environmental • failure analysis & prevention • health • technology development

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Circuit Protection Devices & Arc Fault Detection Schemes for Electrical Automotive Systems

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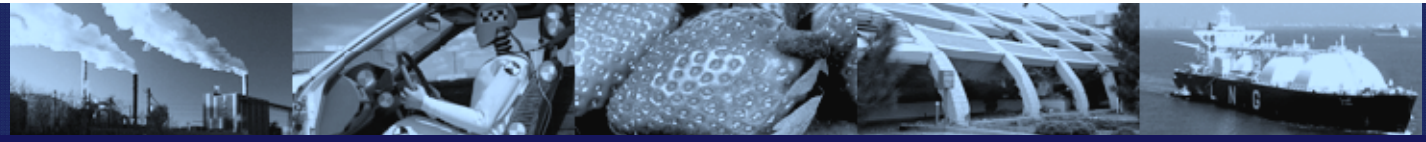
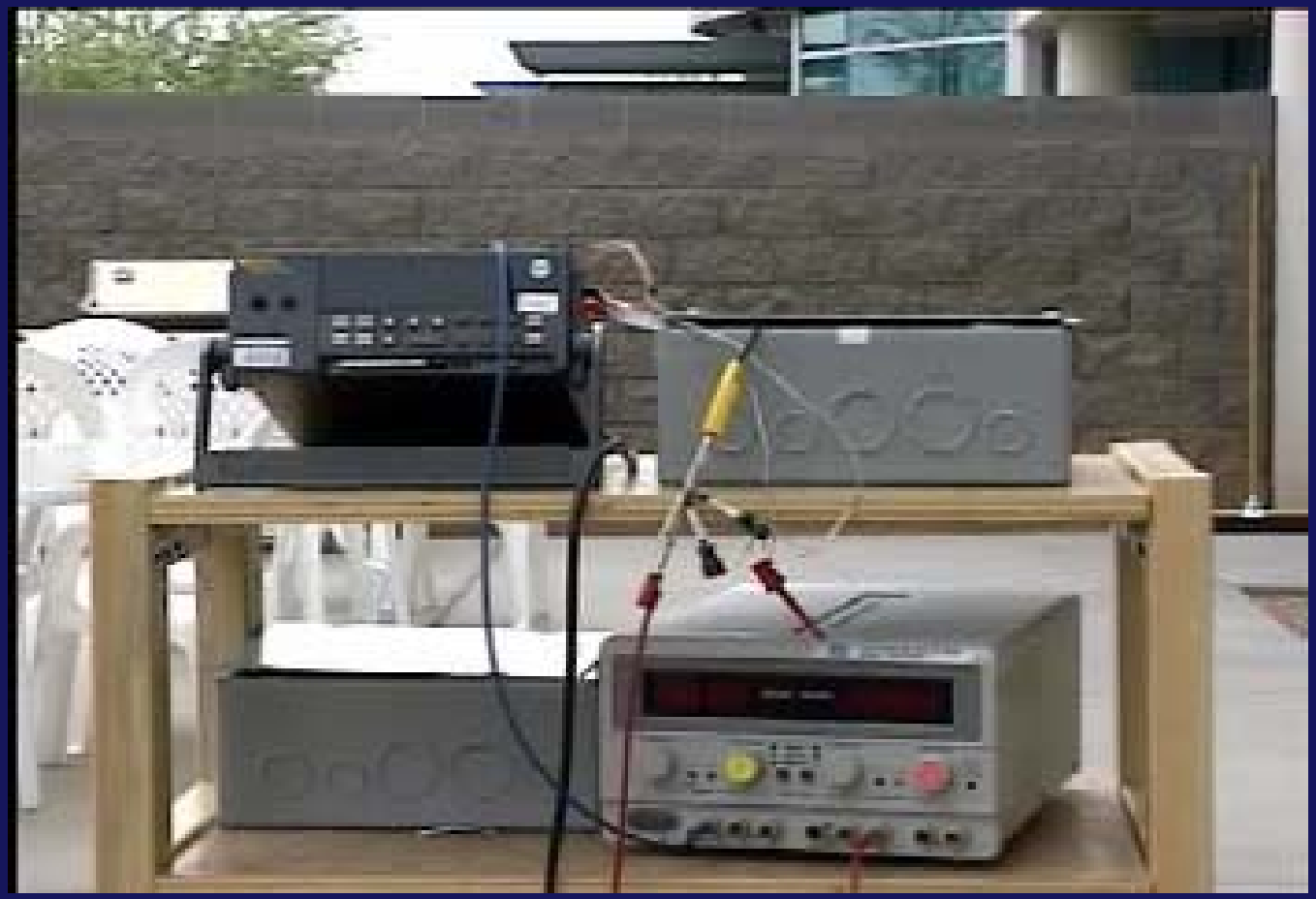
October 21, 2008



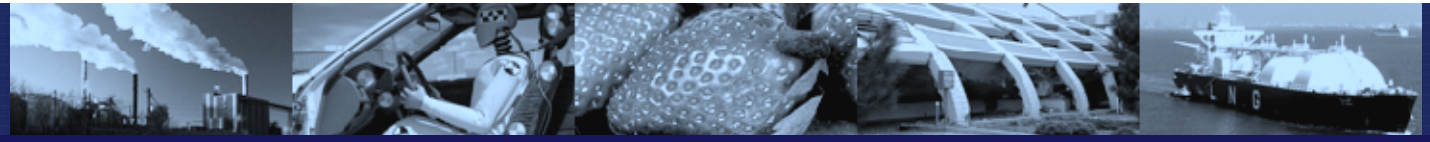
Introduction

- Circuit protection devices are used to provide protection against over/under-voltage, over-current and over-temperature conditions.
- The suitability of a device depends on many factors such as transient/steady state voltage conditions, current and power ratings etc.
- The absence of a protection device or an inappropriately selected protection device may result in failures which may be catastrophic.

Introduction



Introduction

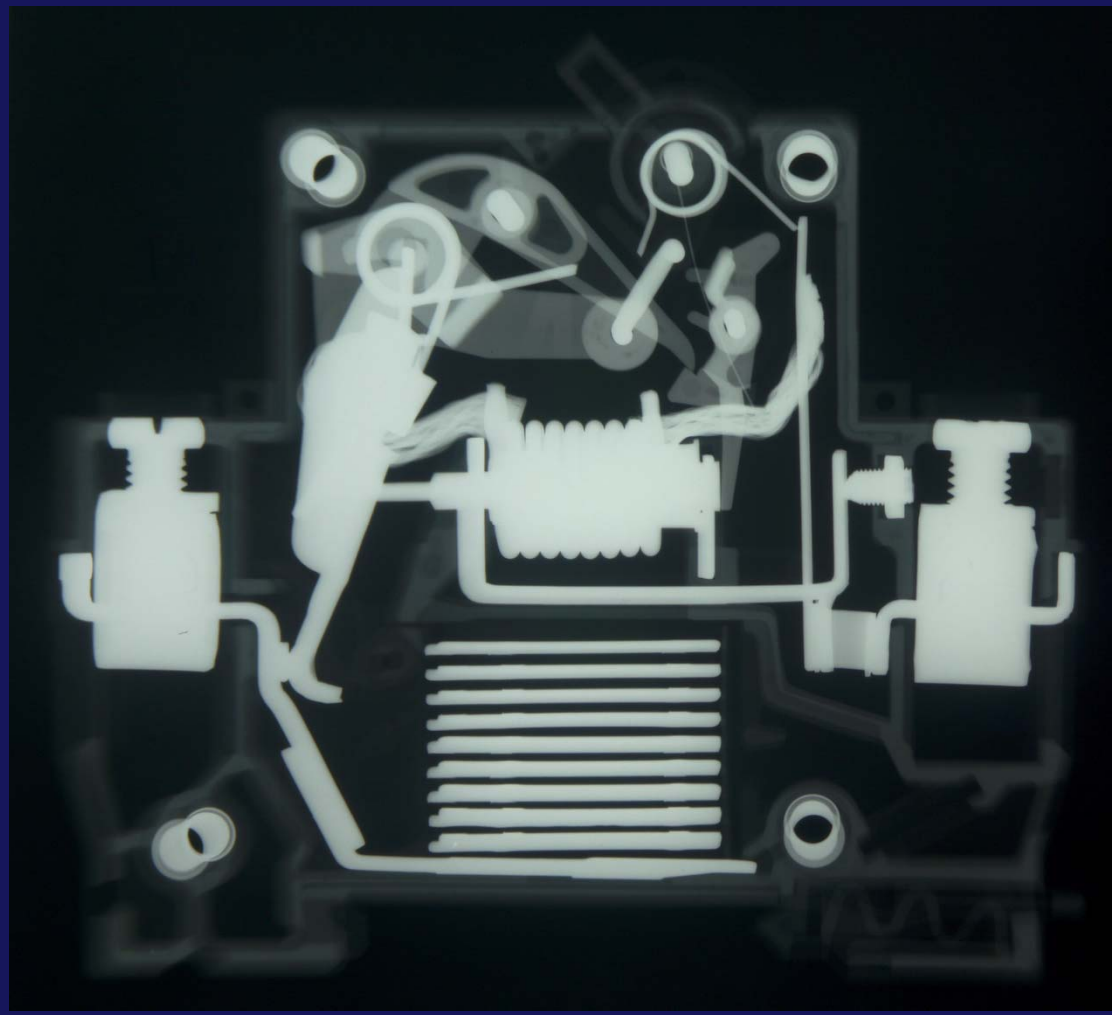


What are we protecting against?

- Current
  - Short circuit current
  - Overload current
- Voltage
  - Over-voltage
  - Under-voltage
  - Transients
- Temperature
  - Excessive ambient temperature
  - Component heat dissipation

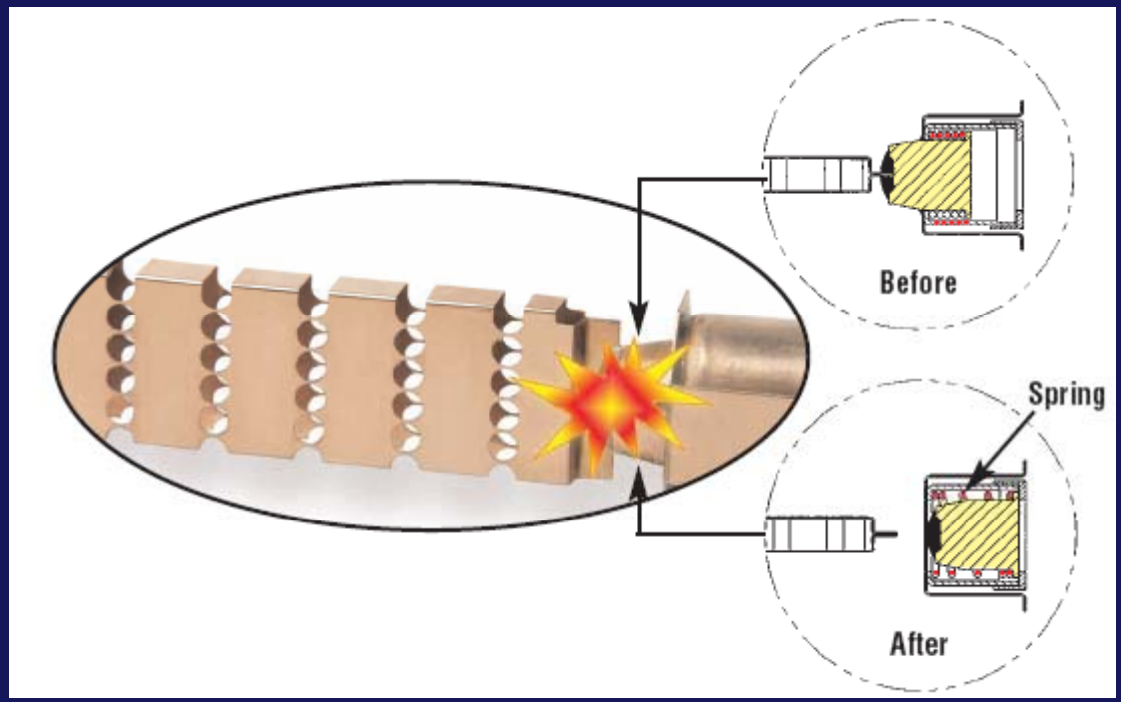
Current

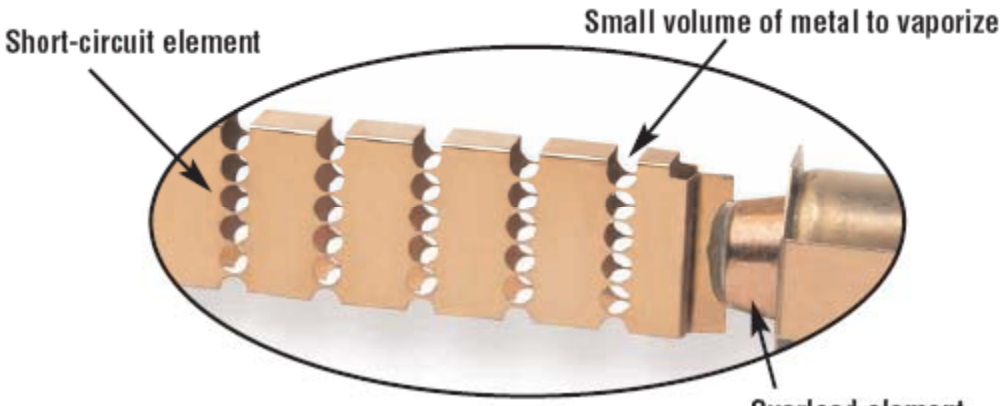
- Usually relies on heat generated by excess current to open circuit
  - Fuses
  - Fusible links
  - Circuit breakers
  - PTCs

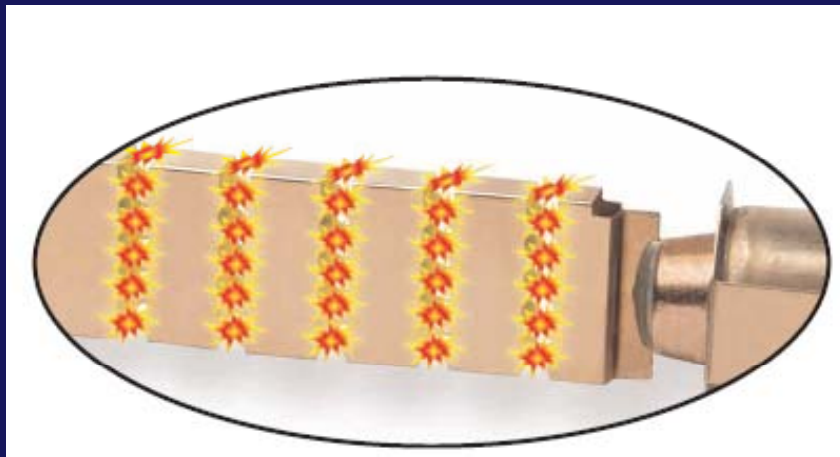


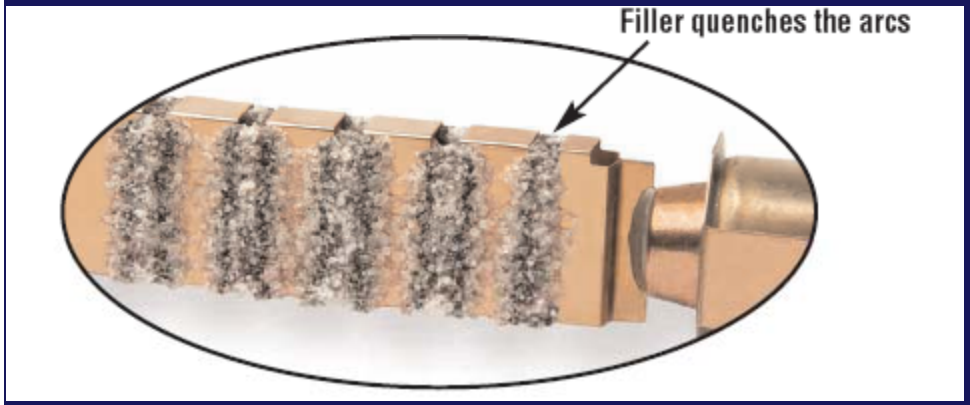
Fuses


Insulated end-caps to help prevent accidental contact with live parts.
Filler material

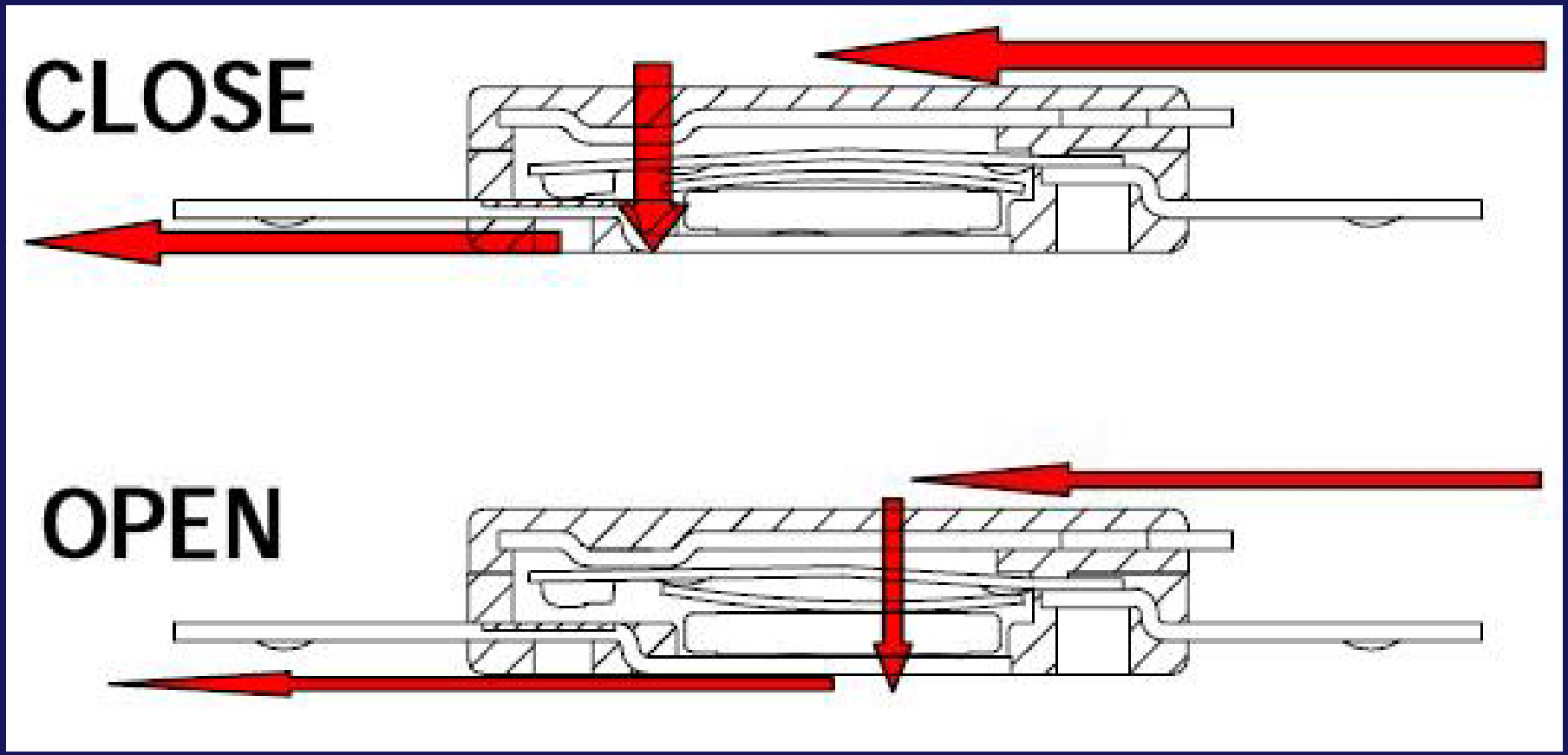

Before
Spring
After


Short-circuit element
Small volume of metal to vaporize
Overload element

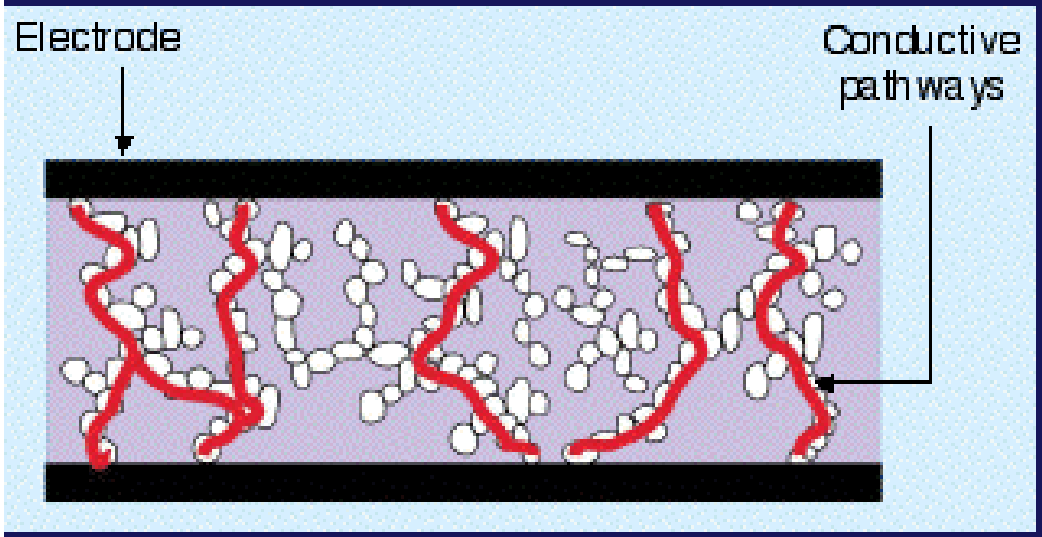


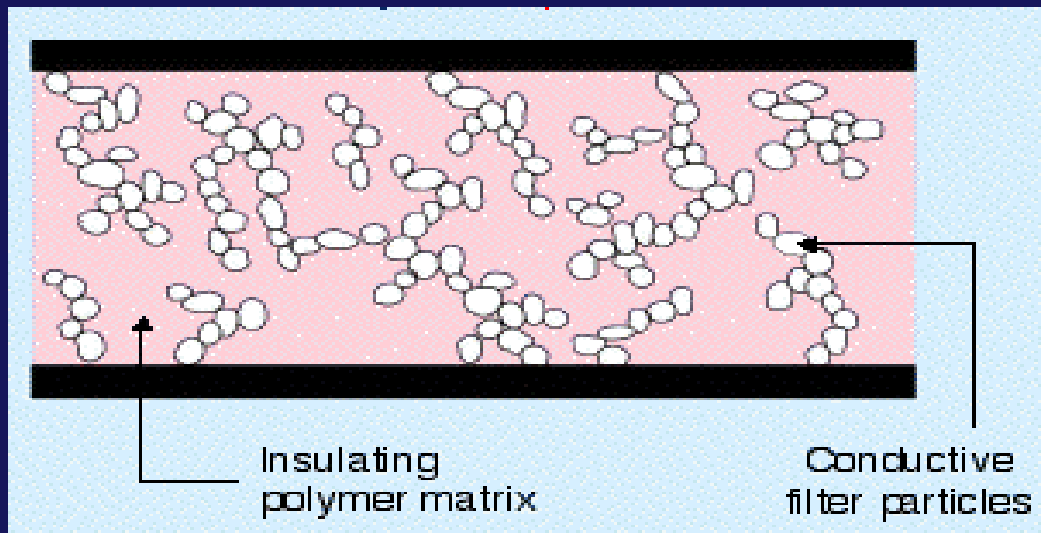

Filler quenches the arcs

Positive Temperature Coefficient (PTC)



Polymeric Positive Temperature Coefficient (PPTC)



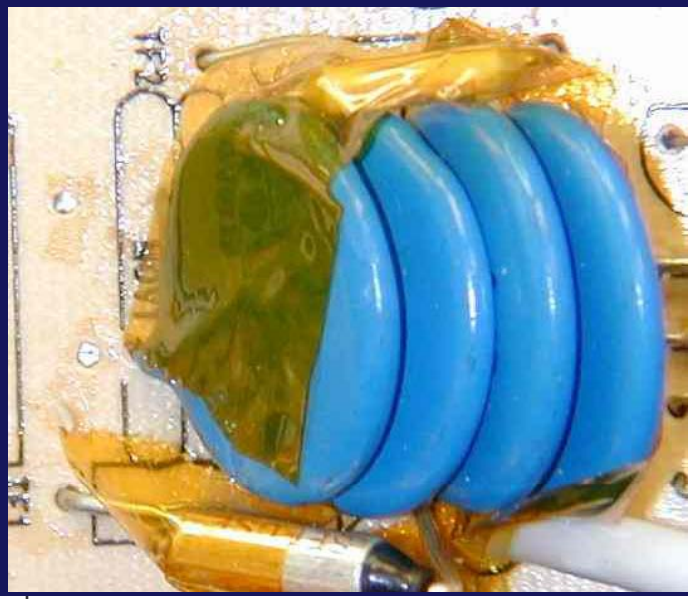


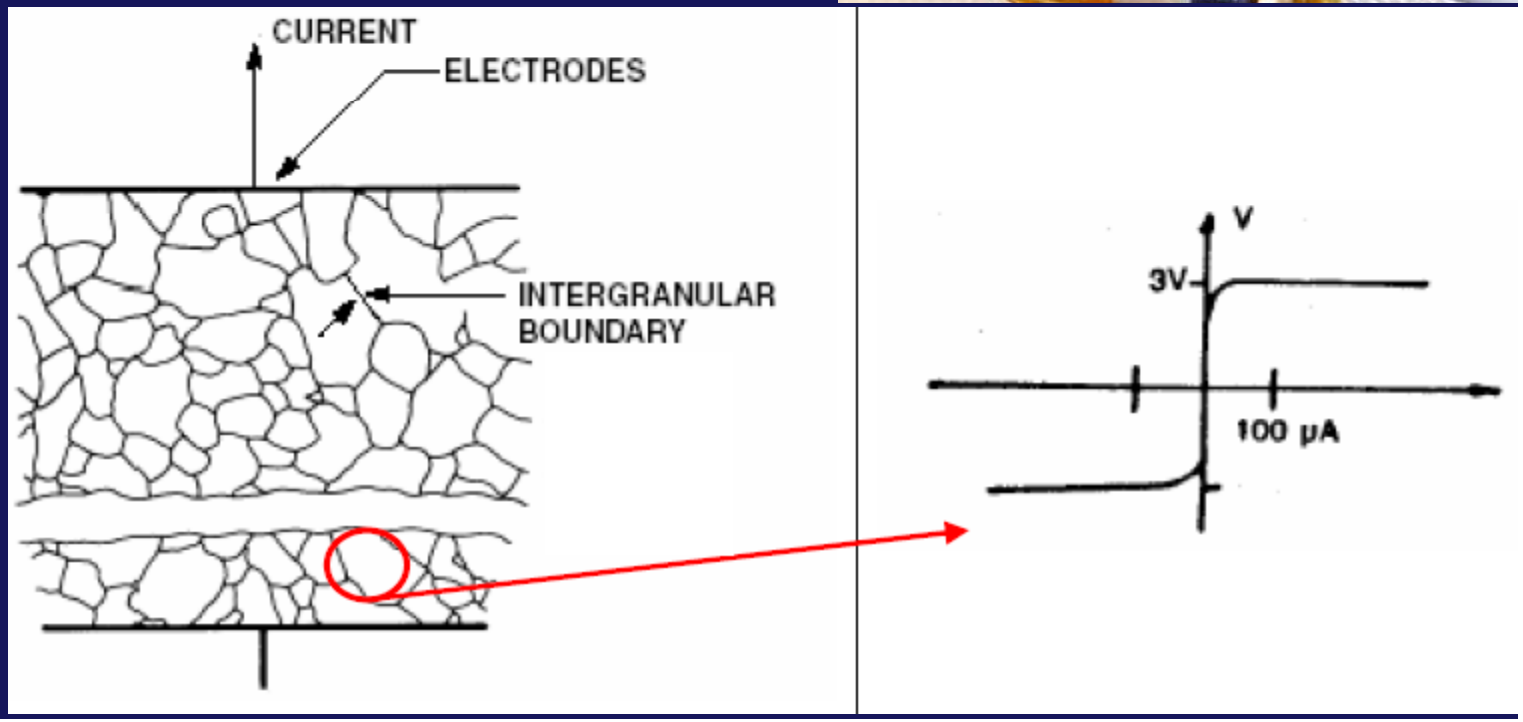
Voltage

- Two categories of overvoltage circuit protection devices
  - Clamping/Foldback
    - MOVs
    - Diodes
    - TVSS
  - Crowbar
    - Gas discharge tubes
    - Thyristor surge suppressors

MOV

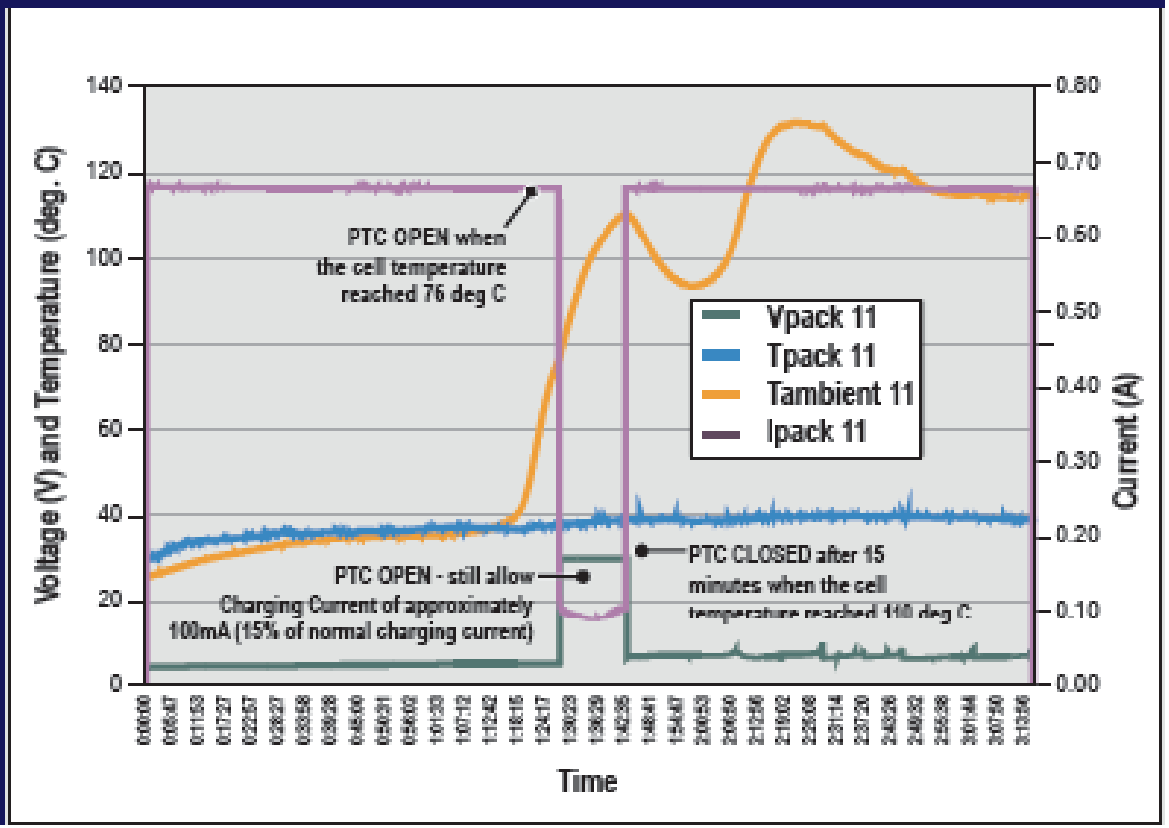
- Used to protect equipment from power line transients and surges
- Consists of metal oxide grains sintered into ceramic disks and encapsulated in an epoxy
- The MOV degrades over time due to the cumulative fusing of grains and the micro-cracking of the disks



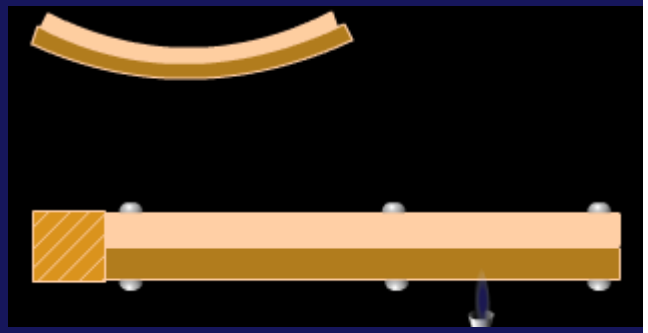


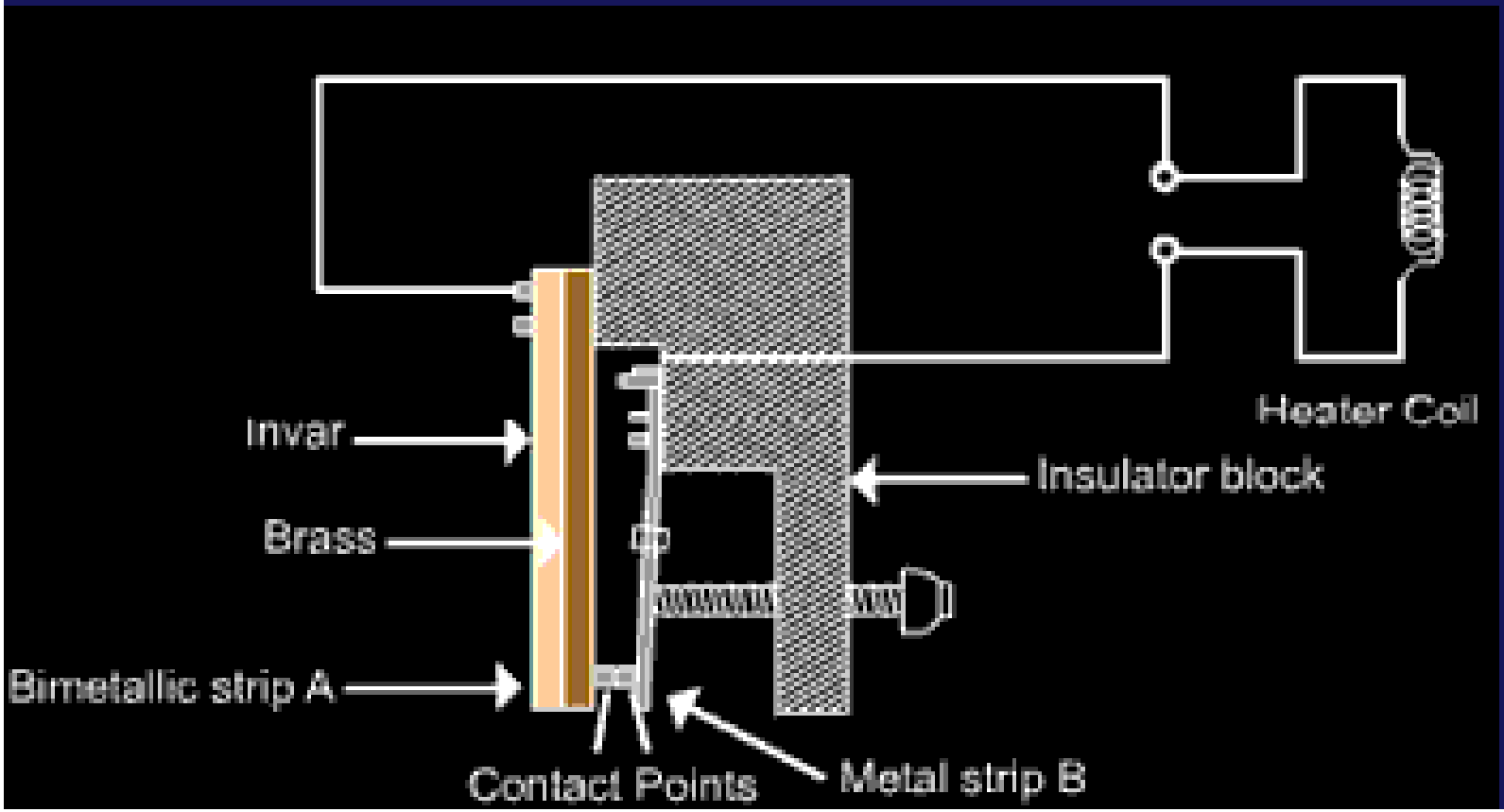
Temperature

- Protection may or may not be re-settable
  - PTC
  - Bi-metal switches
  - Thermal Fuses

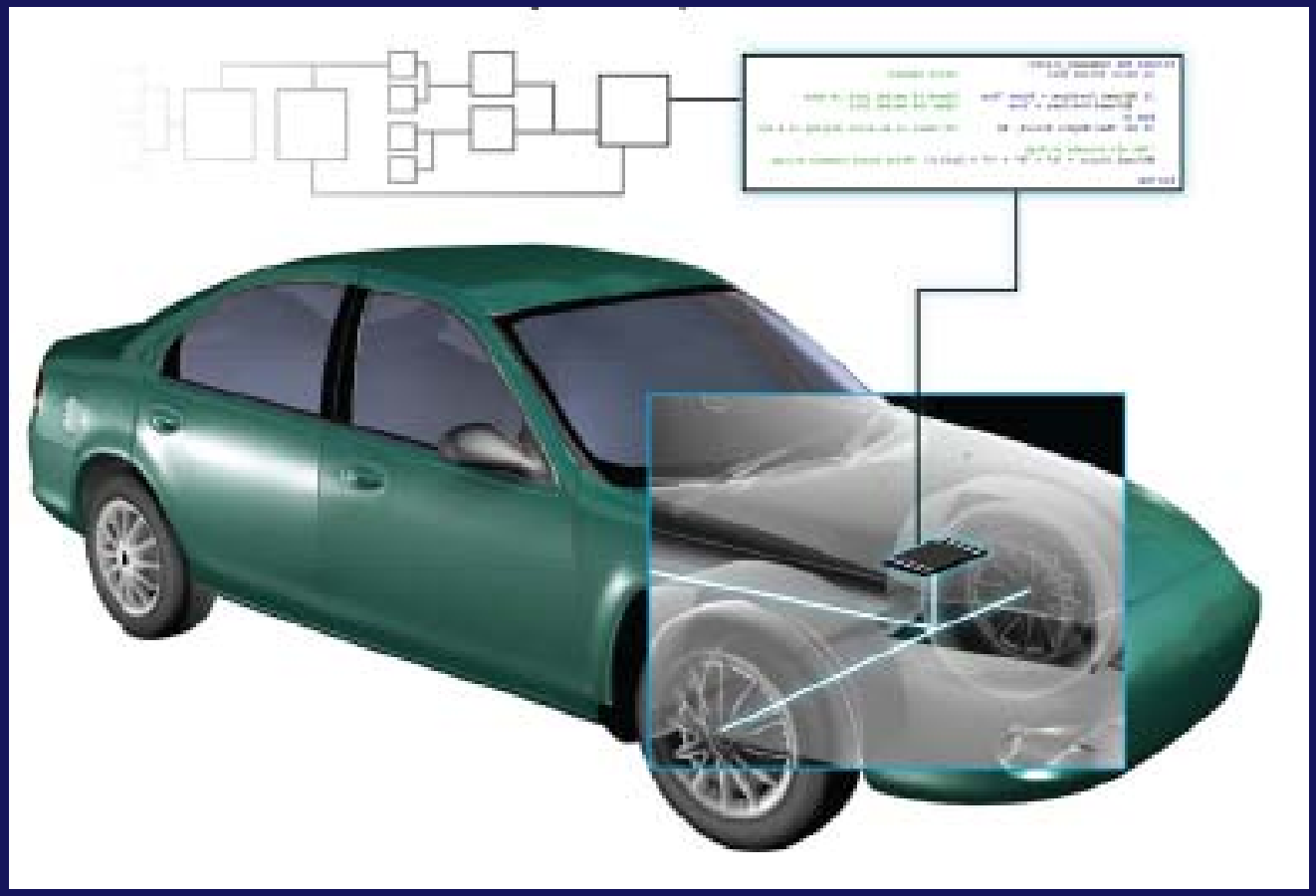


Bi-Metal Switches





Automotive Electrical Systems



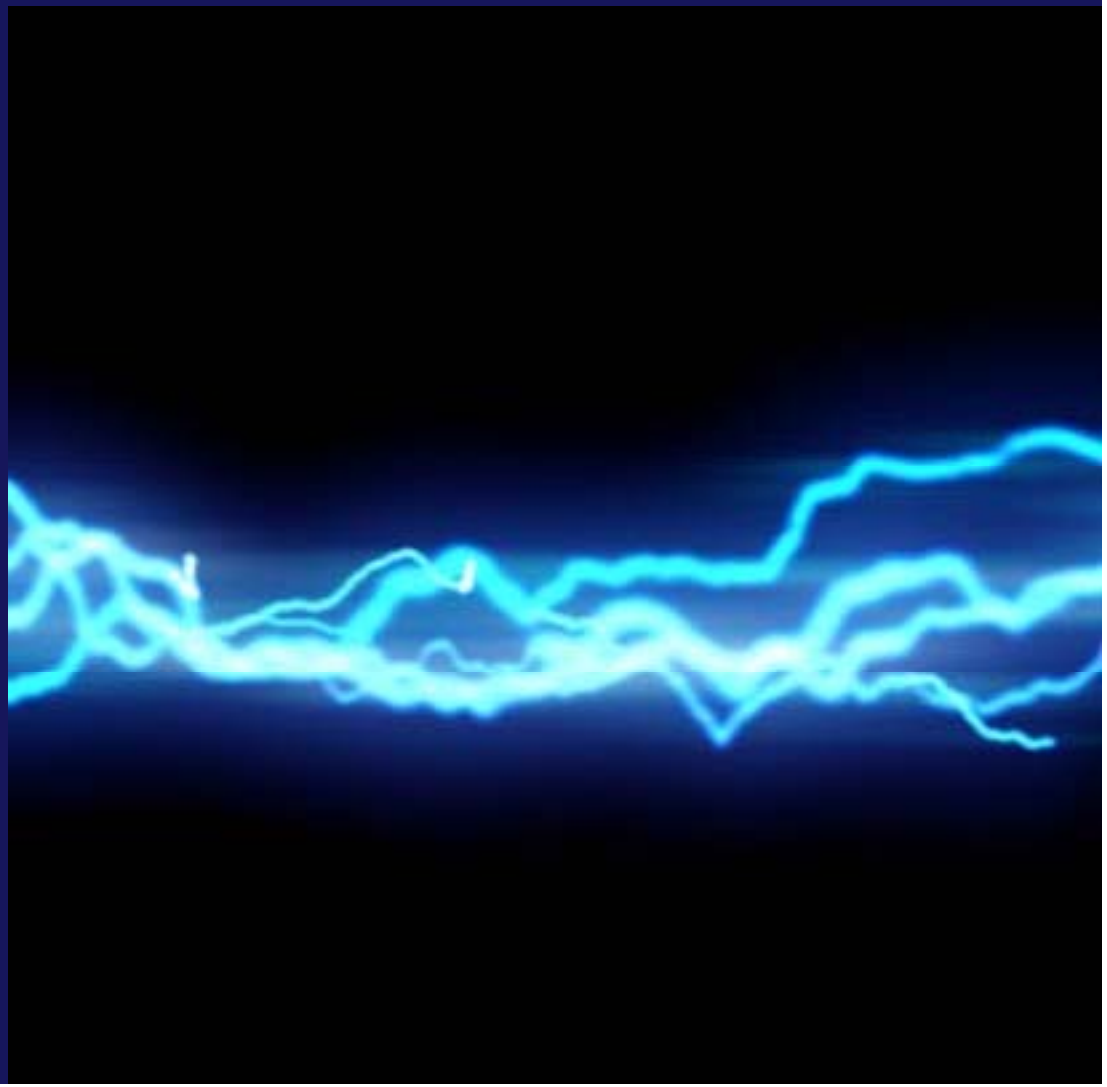
12 V

42 V

360 V

So What is the Problem?

Arcing!!!



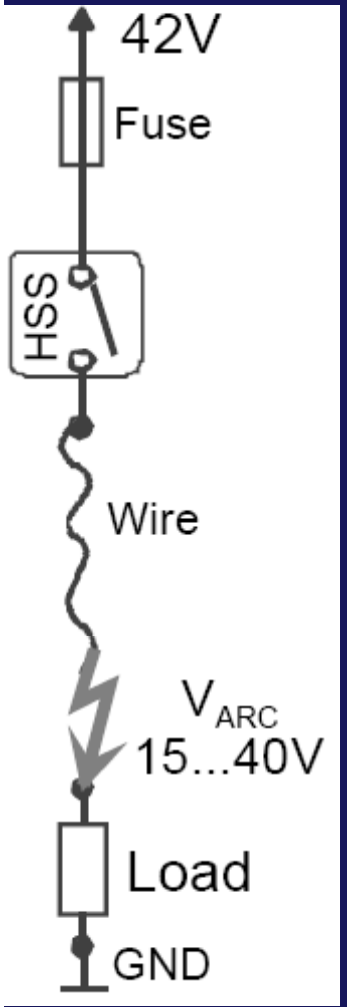
What is Arcing?

- The effect generated when electrical current bridges the air gap between two contacts or conductors

- Arcing may take two forms in a typical automotive environment:
  - Series Arcing
  - Parallel Arcing

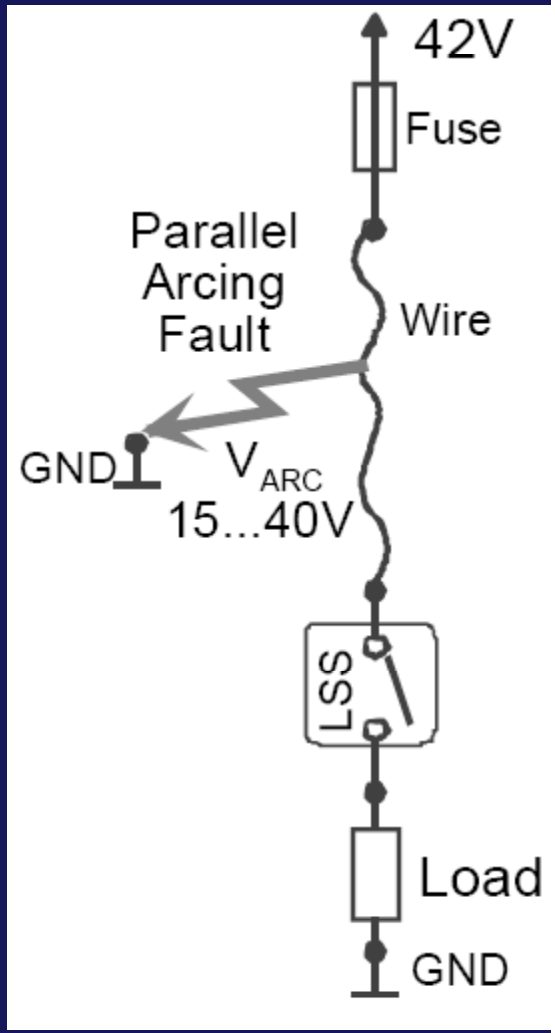
Ref: 42VDC Arc Faults: Physics and Test Methods, Engelbert Hetzmannseder, Joe Zuercher

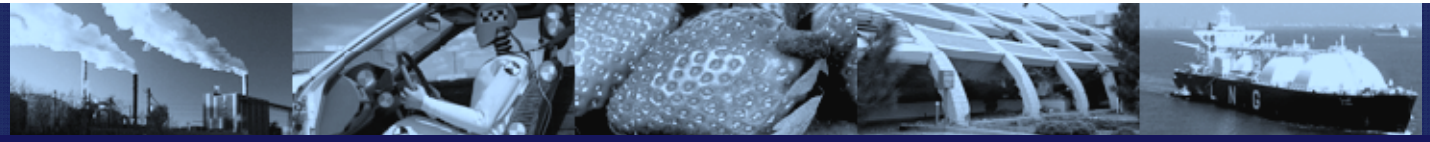
Arc Faults



Parallel Arc Fault

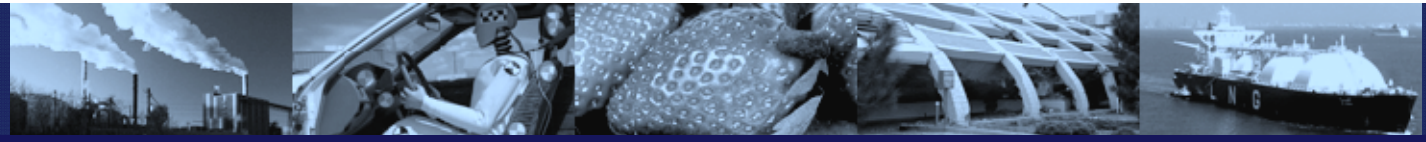
Series Arc Fault





Series Arcing

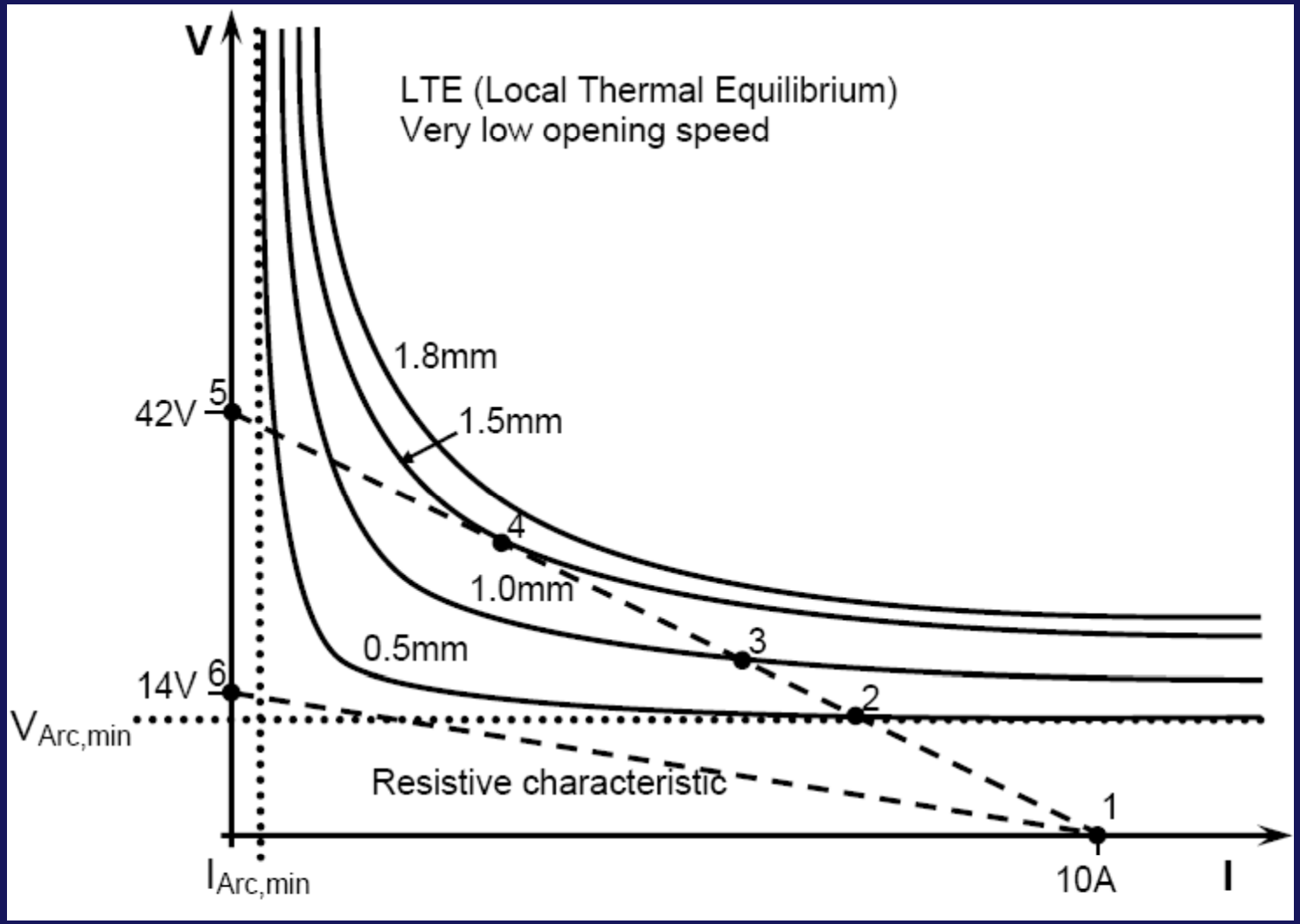
- Faults in series with the load
- Arcing currents less than nominal circuit currents
- Occurs on loose (lugs/terminals), broken (conductors) or otherwise high resistance segment in a single line
- Cannot be detected by using conventional short circuit or overload protection devices
- May result in low reliability and a fire hazard



Parallel Arc

- Faults in parallel with the load
- Arcing currents significantly higher than the nominal currents
- Occurs when damaged wires or wires exposed due to aging insulation touch system ground or auxiliary low voltage bus
- May/may not trip the fuse or breaker due to current limiting nature of the arc
- Potentially more dangerous than a series fault condition

Arc Physics



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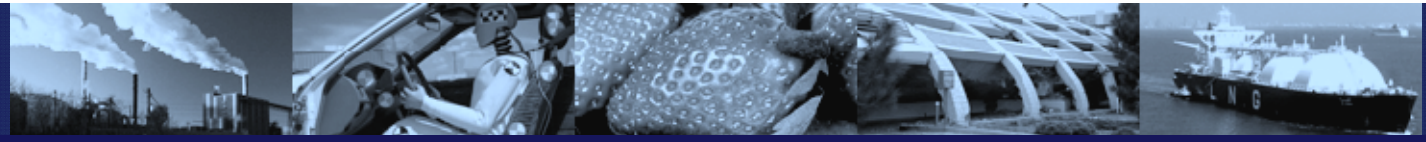
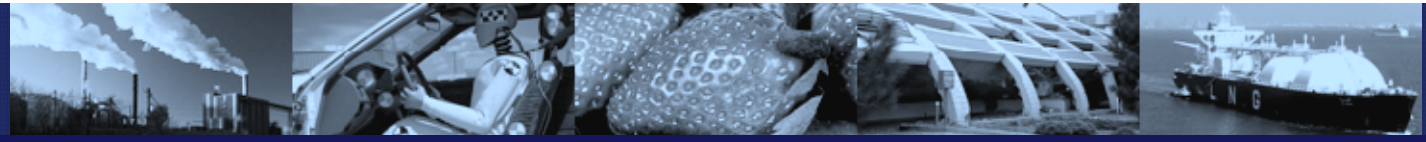


Arc-Fault Current Interrupters (AFCI)

- Required in all circuits that feed receptacles in bedrooms of dwelling units since 1999 by the National Electric Code
- Advanced electronics inside an AFCI breaker detect sudden bursts of electrical current in milliseconds, long before a standard circuit breaker or fuse would trip
- The 2008 NEC requires installation of combination-type AFCIs in all 15 and 20 amp residential circuits with some exceptions (laundries, kitchens etc.)

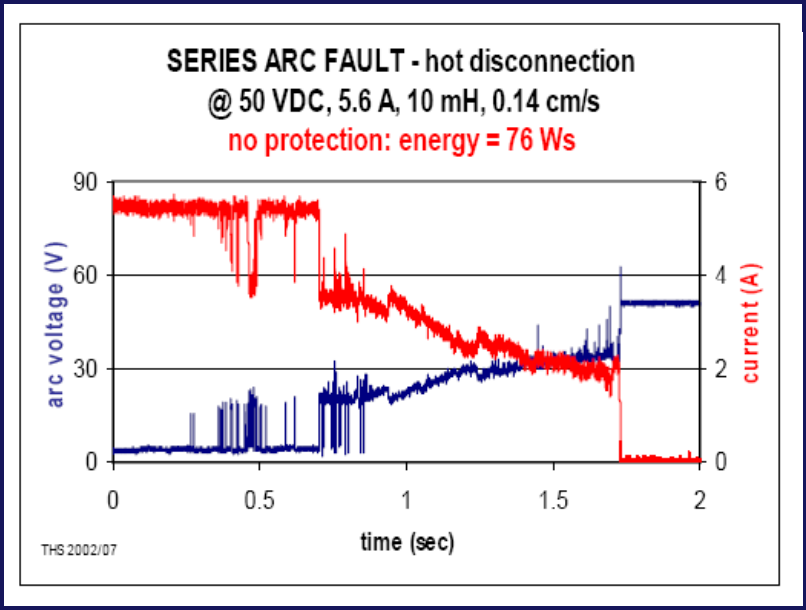


What about DC systems?

- Series Arc Faults
  - Plugging and unplugging connectors under load
  - Lose lugs
  - Breaks in wires
- Parallel Arc Faults
  - Simulation of cutting wires (point contact arc test)
  - Simulation of chafed wires (dry arc propagation test)
  - Influence of contamination (carbonized track test)
  - Water intrusion test of connectors
  - Impact of humidity & salt water (wet-arc propagation test)
  - Simulation of broken/dangling wire (dangling wire test)

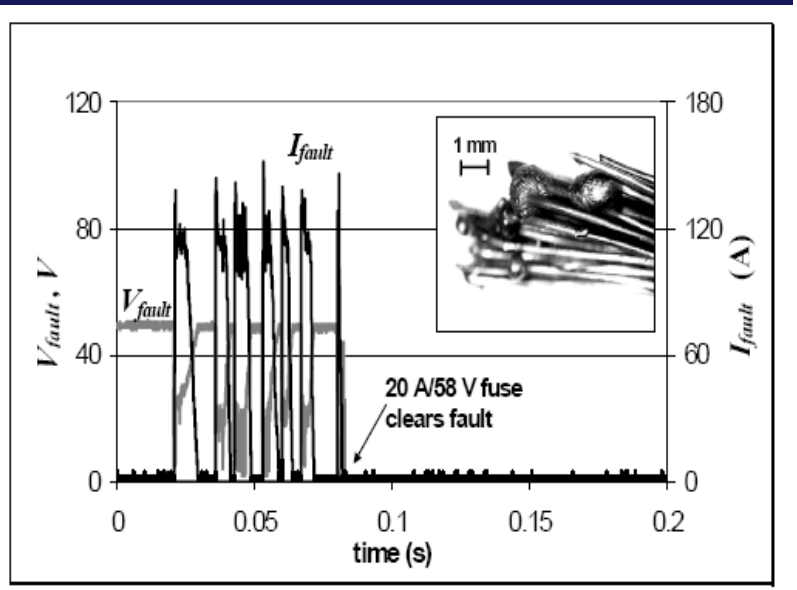
Why can't we use conventional circuit protection devices?

Ref: Mitigation and Analysis of Arc Faults in Automotive DC Networks, Naidu et all, IEEE Transactions on Power Electronics, Vol. 21, No. 3, May 2006

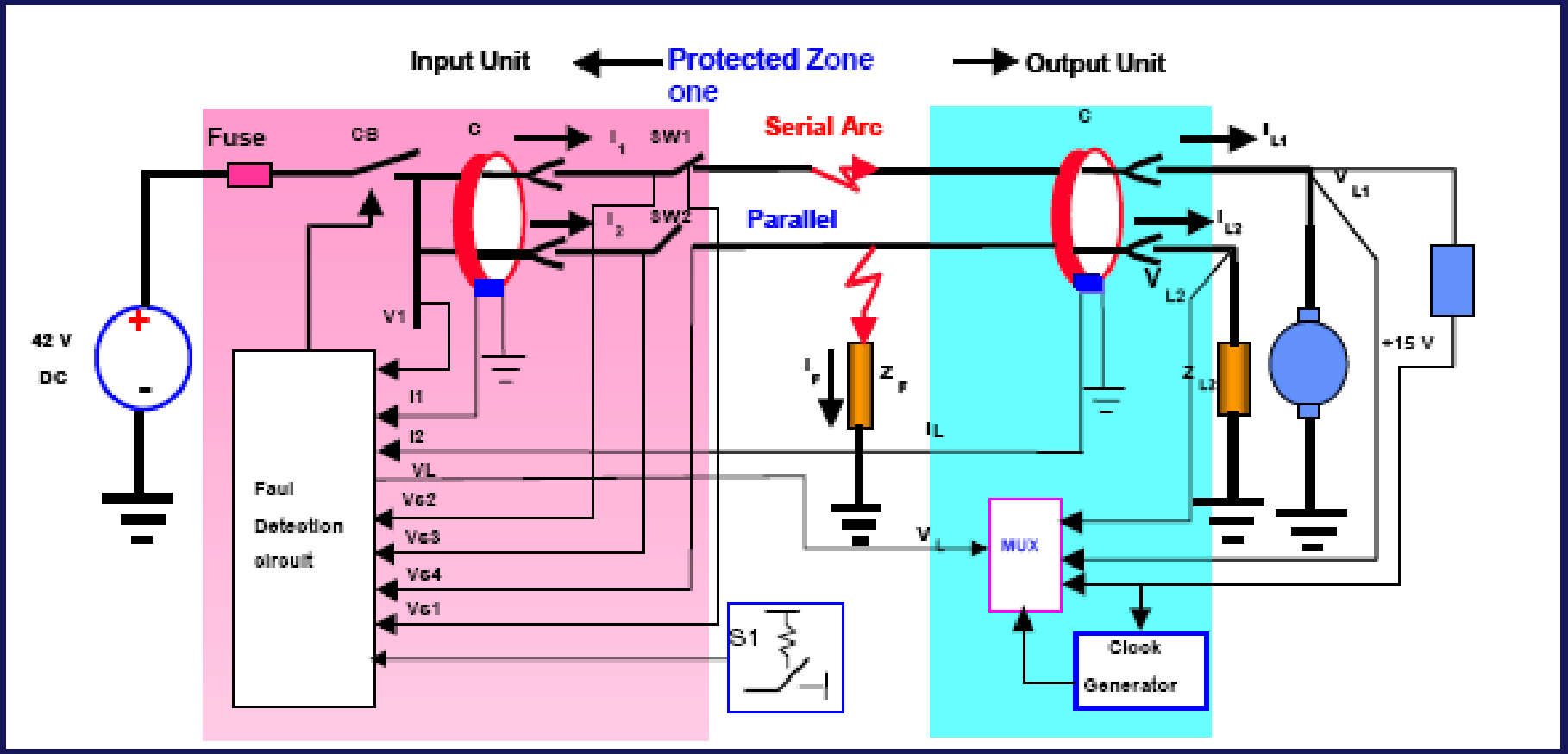


Series Arc Fault

Parallel Arc Fault



What is out there?



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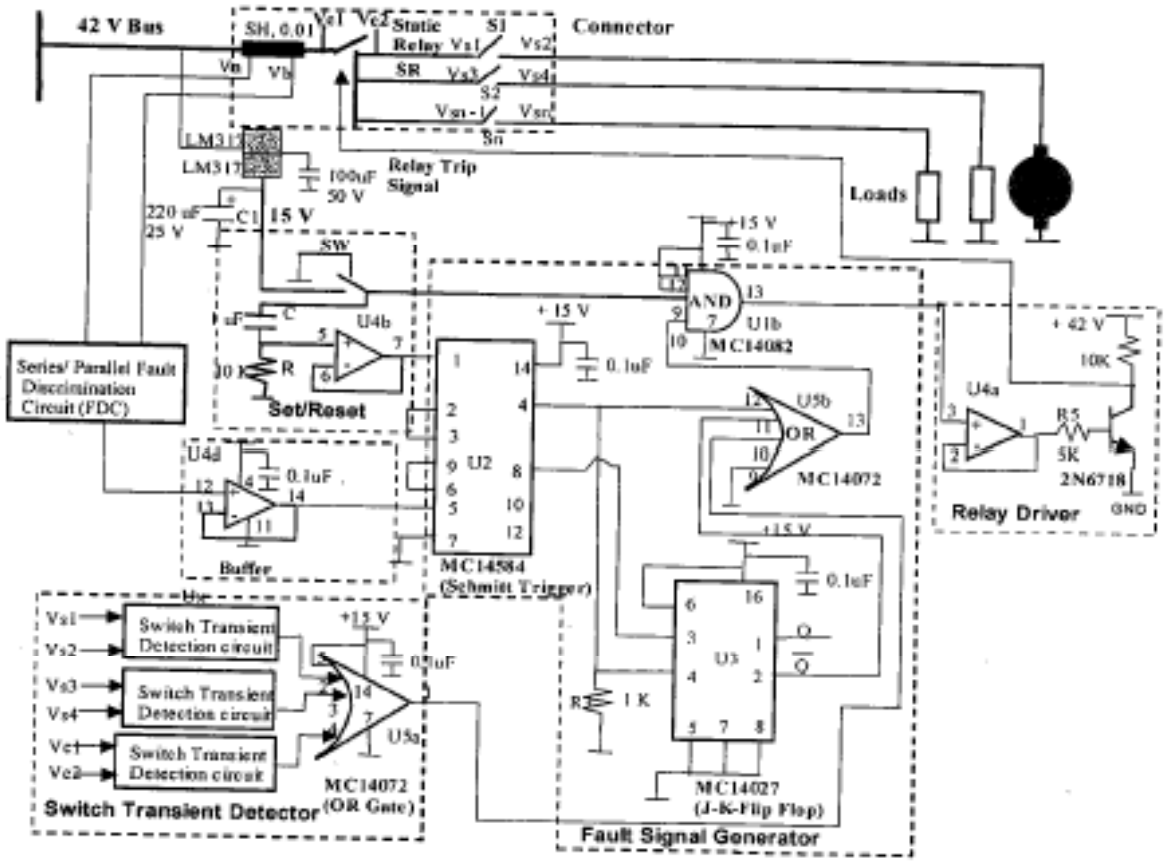

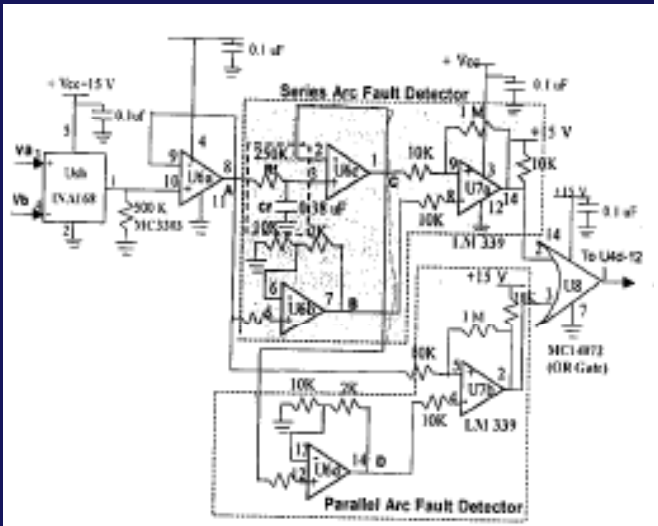

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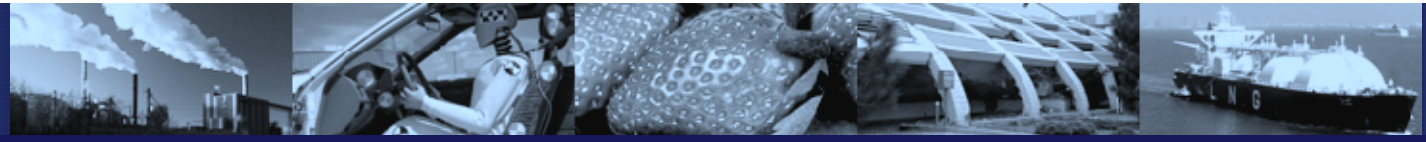
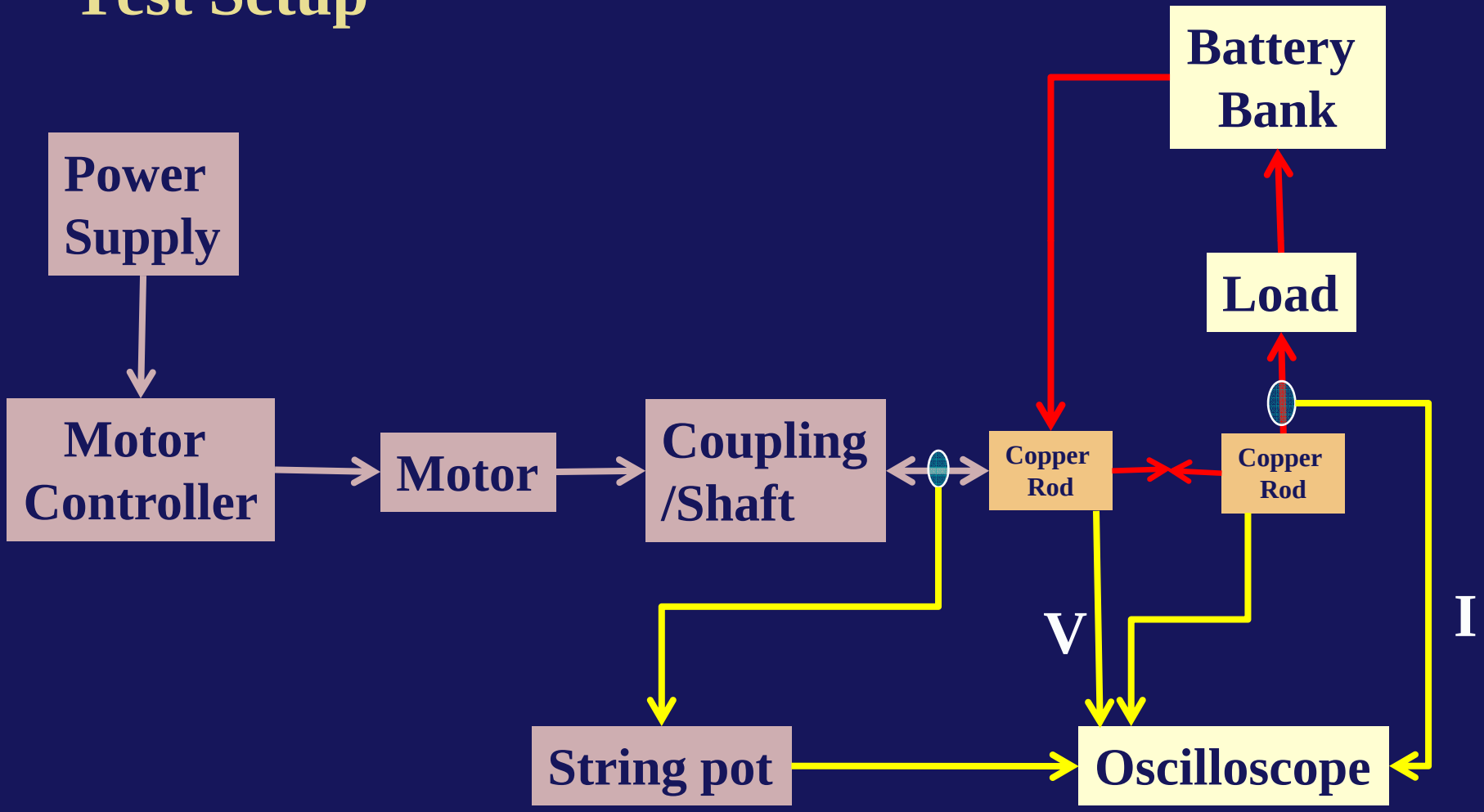
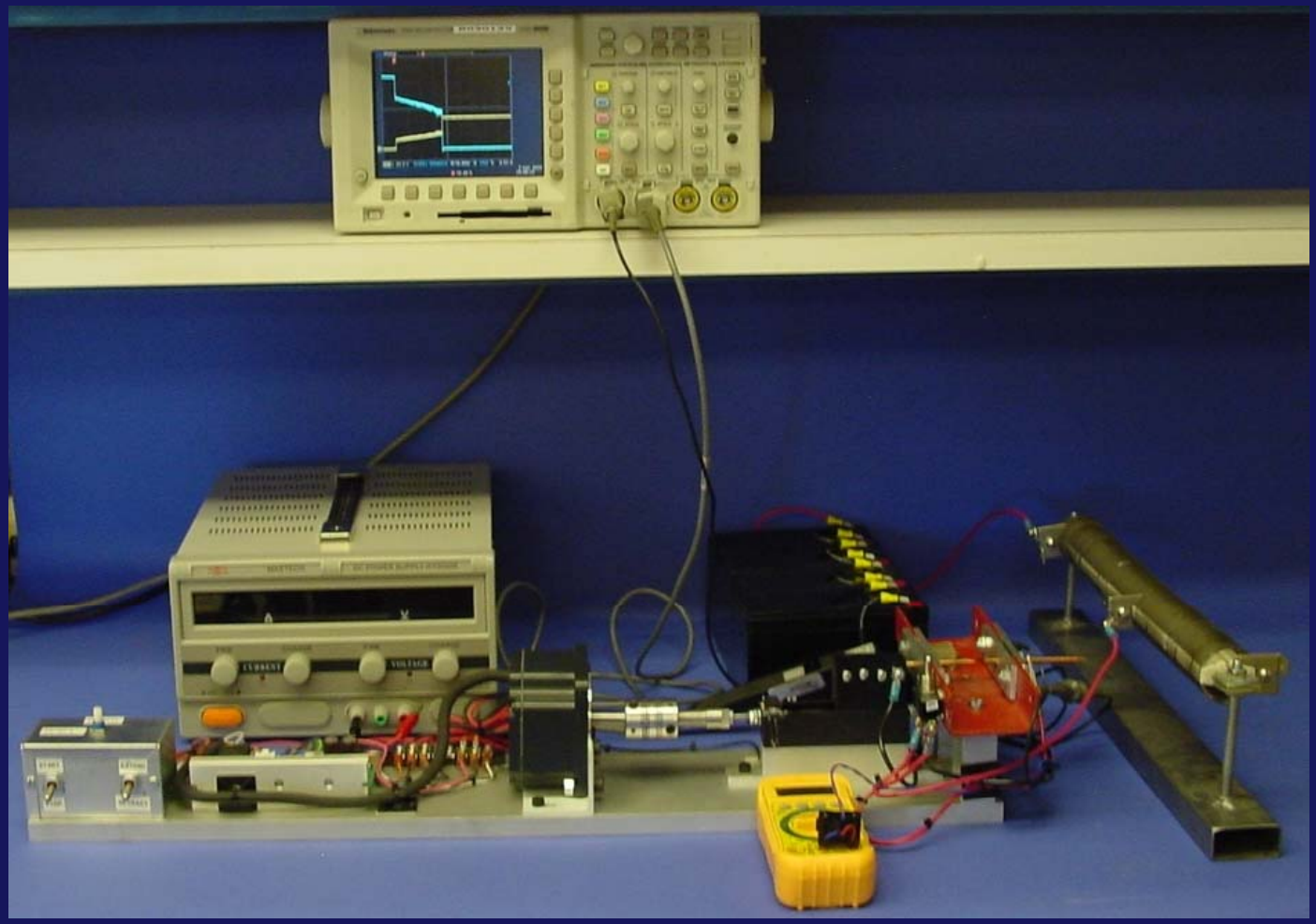


What do we want to do & why

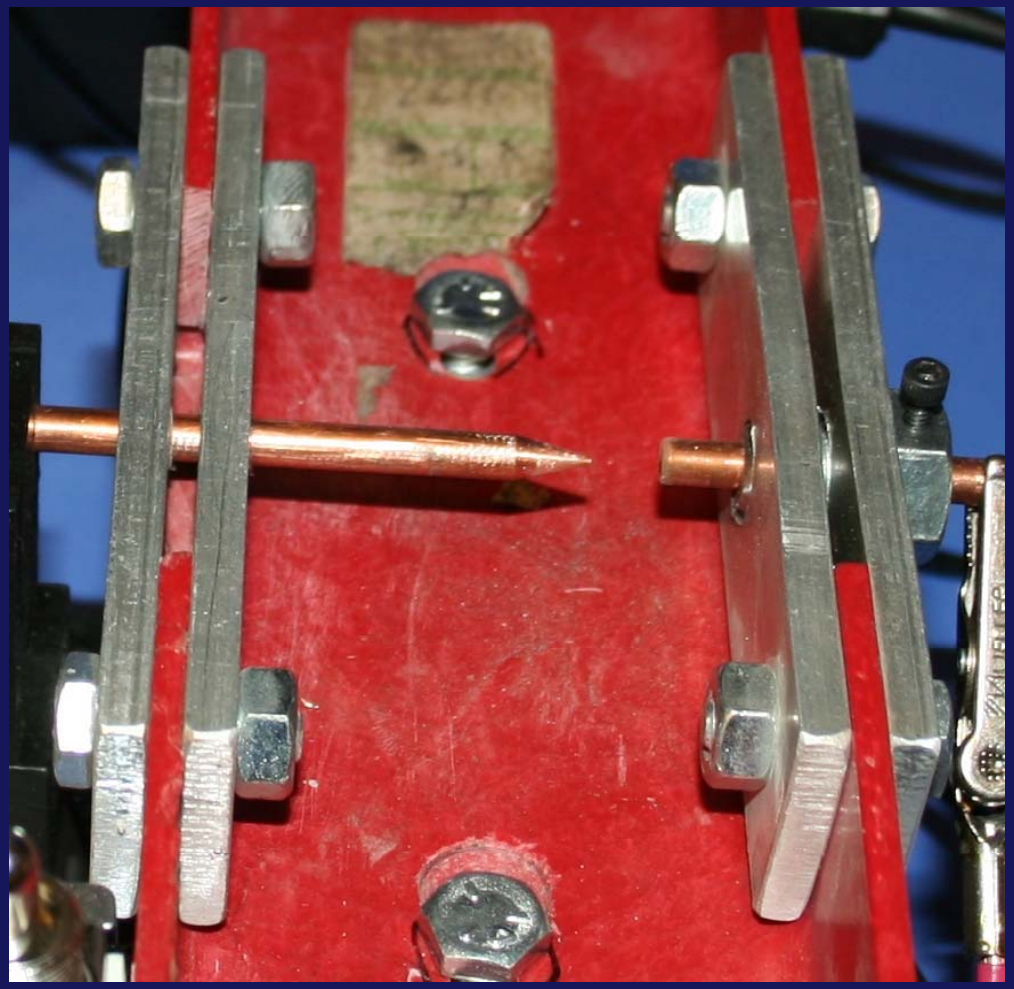
Test Setup


Battery Bank
Power Supply
Load
Motor Controller
Motor
Coupling /Shaft
Copper Rod
Copper Rod
V
I
String pot
Oscilloscope

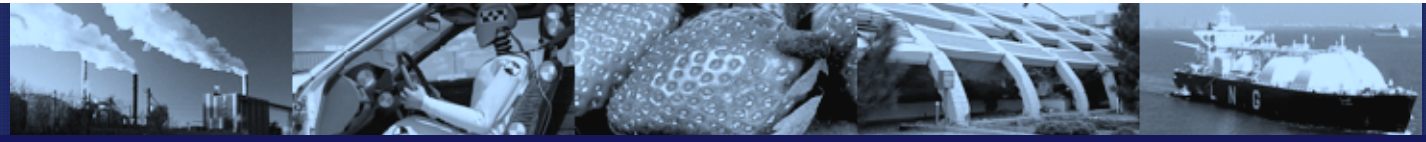
Test Setup



Test Setup



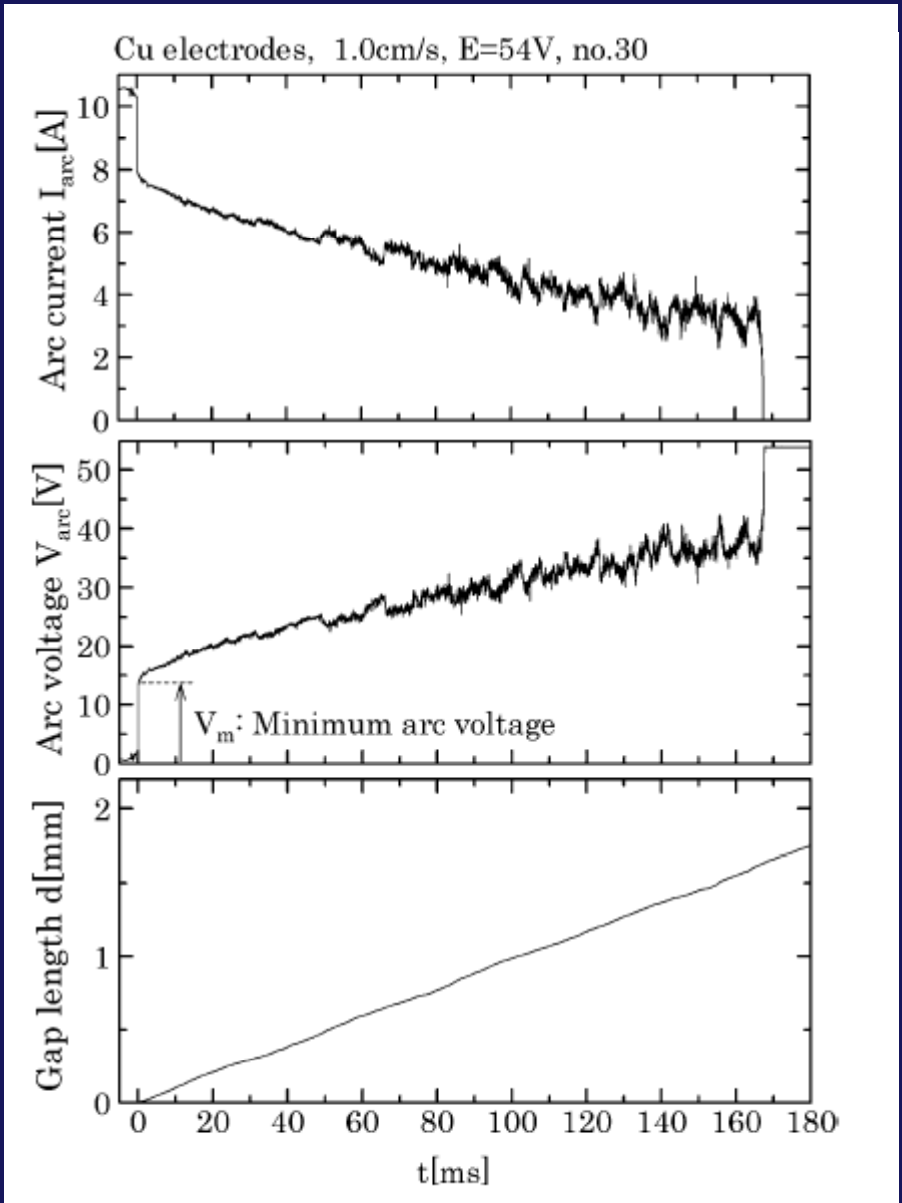
Test Setup



Factors

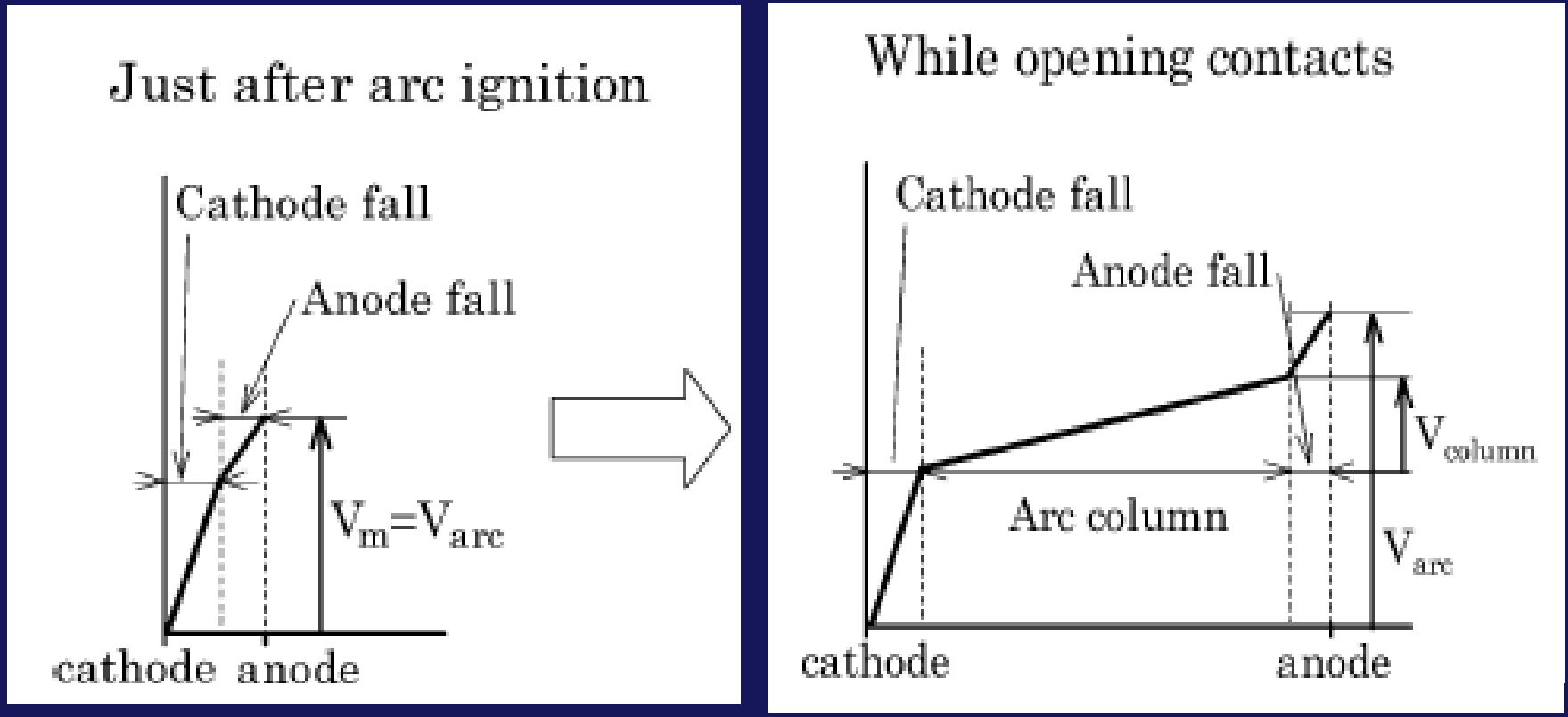
Factor Description	Main Factor Designation	Low Level (-)	Center Point	High Level (+)
Circuit Inductance	A	0 H	500 mH	1 H
Voltage	B	20	31	42
Current	C	100 mA	5 A	10 A
Speed of separation	D	1 cm/sec	10 cm/sec	20 cm/sec
Copper Purity	E	50 %	75 %	95 %
Temperature	F	-10°C	25°C	80 °C
Relative Humidity	G	5%	50%	95%

Series Arcs



Ref: Voltage-Current Characteristics of Breaking Arc at Constant Opening Speed in the Air, Sekikawa et all, IEEE Transactions on Components & Packaging Technologies, Vol. 27, No. 1, March 2004

Arc Discharge Voltage Profile



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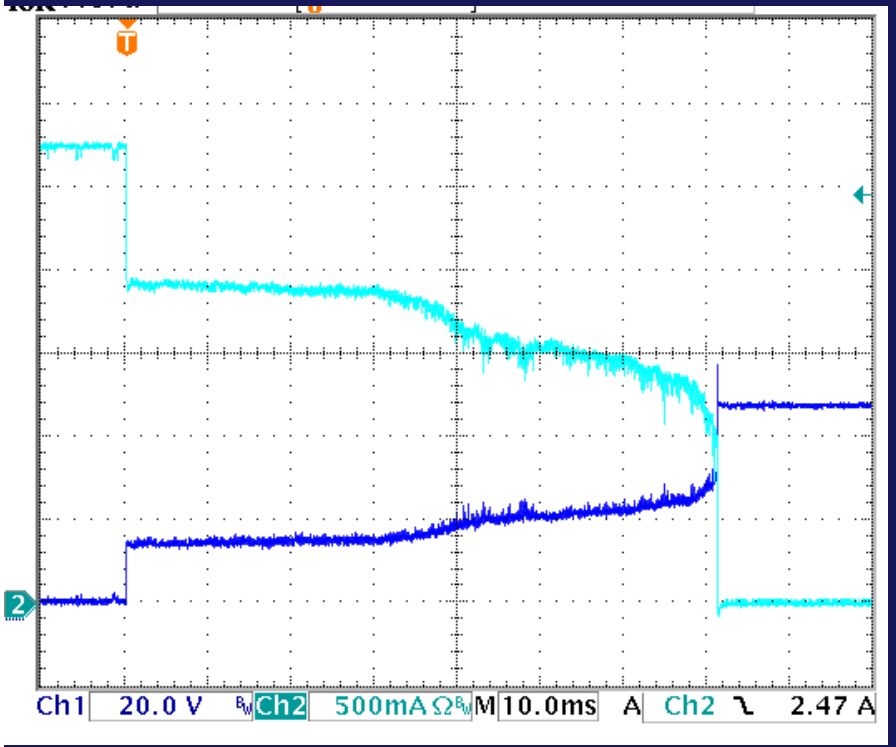
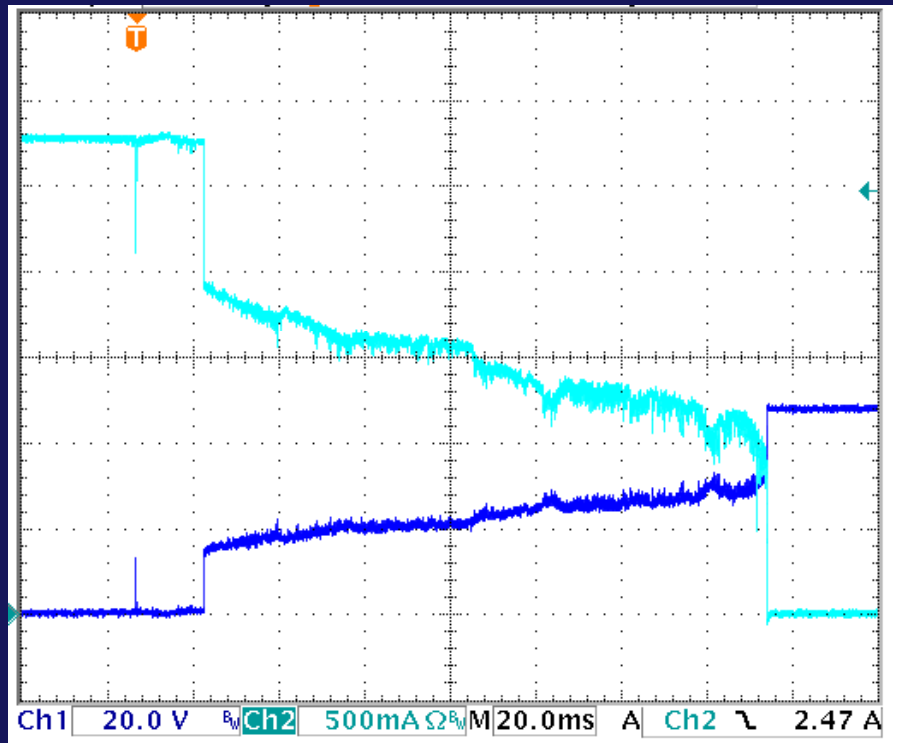
Test Results



20 µH

1100 µH



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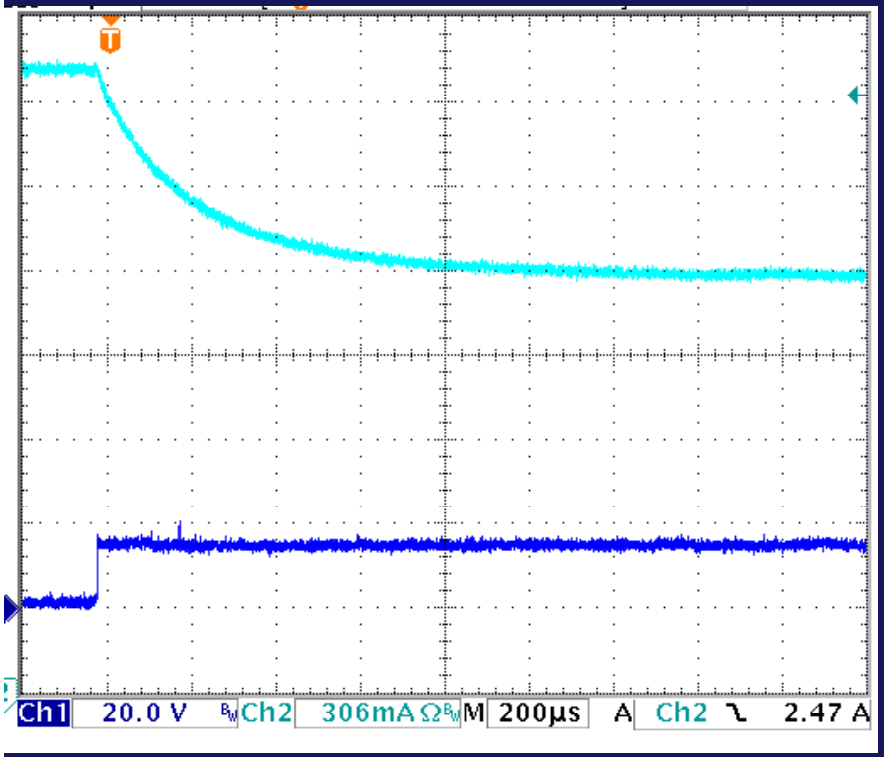
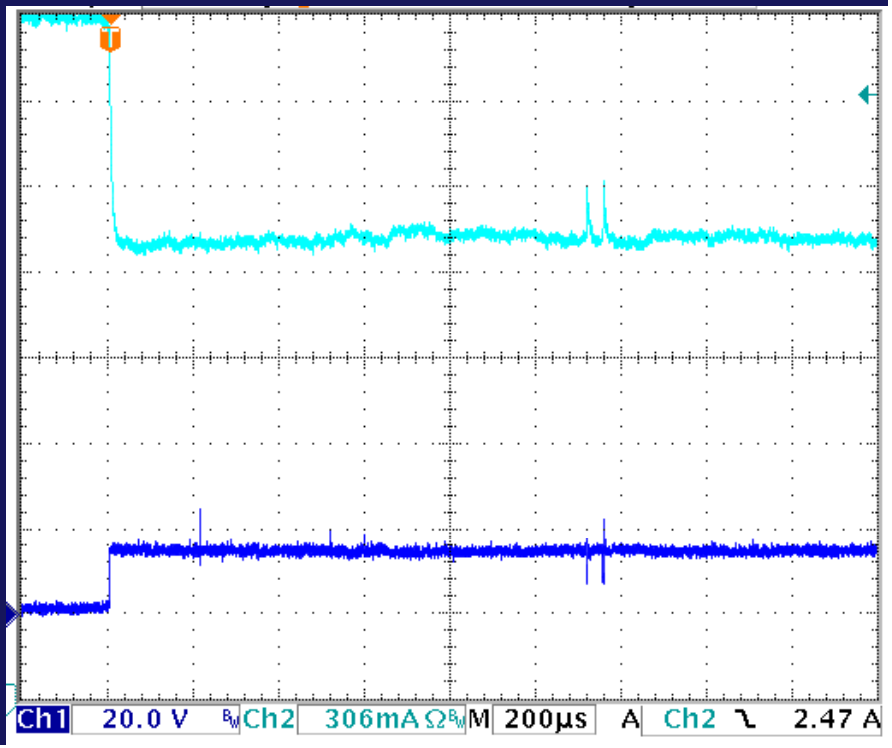
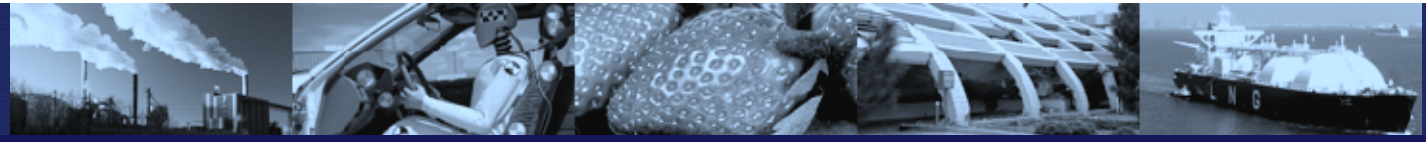


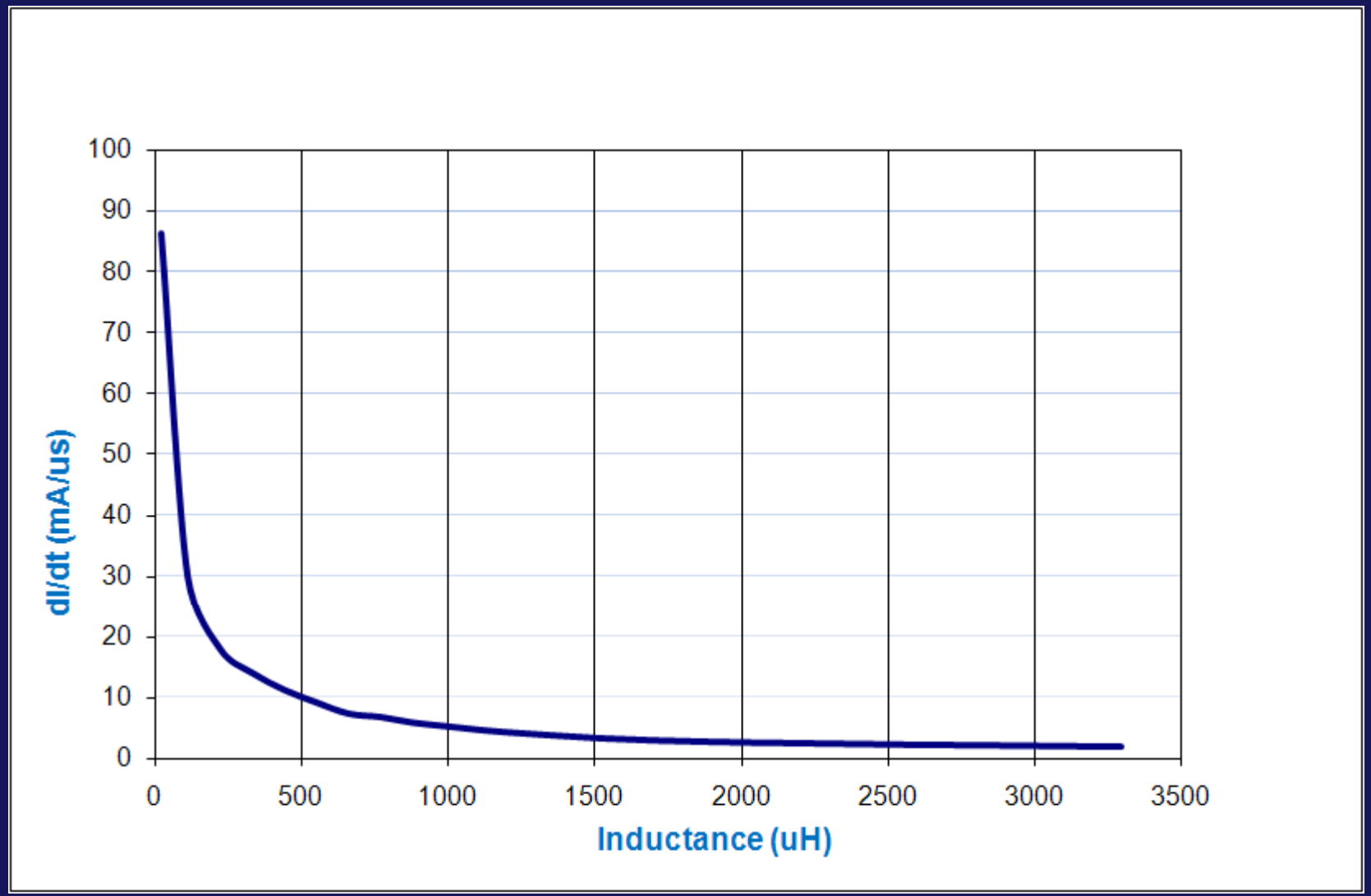
3300 µH

20 µH

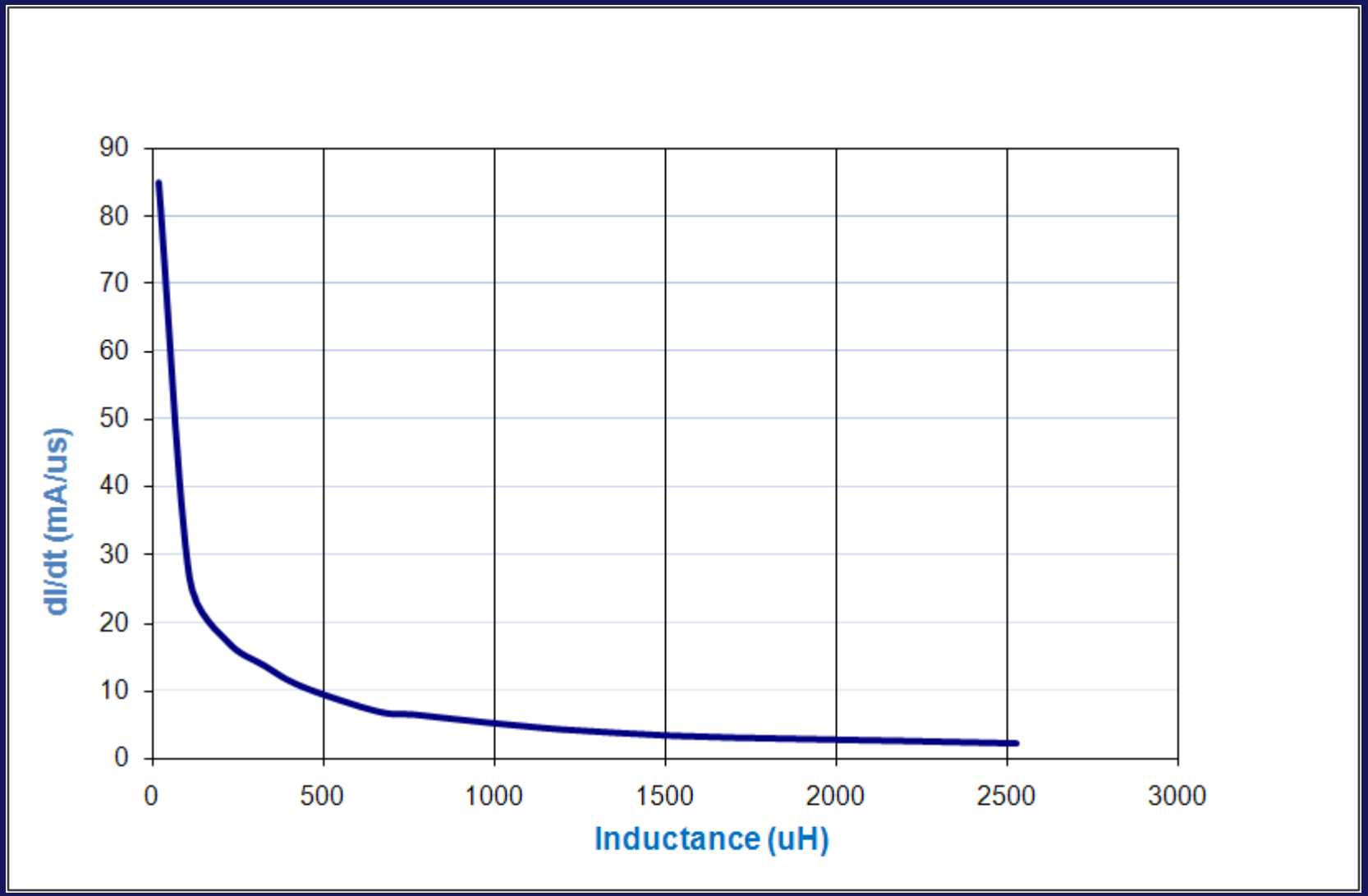


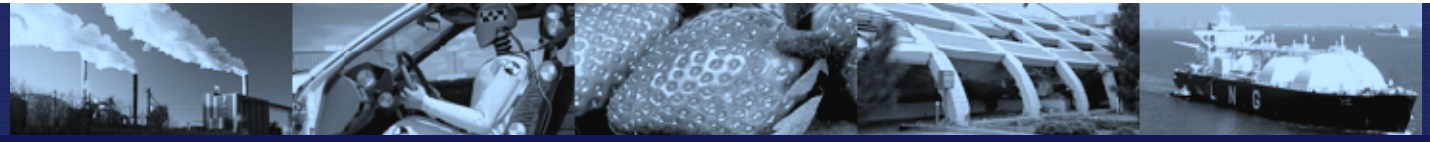


Test Results – 3 mm/second



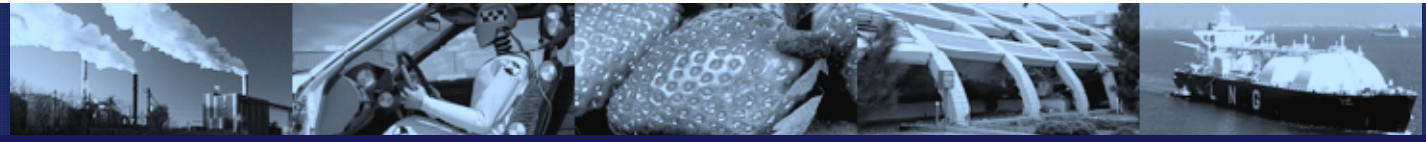
Test Results – 10 mm/second





Test Results

- The current waveform shows an initial drop in current when the arc is initiated
- It may be possible to use this drop in current to detect the initiation of a series arcing event
- The fall time of the current is dependant on the inductance as expected
- Based on the testing performed, it appears that the minimum di/dt is approximately 2 mA/µs
  - This figure is not dependant upon speed of separation or the magnitude of current



Next Steps

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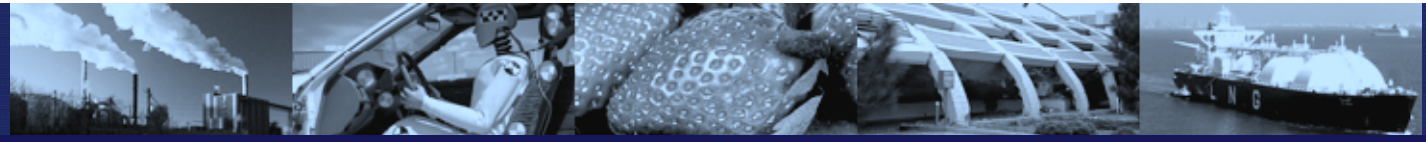
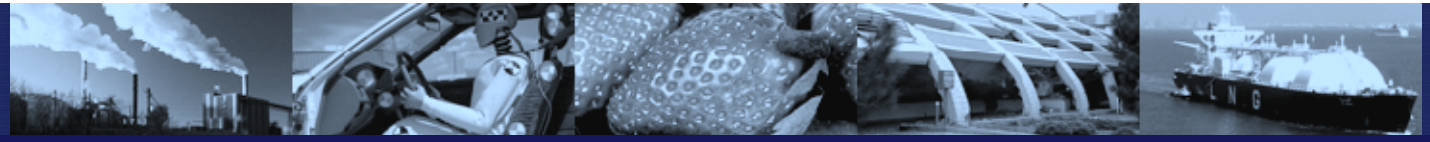


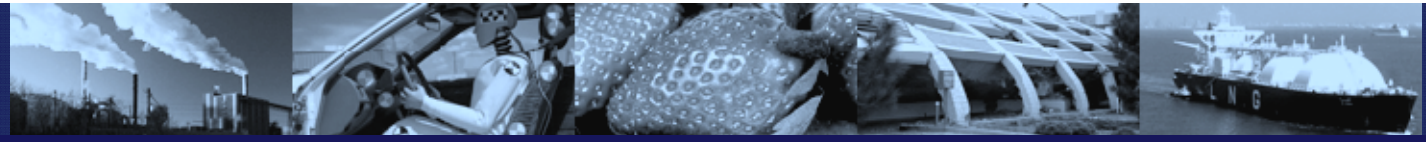
Next Steps

- Determination of the effects of untested factors on the fall time
- Design, implementation and test of a simple circuit to provide series arc fault protection
- Scaling the measurement to higher voltages
- Identifying parameters and potential simpler solutions to parallel arc faults



Summary

- Series arcs may not always be detected by circuits because of the damping effect of the long wire harnesses
- Circuit protection devices commonly available are not designed to detect series arcs specially in automotive applications
- What is required is a detection mechanism as close to the location of the series arc as possible



Summary

- Preliminary testing indicates that a minimum di/dt of approximately 2 mA/µs will be observed at the initiation of the series arc
- A time delay circuit with an integrator/comparator may be implemented to detect and take corrective action in the event of a series arc

QUESTIONS?

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