Understanding Switchboard Arcing Faults

H. Bruce Land, III

March 2009

Contact Information:
Bruce.Land@jhuapl.edu
240-228-6083

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Outline

- Arc Physics:
  - What is an arcing fault?
  - Laws of motion of an arc
  - Damage vs. time
  - Arc velocity vs. current
  - Arc movie
  - Bus bar insulation, good or bad?
  - Obstructions
- Arc Fault Forensics
  - Arc initiation and the remains from initiation
  - Arc Tracks
  - Arc behavior on vertical bus
  - Three case studies
- Conclusions

Arc Fault Definition

Double exposure, 1/3MW Arc

- Discharge of electricity through the air between two conductors creating large quantities of radiation over a broad spectral range
- The light radiated spans from far infrared to far ultraviolet
- There is a wide range of radio frequency and magnetic radiation
- Arc temperatures range from a few thousand degrees in thin plasma to ~ 20,000ºC

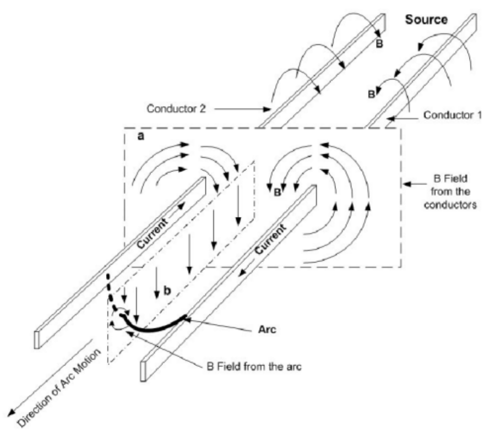
Jacob's Ladder

- High voltage, low current arc
- Arc strikes where the gap is more narrow than the insulation value of the air
- Arc rises due to thermal forces and is extinguished when the arc length is too long
- Arc restrikes and repeats
- These are not the arcing faults under discussion

Arcing Faults

Main power distribution switchboards can be reduced to scrap in seconds by arcing faults with currents too small to trip the main circuit breakers.

Motion of High Current Arcs



- **Lorentz Force Law states that the Force vector = cross product of velocity vector of the charge and the magnetic field**

  $$\vec{F} = q\vec{v} \times \vec{B}$$

- **Magnetic field = permeability of free space ($4\pi*10^7$ Newtons per amp) * current/distance**

  $$B = (\mu_0 I)/(2\pi R)$$

- **The Bottom Line:**
  - **"Right Hand Rule"**
  - **Applies for AC and DC**
  - **Arc moves away from the source**

Very Short Duration Arcs (100ms @ 3700A)

Bus Bars

- Arc initiated on the three bus ¾" from the side of the switchboard
- Switchboard was ungrounded with respect to the power system
- Arc moves rapidly from spot to spot in a random fashion
- Smoke damage
- Figure of merit for testing was the time to burn through the side of the switchboard

Slightly Longer Duration Arcs (350ms@3600A)

Bus Bars

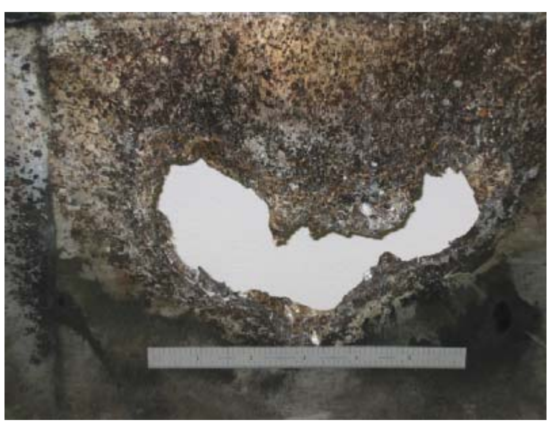
- Arc motion becomes a weighted random function
- Arc contact returns to certain areas causing damage to the surface
- Pitting and pooling occurs on the surface

4,800A Arc for 0.4 Seconds

- Arc attaches to edges of pits and tips of pools until a hole appears in the side of the switchboard
- Arc works the edges of the hole as it unzips the hole larger
- Edges of holes are very sharp
- 450 VAC 3 phase AC arc at 4800 A for 0.4 seconds
- Arc passes from phase to side panel and back to phase as the plasma expands

Bus Bars

4,100 A Arc for 0.7 Seconds

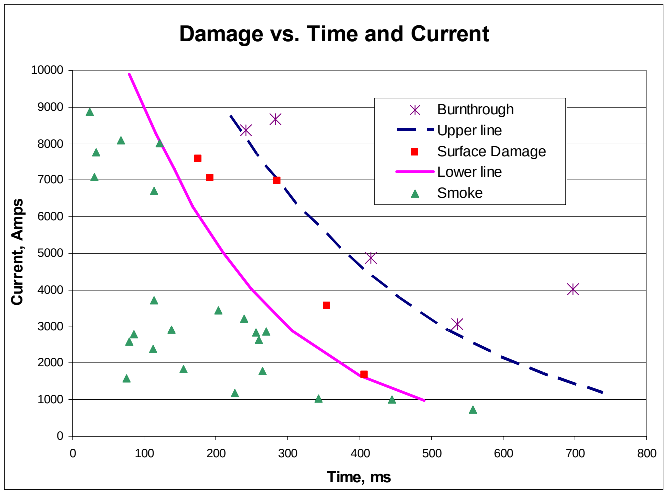


- Six inch hole in the side of the switchboard
- This is collateral damage
- Similar amounts of material missing from the bus bars
- Damage rate accelerates with time until the switchboard is destroyed

Bus Bars

17 FEB 20052/24/09

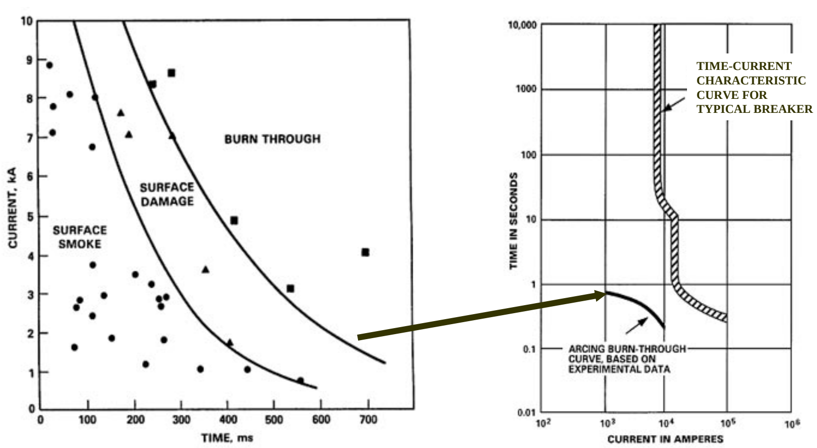
Arc Damage Progression within a 450 VAC Switchboard



11

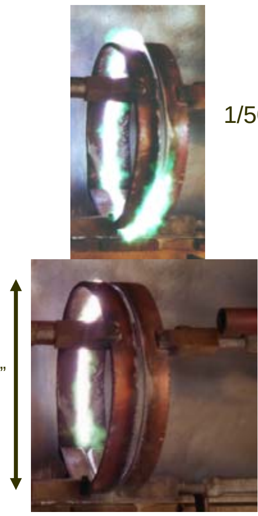
17 FEB 20052/24/09

Arc Damage Test Results and Time Current Characteristics of Breakers



12

Arc Velocity Testing



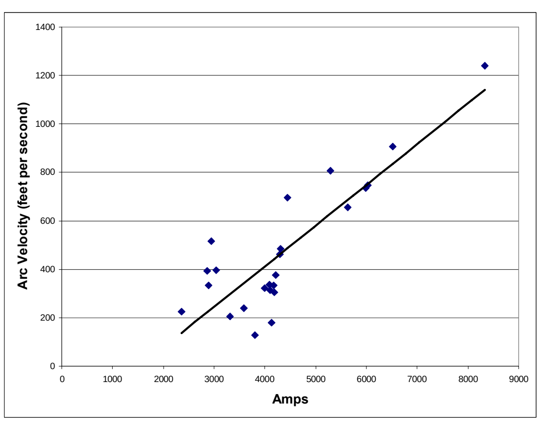
1/500 second

8.25”

1/1000 second

- Arc struck between two circular electrodes
- Magnetic forces cause the arc to rotate around the two electrodes
- Current, voltage, etc. sampled at 100,000 samples per second
- Photo detector times passage of arc
- Arc velocity calculated from time and distance

Arc Velocity vs. Current



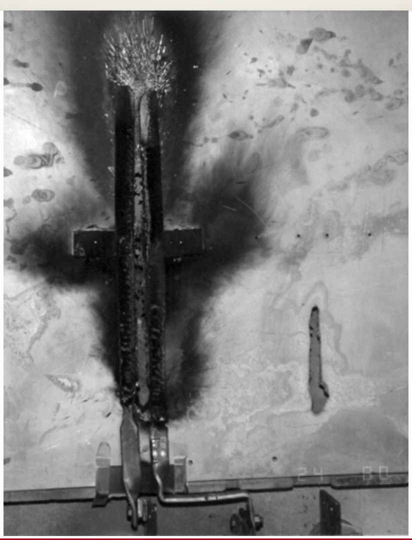
$$V = (0.186 * I) - 259$$

- A 5000 A arc can traverse a typical switchboard in 0.01 seconds
- The arc velocity is slowed by bus bar insulation
- The speed of sound at sea level is 1116 ft/s
- A 8000A arc can break the sound barrier

Arc Movie

- Power supplied by 7mH inductor
- Initial conditions 2KV @ 4KA
- Video recorded at 2000 frames/sec
- Arc struck with starter wire across horn gap electrodes
- Notice relative speed of falling sparks to the speed of the arc for a sense of time
- Arc lasted ~0.5 seconds in real time
- Arc reached over 6 feet in length

Bus Bar Insulation



- Arc temperatures ~ 20,000 ºC
- Sun temperature ~5,000 ºC
- Insulation will not quench an arc
- Tests conducted at 155 VDC with ½" bus bar spacing
- Ionization of insulation lowers the resistance of the air and increases the current
- Insulation does protect against fallen objects, but the lower the mass of the insulation the better
- Test results repeated with Glyptal, fiberglass cloth, and Nomex
- Insulation exacerbated the fire

Obstructions

- Bus bar supports or wire bundles can cause plasma to collect and "pool"
- Pooling of plasma increases the temperature and lowers the arc resistance which increases the current
- Damage increases dramatically when the plasma is allowed to pool

APL

Summary of arc physics

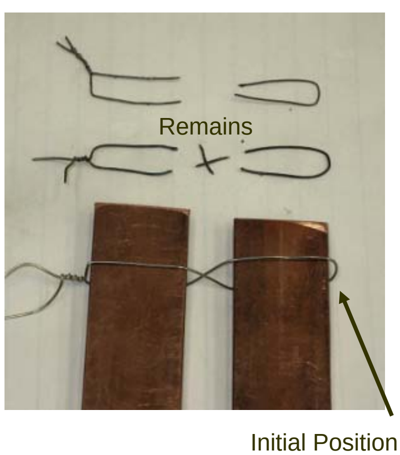
- Arcs will move away from the power source
- Damage vs. time curves were developed
- Bus bar insulation helps protect against falling objects, but accelerates damage if an arc should occur
- An arc moves very rapidly, too rapidly for manual intervention to prevent damage
- Testing yielded descriptions of arc motion which help in performing forensic analysis of arcing failures
- Analysis of test results led to the development of systems which meet the new American Bureau of Shipping requirement for arc fault detection in Naval vessels

APL

Investigation of an Arcing Event

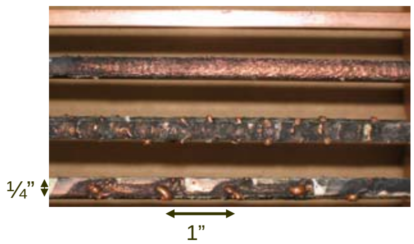
- National Fire Prevention Association "Guide for Fire and Explosion Investigations," NFPA 921 gives information on recording the scene and on identifying, collecting, and interpreting evidence
- A.H. Magee and R.J. Alonzo go beyond NFPA
- McClung and Vallejo discuss forensic analysis
- JHU/APL added over 2000 laboratory arcing tests from a few hundred amps to 30,000 amps over a range of 155 V to 4160 V
- Photographs are of great importance and should be taken from multiple angles and at multiple exposures

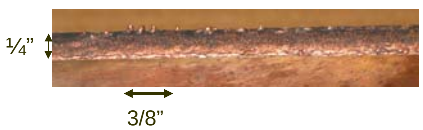
Arc Initiation



- 20 Awg copper wire stretched between bus bars
- Current applied
- High current through a small wire creates enough plasma to initiate the arc over wide gaps
- The center wire remains are usually recoverable, but sometimes they are completely vaporized
- The outside pieces of the starter wire are always recoverable

Evolution of Arc Tracks (Barbs) on Bus Bars





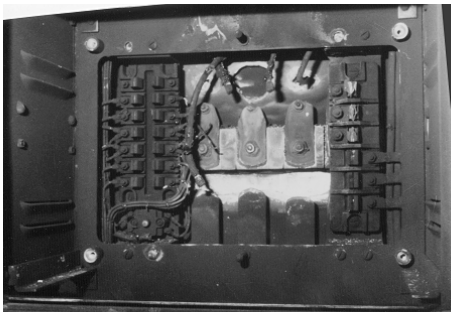
- Arc moves rapidly along the bus bars due to the magnetic forces
- Velocities of 1000 ft/sec typical for 7000A arcs
- Temperatures where the arc contacts the conductor are ~20,000°C
- Copper melts & solidifies into small barbs due to surface tension of the liquid copper
- High speed arcs leave small sharp barbs
- Arc Tracks may be too small to see with the unassisted eye
- Arc Tracks help to backtrack the arc to its origin

Arc Restrike on Vertical Bus Bars

- Arcs move away from the source of the current
- Arcs attach to the most distant end of the bus bars
- Plasma cloud billows out from the arc channel
- Arc involves adjacent conductive material as an incidental conductor
- Arc moves up the switchboard side until the path length is too long for the applied voltage
- Arc restrikes lower on the bus bar
- Process repeats, enlarging the damaged area

17 FEB 20052/24/09

Case 1: Optimum Manual Intervention



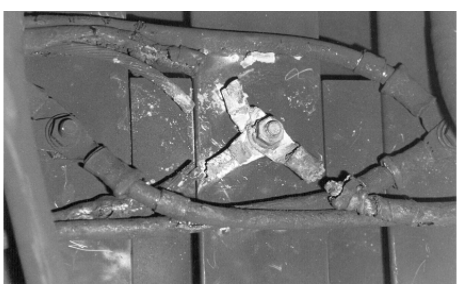
2.5” Bus with 1.75” between them

- Crew in position for emergency drill at that time
- Crew immediately opened turbine generator breaker
- Covers blown off by pressure
- Holes through the rear of switchboard at bus bar tips
- Bus bars cut and larger hole under the insulator 6” below
- Arc splatter found 15 feet away
- Damage found to breaker stabs
- Crew felt that faulty breaker stabs were the root cause

23 APL

17 FEB 20052/24/09

Case 1: Arc Origin



Root Cause of Case 1:
Faulty crimp caused in-line arc

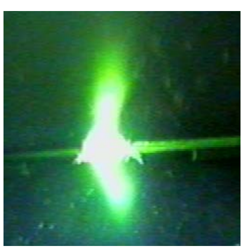
- Entire inside of switchboard was black with soot
- Arc tracks (barbs) led lower into the switchboard
- Investigated which loads were energized at the time of the event
- Faulty lower left crimp caused localized overheating, melting the cable, resulting in an arc
- IR imaging of no assistance
- Magnetic forces caused the cables supplying this switchboard to burst 75 pound cable ties in the supply switchboard

24 APL

Case 2: Front of one of the Switchboards

- Ship was at sea under steady normal power
- Billowing sparks and arc flames drove crew from the switchboard compartment
- Generators were seen jumping on motor mounts before being manually shut down
- Ship towed to port
- Crew blamed arcing on voltage spikes from hopping generators
- Spikes can cause arcing, but spikes are rare aboard ship
- Paschen's Law shows the limits of this possible cause

Voltage Breakdown of Air



4160 V arc in bright sunlight

- Paschen's Law: Breakdown voltage is a function of pressure and distance

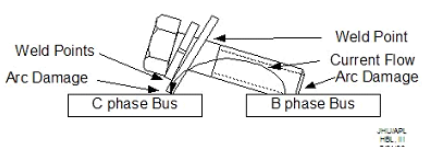
$$V = f(pd)$$

- Affected by type of gas, surface irregularities, temperature, electrode size and shape
- Breakdown for sharp points ~13kV per cm in normal air
- Can a 450 V generator create the ~50KV to jump 1.5" bus gap?
- What about over-voltage protective circuits?

Case 2: Loose Bolt Found Inside of Switchboard

- Bolt found on angle brace in the front of switchboard
- Washers welded to the bolt due to heat
- Tip of threads and washer damaged by arcing
- Could bolt have shorted the bus and created the arc?
- If the bolt touched copper conductors wouldn't it become welded to the bus bar or completely vaporized?
- Arc physics and tracks showed that the arc initiated just above and to the right of the position where the bolt was found.

Current Path Through a Bolt



- Testing conducted with bolt placed across bus
- Bolt always flipped off the bus in the direction that the head was pointing
- Arcing damage to test bolts was similar to that found in the switchboard after fire
- Bolts never remained attached to the conductors

Root Cause of Case #2: Inadequate procedures allowed a loose bolt to remain in the switchboard.

Case 3: Top of Switchboard

- Ship responding to a flank speed bell
- Sudden noise, flash of light, and loss of power
- Light smoke damage to top inside of switchboard
- Damage limited to the tip of two bolts
- Automatic Arc Fault Detection System opened all supply breakers in <0.2 sec, minimizing damage
- No other damage immediately apparent

17 FEB 20052/24/09

Case 3: Front of Switchboard

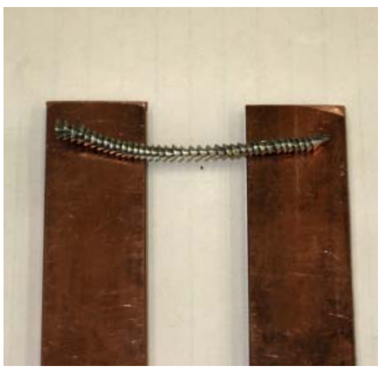
- Note that the entire inside of the switchboard was not covered in soot as with most arcing events.
- Compare damage here with that of manual intervention in Case #1
- Automatic response of Arc Fault Detection (AFD) System limited damage
- Crew surmised that a faulty breaker in the top of the board started the arc

Case 3: Middle of Switchboard

- Drill shaving found on bus support 1/3 down the switchboard
- Arc tracks, too small to be seen without magnification, began on two phases just below the bus support and led to the top of the switchboard
- Can drill shavings initiate an arc?

APL

Case 3: Cause



- Aluminum drill shaving similar to that found inside of the switchboard
- Testing confirmed that drill shavings can initiate an arc

Root Cause of Case #3: Inadequate inspection resulted in loose conductive material in the switchboard

APL

17 FEB 20052/24/09

Conclusions

- Arcing failures put the ship, crew, mission, etc. at great risk
- Neither current breakers, manual intervention, nor better procedures will completely remove the risk of arcing faults
- True cause of arcing failures is not always readily apparent
- Each failure requires a detailed structured investigation
- An understanding of arcing behavior helps determine the origin of the arcing event
- Better designs, inspections, training and maintenance can reduce the frequency, but will not eliminate arcing events
- 2004 American Bureau of Shipping Naval Vessel Rules requires approved arc fault detection systems for all new switchboards, but these systems will find even more value in existing switchboards

33 APL

17 FEB 20052/24/09

References

- Arc Fault Detection on Navy Submarines and Ships, H. B. Land, III, Research & Technology Development Notes, JHU/APL publication, Winter 1998/99
- Arc Fault Detection Systems, Brock Koren, Photonics Spectra, February 2002, pp 131
- Sensing Switchboard Arc Faults, H. B. Land, III, IEEE Power Engineering Review, Vol. 22 April 2002, pp 18-20, 27
- Design of a Sensor to Predict Arcing Faults in Nuclear Switchgear, H. B. Land, III, IEEE Symposium on Nuclear Power Systems, November 2002
- Design of a Sensor to Predict Arcing Faults In Nuclear Switchboards, IEEE Transactions on Nuclear Science, Vol 50, No 4, Aug 2003, pp 1161-1165
- Evolution of Arc Fault Protection Technology at APL, H. B. Land, III, et al., The Johns Hopkins APL Technical Digest, April 2004, Vol 25, No. 2
- The Behavior of Arcing Faults in Low Voltage Switchgear, H. B. Land, III, Electric Ship Technologies Symposium, 2005, IEEE
- Determination of the Cause of Arcing Faults in Low Voltage Switchboards, H. B. Land, H. B. Land, III, Electric Ship Technologies Symposium, 2005 IEEE
- The Behavior of Arcing Faults in Low Voltage Switchgear, H. B. Land, III, IEEE Transactions on Industry Applications, Vol 44, issue 2, March-April 2008, PP 437-444
- Determination of the Cause of Arcing Faults in Low Voltage Switchboards, H. B. Land, H. B. Land, III, Transactions on Industry Applications, Vol 44, issue 2, March-April 2008, PP 430-436

34 APL

Acknowledgements

- Arc research began at JHU/APL in 1978. All of the work was Navy funded with the most recent under contract N00024-97-C-8119.
- H. B. Land, JHU/APL Program Manager since 1991
- D. E. Strawser of NAVSEA 05Z43, Navy program sponsor
- R. T. Cusick and J. George, previous JHU/APL program managers
- L. R. Gauthier, velocity testing and analysis
- H. E. Benden, lead test assistant

APL