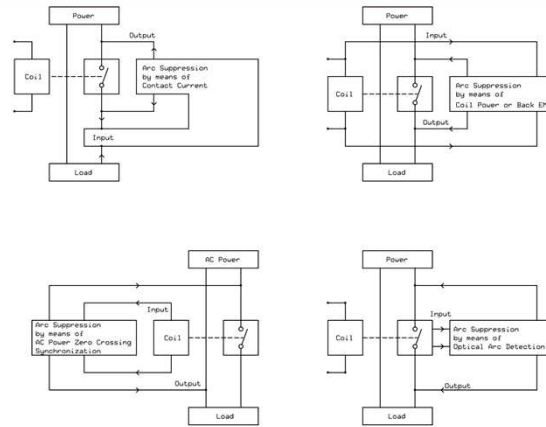
At the top: General (Symmetrical) four-port network element configuration (balanced input and balanced output)

In the middle: Special (Asymmetrical) four-port network element configuration (unbalanced input and unbalanced output)

At the bottom: Two-port network element configuration (with input and output sharing the same connection leads)

Each variant displays the associated input, output, sensing and suppression aspects of the design.

Examples of Four-Port Contact Arc Suppression



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This slide shows four example schematics of four-port contact arc suppression:

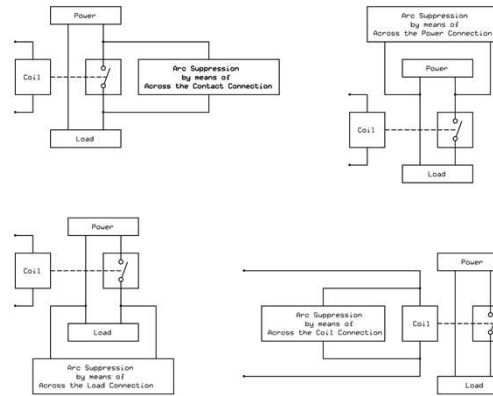
Top left: Shows the input being derived from sensing the change in contact current and timing the suppression means from this input.

Top right: Shows the input being derived from sensing coil power back EMF and timing the suppression means from this input.

Bottom left: Shows the input being derived from the coil, which is used to attempt to synchronize the contact activation with AC zero-crossing to provide suppression.

Bottom right: Shows the input being derived from an optical sensor detecting the arc visually and timing the suppression means from this input.

Examples of Two-Port Contact Arc Suppression



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This slide shows four example connections of two-port contact arc suppression:

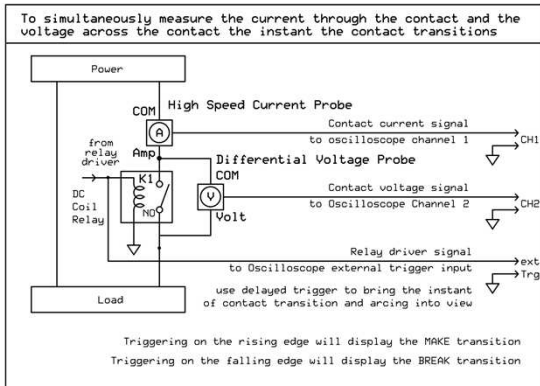
Top left: Shows the contact arc suppression means connected across the power source.

Top right: Shows the contact arc suppression means connected across the contact.

Bottom left: Shows the contact arc suppression means connected across the load.

Bottom right: Shows the arc contact suppression means connected across the coil connection.

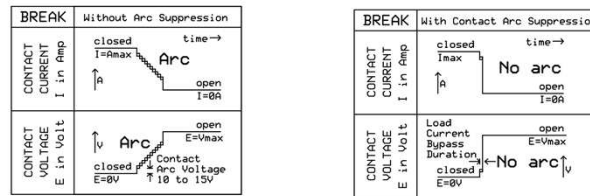
Contact Arcing Measurement Test Set-up



This slide illustrates a contact arcing measurement test set-up:

The results obtained using this test set-up allow for determining the effectiveness of a contact arc suppression on either an electromechanical relay or a contactor. This is achieved by simultaneously measuring the current through the contact and the voltage across the contact during either the MAKE or BREAK transitions. This test requires both a high-speed current probe and a high-voltage differential voltage probe, as well as a two-channel, externally and delay triggered oscilloscope. The current probe must be connected to measure the current through the contact, with its output signal fed into the oscilloscope's channel 1. The voltage probe must be connected across the contacts, with its output signal fed into the oscilloscope's channel 2. The relay driver's signal should be fed into the oscilloscope's external trigger input, and a delayed trigger employed to bring the instant of contact transition into view on the scope. Triggering on the rising edge will display the MAKE transition, while triggering on the falling edge will display the BREAK transition.

Contact Arcing Presentation



Unsuppressed Break Arc Suppressed Break Arc

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This slide illustrates a comparison of contact arcing presentation for an unsuppressed (primary) break arc and a suppressed (primary) arc.

Left: measurement of a voltage (E) across the contact and a current (I) through the contact without arc suppression during the BREAK transition in which the contacts move from the CLOSED state to the OPEN state. In the CLOSED state, current is at its maximum ($I = I_{max}$) and there is practically (assumed) no voltage across the contact ($E = 0V$). As the contact opens, contact arc voltage occurs between 9V to 15V, with the BREAK Arc burning until the contact gap reaches a distance where the arc cannot be thermodynamically supported, the arc extinguishes and the current flow stops. During the OPEN state, there is no current flow through the contact ($I = 0A$), and the voltage across the contact is at maximum ($E = V_{max}$).

Right: measurement of a voltage (E) across the contact and a current (I) through the contact with arc suppression during the BREAK transition in which the contacts move from the CLOSED state to the OPEN state. In the CLOSED state, current is at its maximum ($I = I_{max}$) and there is practically (assumed) no voltage across the contact ($E = 0V$). As the contact opens, contact arc voltage occurs between 9V to 15V, with the primary BREAK Arc forming until the arc suppressor bypasses the contact current away from the contact. The current flow through the contact stops. During the OPEN state, there is no current flow through the contact ($I = 0A$), and the voltage across the contact is at maximum ($E = V_{max}$).

Contact Arc Suppression Factor Calculation



Contact Arc Suppression Factor Calculation

Average Energy of Arc = $V_{arc}(avg) * I_{arc}(avg) * T_{arc}(avg)$
Average Energy of Arclet = $V_{arclet}(avg) * I_{arclet}(avg) * T_{arclet}(AVG)$

$$ASF(avg) = \frac{\text{Avg Energy of Arc (without arc suppression)}}{\text{Avg Energy of Arclet (with arc suppression)}}$$

Note: I_{arclet} is generally slightly less than the full load current

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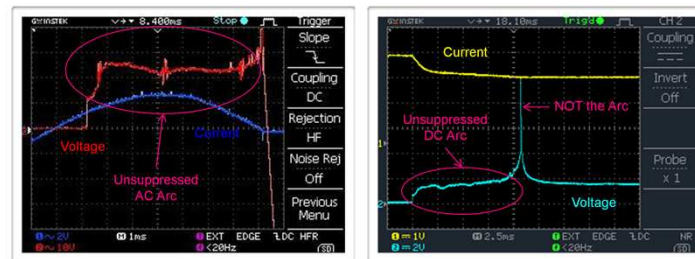
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This slide introduces the contact arc suppression factor calculation:

The contact arc suppression factor is a figure of merit allowing for a device to device and application to application comparison of efficacy. For example the ASF for a typical 0.1uF capacitor in series with a 100Ω RC Snubber is slightly greater than one (1) and the AST for a two-port contact arc suppressor in a low power applications is in the hundreds (100's) and in high power applications in the tens of thousands (10k's).

Examples of AC & DC Contact Arc Measurements



AC Contact Arc

DC Contact Arc

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This slide shows examples of AC & DC contact arc measurements:

These measurements were obtained via the contact arcing measurement test set-up of the previous slide.

Left Graph Discussion:

AC Contact Arc Measurement of a T9A style relay normally open contact.

Voltage is 240Vac, current is 12.5Arms (17.7Apk), resistive load rated at 3kW.

Y-axis: CH1, Current through the contact shown by the blue trace (sinusoidal wave), 13.5A/div

Y-axis: CH2, Voltage across the contact shown by the red trace (sinusoidal wave), 10V/div

The instant of momentary contact separation where for a very short moment in time an air gap exists as a very fast rising edge transitioning from 0V to about 12V. The risetime of the contact separation event is extremely fast and can reach speeds of around 8kV/us. At a voltage of about 12V (this “arc voltage” is dependent on the specific contact metal alloy) the arc ignites. Once established the arc continues to burn in this graph for about the next seven milliseconds. The arc extinguishes at the moment in the vicinity of the zero crossing where the current is not sufficiently large enough and the air gap is sufficiently wide enough to thermodynamically support the arc. Note that the current continues to flow almost as if the contact has not yet opened while the arc is burning between the two contact electrodes. Another fact to note is

that the dynamic arc impedance negative and thus has a voltage regulating effect on the burning ac arc. In this case the arc voltage levels out at an average of about 25V.

Right Graph Discussion:

DC Contact Arc Measurement of a T9A style relay normally open contact.

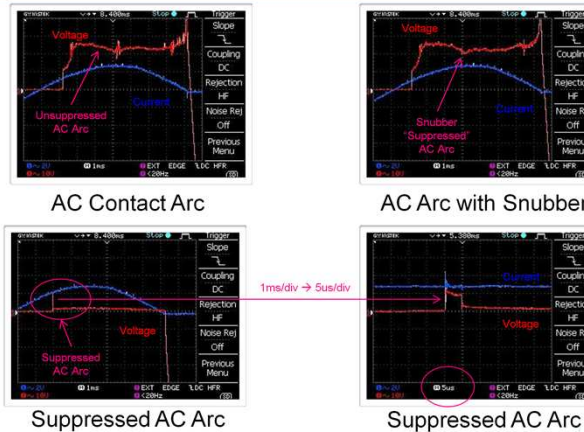
Voltage is 33Vdc, current is 6.75A, inductive load 1.6H + 4.9Ω

Y-axis: CH1, Current through the contact shown by the yellow trace, 6.75A/div

Y-axis: CH2, Voltage across the contact shown by the cyan trace, 36V/div

The instant of momentary contact separation where for a very short moment in time an air gap exists as a very fast rising edge transitioning from 0V to about 12V. The risetime of the contact separation event is extremely fast and can reach speeds of around 8kV/us. At a voltage of about 12V (this “arc voltage” is dependent on the specific contact metal alloy) the arc ignites. Once established the arc continues to burn in this graph for about the next eleven milliseconds. The arc extinguishes at the moment where the current is not sufficiently large enough to thermodynamically support the arc through the widening air gap. The moment the arc extinguishes and the air gap opens, current stops flowing through the inductor, its magnetic field collapses and the inductor responds with a counter electro-motoric force (CEMF) aka back EMF in form of a high voltage spike. Contrary to popular belief, this voltage spike is NOT the arc. If this voltage spike is high enough and if there is still sufficient residual ionization in the air-gap, a secondary break arc may ignite. The secondary break arc will be of a much shorter duration than the primary break arc and thus be less energetic. This voltage spike may be reduced and or clipped by connecting a voltage limiter across the contact. Please note that the clamping voltage of this voltage limiter must be greater than the maximum operating voltage across the open contact. Also note that in this case the current continues to drop towards zero as soon as the contact electrodes separate. A further fact to notice is that this primary break dc arc burns for almost as long as the contact travels to its open state end point. This of course is a fire hazard and this condition must be recognized and avoided.

Examples of AC Contact Arc Measurements



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Prepared and Presented by: ARC SUPPRESSION TECHNOLOGIES

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This slide shows examples of AC contact arc measurements:

These measurements were obtained via the contact arcing measurement test set-up of the previous slide.

Common Conditions:

AC Contact Arc Measurements of a T9A style relay normally open contact.

Voltage is 240Vac, current is 12.5Arms (17.7A_{pk}), resistive load rated at 3kW.

Y-axis: CH1, Current through the contact shown by the blue trace (sinusoidal wave), 13.5A/div

Y-axis: CH2, Voltage across the contact shown by the red trace (sinusoidal wave), 10V/div

Left Top Graph Discussion: AC Contact arc measurement. The instant of momentary contact separation where for a very short moment in time an air gap exists as a very fast rising edge transitioning from 0V to about 12V. The risetime of the contact separation event is extremely fast and can reach speeds of around 8kV/us. At a voltage of about 12V (this “arc voltage” is dependent on the specific contact metal alloy) the arc ignites. Once established the arc continues to burn in this graph for about the next seven milliseconds. The arc extinguishes at the moment in the vicinity of the zero crossing where the current is not sufficiently large enough and the air gap is sufficiently wide enough to thermodynamically support the arc. Note that the current continues to flow almost as if the contact has not yet opened while the arc is

burning between the two contact electrodes. Another fact to note is that the dynamic arc impedance negative and thus has a voltage regulating effect on the burning ac arc. In this case the arc voltage levels out at an average of about 25V.

Arc Suppression Factor Calculation:

$$Warc0 \approx Iarc * Varc * Tarc$$

$$Iarc0 \approx 13.0A \text{ (average)}$$

$$Varc0 \approx 25V \text{ (average)}$$

$$Tarc0 \approx 7ms$$

$$Warc0 \approx 1.05J$$

The energy contained in this unsuppressed primary contact break arc is 1.05Joules.

Right Top Graph Discussion: AC Arc with Snubber measurement. Same conditions and comments as for the left top graph discussion except that in this case, the arc burns between the two contact electrodes with a little bit less pronounced voltage excursions. The snubber appears to have removed some high speed transients while the arc was burning and in effect reduced the electromagnetic emissions originating from the burning arc.

Unsuppressed Arc Energy Calculation:

$$Iarc1 \approx 13.0A \text{ (average)}$$

$$Varc1 \approx 25V \text{ (average)}$$

$$Tarc1 \approx 7ms$$

$$Warc1 \approx 1.05J$$

The energy contained in this snubber suppressed primary contact break arc is 1.05Joules.

Left Bottom Graph Discussion: Suppressed AC Arc Measurement at 1ms/div time base. Same conditions as for the left top graph discussion except that in this case, as soon as the contact separates and the arc ignites, it is extinguished within about 5us by the half ac cycle crowbar type current bypass occurring within the two-port contact arc suppressor that is connected across this contact.

Energy Dissipated within Crowbar Arc Suppressor Calculation:

$$Iarc2 \approx 13.0A \text{ (average)}$$

$V_{arc2} \approx 2V$ (average)

$T_{arc2} \approx 7ms$

$W_{arc2} \approx 182mJ$

The energy dissipated inside the crowbar type two-port contact arc suppressor in this case is 182mJ.

Right Bottom Graph Discussion: Suppressed AC Arc Measurement at 5us/div time base. Same conditions as for the left bottom graph discussion except that in this case, the time scale has been reduced from 1ms/div to 5us/div to zoom in on the residual arc (arclet) of the suppressed AC arc.

Suppressed Arc Energy Calculation:

$I_{arc3} \approx 17.0A$ (average)

$V_{arc3} \approx 12V$ (average)

$T_{arc3} \approx 5us$

$W_{arc3} \approx 1.02mJ$

The energy contained in this suppressed primary contact break arclet is 1.02milliJoules.

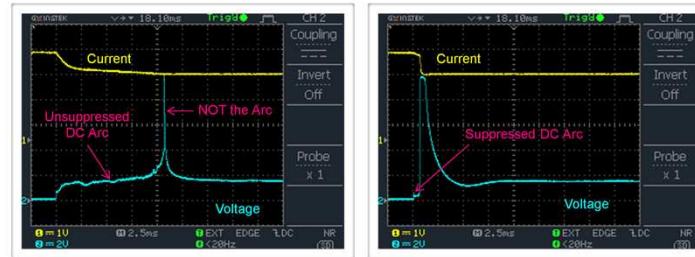
Arc Suppression Factor Calculation:

$W_{arc0} \approx I_{arc} * V_{arc} * T_{arc}$

$ASF = W_{arc0}/W_{arc3} = 1.05J/1.02mJ = 1,029$

The arc suppression factor in this case is about 1.029. In other words, this figure of merit constitutes a reduction in arc energy of slightly over 1000 fold.

Examples of DC Contact Arc Measurements



Unsuppressed DC Arc

Suppressed DC Arc

This slide shows examples of DC contact arc measurements:

These measurements were obtained via the contact arcing measurement test set-up of the previous slide.

Common Conditions:

DC Contact Arc Measurement of a T9A style relay normally open contact.

Voltage is 33Vdc, current is 6.75A, inductive load 1.6H + 4.9Ω

Y-axis: CH1, Current through the contact shown by the yellow trace, 6.75A/div

Y-axis: CH2, Voltage across the contact shown by the cyan trace, 36V/div

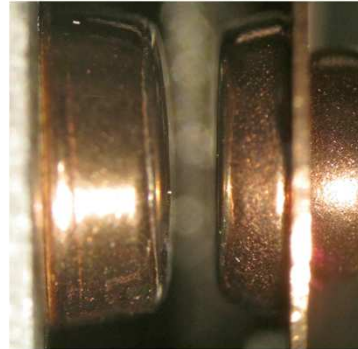
Left Graph Discussion: Unsuppressed DC Arc Measurement. The instant of momentary contact separation where for a very short moment in time an air gap exists as a very fast rising edge transitioning from 0V to about 12V. The risetime of the contact separation event is extremely fast and can reach speeds of around 8kV/us. At a voltage of about 12V (this “arc voltage” is dependent on the specific contact metal alloy) the arc ignites. Once established the arc continues to burn in this graph for about the next eleven milliseconds. The arc extinguishes at the moment where the current is not sufficiently large enough to thermodynamically support the arc through the widening air gap. The moment the arc extinguishes and the air gap opens, current stops flowing through the inductor, its magnetic field collapses and the

inductor responds with a counter electro-motoric force (CEMF) aka back EMF in form of a high voltage spike. Contrary to popular belief, this voltage spike is NOT the arc. If this voltage spike is high enough and if there is still sufficient residual ionization in the air-gap, a secondary break arc may ignite. The secondary break arc will be of a much shorter duration than the primary break arc and thus be less energetic. This voltage spike may be reduced and or clipped by connecting a voltage limiter across the contact. Please note that the clamping voltage of this voltage limiter must be greater than the maximum operating voltage across the open contact. Also note that in this case the current continues to drop towards zero as soon as the contact electrodes separate. A further fact to notice is that this primary break dc arc burns for almost as long as the contact travels to its open state end point. This of course is a fire hazard and this condition must be recognized and avoided.

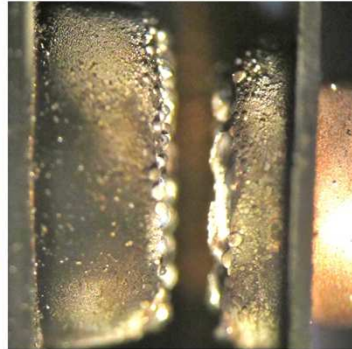
Right Graph Discussion: Suppressed DC Arc Measurement. Same conditions as for the left graph discussion except that in this case, as soon as the contact separates and the arc ignites, it is extinguished within about 5 μ s by the pulse type current bypass occurring within the two-port contact arc suppressor that is connected across this contact. The DC arclet is the tiny overshoot at the instant of contact separation where the voltage across the contact reaches about 12V. The DC arc suppression pulse duration is about 500 μ s during which the current bypass occurring within the two-port contact arc suppressor temporarily carries the full contact current. The moment the arc suppression pulse ends, current stops flowing through the inductor, its magnetic field collapses and the inductor responds with a counter electro-motoric force (CEMF) aka back EMF in form of a high voltage spike. Note that this voltage spike is now much closer to the contact separation point and that the current through the contact drops to zero as soon as the arc suppression bypass pulse duration is over.

Example of Contact Degradation

Unused Contacts



100K Cycles
Unsuppressed



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This slide shows T9A style relay contact electrodes in comparison under a 20x inspection microscope magnification:

Left:

**Brand new (fresh-out-of-the-box),
Normally open Contacts from a
T9A style,
a most popular relay,
Sealed case was destroyed for photo shoot**

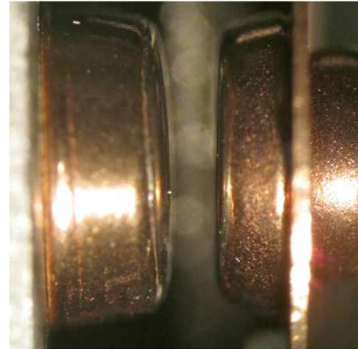
Right:

**Very used,
Same type of relay as above
240Vac,
resistive load,
20A (half its rated current),
4 second cycle time,
50% duty cycle,**

**100k cycles,
operating Non-vented at 22°C ambient,
Continuous operation for 4.63 Days,
without contact arc suppression,
and at its End-of-Life (EOL)**

Example of Minimal Contact Degradation

Unused Contacts



1 Million Cycles Suppressed



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This slide shows T9A style relay contact electrodes in comparison under a 20x inspection microscope magnification:

Left:
Brand new (fresh-out-of-the-box),
Normally open Contacts from a
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Sealed case was destroyed for photo shoot

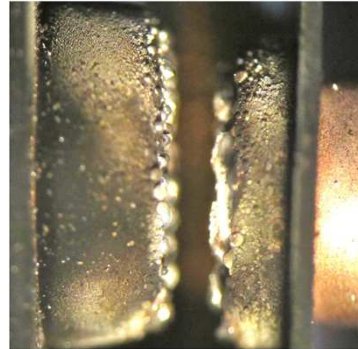
Right:
Extremely used,
Same type of relay contact as on the left
240Vac,
resistive load,
20A (half its rated current),
4 second cycle time,
50% duty cycle,

**1M cycles,
46.3 Days or about 1.5 Months of continuous operation,
at 22°C ambient,
with contact arc suppression,
and still looking as if in its operational infancy**

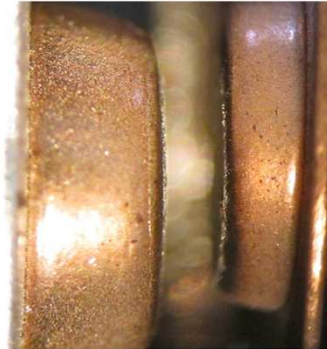
Example of Contact Degradation Contrast



**100K Cycles
Unsuppressed**



**1 Million Cycles
Suppressed**



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This slide shows T9A style relay contact electrodes in comparison under a 20x inspection microscope magnification:

Left:
Very used,
Same type of relay as above
240Vac,
resistive load,
20A (half its rated current),
4 second cycle time,
50% duty cycle,
100k cycles,
operating Non-vented
at 22°C ambient,
Continuous operation for 4.63 Days,
without contact arc suppression,
and at its End-of-Life (EOL)

Right:
Extremely used,
Same type of relay contact as on the left
240Vac,
resistive load,
20A (half its rated current),
4 second cycle time,
50% duty cycle,
1M cycles,
46.3 Days or about 1.5 Months of continuous operation,
at 22°C ambient,
with contact arc suppression,
and still looking as if in its operational infancy

QUESTION: How long can we run the contact on the right until it matches the look of the contact on the left?

What We Have Learned:



- There are up to five (5!) different arcs in a contact cycle
- Discrete components have either limited or minimal effect on contact current arcing
- Contact design based arc suppression can work well in very specific applications
- Four-port hybrid power switching devices can work well, however, they are typically designed to be very application specific
- Two-port hybrid power devices both work effectively, are application agnostic and are easily added to the contact

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This slide shows What We Have Learned:

Off script: Arc suppressed contacts live a very long and healthy life.

What We Have Learned: Five Arcs



- There are up to five (5!) different arcs occurring during a single contact cycle

CONTACT CYCLE SEQUENCE									
Time is generally moving in this direction ----> (Note: not to scale)									
Open State	Make Transition			Closed State	Break Transition			Open State	
Gap Widest	Gap Narrowing			No Gap	Gap Widening			Gap Widest	
Voltage Across Contact	Current Through Contact				Current Through Contact				Voltage Across Contact
No Arcing	Make Arc	Make Bounce Arc	No Arcing	Break Bounce Arc	Primary Break Arc	Secondary Break Arc	No Arcing		
Broken Microwelds	Make New Microweld	New Microweld	Break Microweld	Broken Microwelds					
Metal Cooling or Cold	Metal Softening, Melting & Boiling		Metal Cooling or Cold	Metal Softening, Melting & Boiling			Metal Cooling or Cold		

1. Make Arc
2. Make Bounce Arc

3. Break Bounce Arc
4. Primary Break Arc
5. Secondary Break Arc

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This slide shows What We Have Learned: Five Arcs

At power source voltages of less than 15V there is typically very little arcing going on. The current automotive battery standard of 12Vdc is one method to significantly reduce arcing in relays and switches in cars. The move to the new proposed automotive battery standard of 42Vdc is going to create unprecedented contact deterioration due to contact arcing in relays and switches in future cars. Just take a look at the hardest working contact in your car, the car starter solenoid, if you open it up even after tens of thousands of miles, you will see the bright red contact copper without significant contact discoloration from carbon deposits. At 42Vdc contact arcing and contact deterioration occurs every time the contact switches a load over 1Amp.

What We Have Learned: Discrete Components

- Current limiters reduce the arc current but do not suppress contact arcing
- Voltage limiters cannot suppress the Primary Break Arc
- Rise-time limiters (Snubbers) do not suppress the primary contact break arc at load currents greater than 1Amp

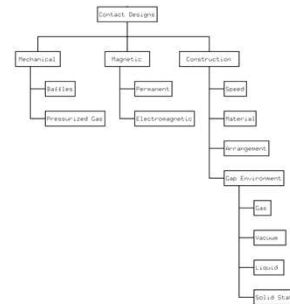


This slide shows What We Have Learned: Discrete Components

Neither snubbers nor diodes nor MOV's extend contact life in any significant way.

What We Have Learned: Contact Designs

- Mechanical baffles extend the length of the arc
- Pressurized gases influence the direction of the arc
- Magnets deflect the path of the arc
- Unique contact construction reduces arcing by speeding up contact travel, special contact arrangements or by providing controlled air gap environments

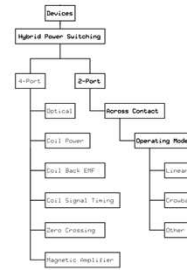


This slide shows **What We Have Learned: Contact Designs**

Mechanical baffles, pressurized gases, magnets and unique contact construction are typically employed when contact currents and especially interrupt currents are measured in many kilo amperes.

What We Have Learned: Hybrid Power Switching Devices

- Contact arc suppression must be connected across the contacts in order to suppress all damaging contact arcs
- Two-port contact arc suppression is simple and most effective



This slide shows **What We Have Learned: Hybrid Power Switching Devices**

Recap

- The most common forms of Arc Suppression, discrete components, provide either limited or negligible effectiveness
- Two-port arc suppressors are most effective, as they
 - Significantly extend contact life
 - Significantly reduce electromagnetic emissions
 - Significantly reduce air pollution
 - Significantly support safer operation

Questions and Discussion

“You can achieve the impossible, for the impossible is only in other people’s heads!” –rh

Thank You!

Thank you very much for the opportunity to share with you what I have learned!