# Partial Vacuum Flashover Phenomenon

November 1997
Insulated Conductor Committee
Presentation

COOPER

Cooper Power Systems

# *LOW CURRENT SWITCHING PHENOMENA*

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ICC Project 10-46

# *LOW CURRENT SWITCHING PHENOMENA*

- History
- Products Involved
- Failure Modes & Effects
- Common Factors
- Testing Experience
- Hypothesis on Causes
- Possible Solutions

# *LOW CURRENT SWITCHING PHENOMENA*

- History
  - Initial reports implicated capacitive switching
    - Long runs of cable
    - Particular configurations
  - Vacuum discounted - contacts don’t separate until after vacuum is dissipated

# *LOW CURRENT SWITCHING PHENOMENA*

***Products Involved:***

- All manufacturers products involved
- Problem increases as voltage increases
- Elbows and caps on inserts and junctions
- Problems at all points of system
  - Open end of cable
  - At source end of dead ended cable
  - Opening loop

# *LOW CURRENT SWITCHING PHENOMENA*

***Failure Modes and Effects:***

- Interface flashes during separation
- Flash self clears or operates system protection
- Requires significant downtime to replace inserts and elbows (flash results in carbon deposition)
- Exposes all in area to effects of free arc in air

# *LOW CURRENT SWITCHING PHENOMENA*

***Common Factors:***

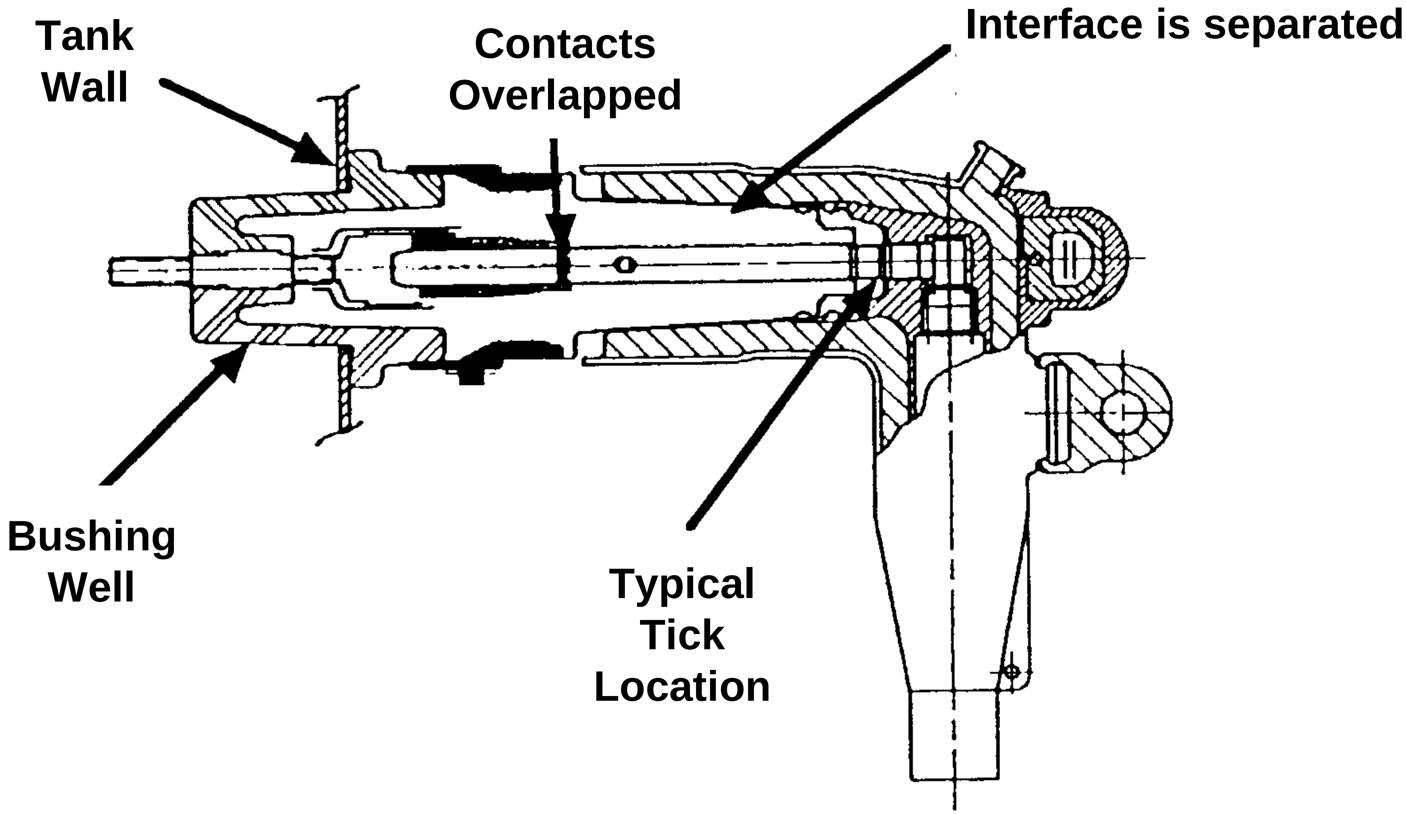
- Occurs prior to contact separation
- Low or now current
- Tick marks at back end of probe
- Occurs on both inserts and junctions
- Occurs with insulated and conductive cuffs

# *LOW CURRENT SWITCHING PHENOMENA*

***Common Factors:***

- At 25 kV, most prevalent in Canada & North East and North Central U.S.
- More common below 35°F (2°C)
- Stuck interfaces increase probability
- Few incidents reported when switching higher load current (rarely done, results in outage)

# *LOW CURRENT SWITCHING PHENOMENA*



# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience:***

- Testing done with Wisconsin Public Service
- Dielectric Withstands in Air
- Switching elbows/caps with Wisconsin Electric Power
- Pressure Measurements
- Library Inputs

# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience - Wisconsin Public Service:***

- Testing done at site of flashover, 44 live operations
- Voltages measured and recorded
- Believed cable switching cause
- Maximum voltage found was 41 kV Peak (2 P.U.) on a system with 14.4 kV RMS available
- No overvoltages measured on “Make” operation

# *LOW CURRENT SWITCHING PHENOMENA*

## *Test Experience - Tests in Air:*

- Series of elbows tested in air for voltage withstand
- Elbow/bushing interface separated; contacts touch
- 25 kV class elbows/bushings withstand 42 kV RMS (59.4 kV Peak)

# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience - Wisconsin Electric Power:***

- Test Circuits
  - Radials with transformer and without transformer
  - Branches with and without transformer
  - Simulate conditions with known flashover in field
- Locations of Switching Operations
  - Start, middle, and end of radial
  - Source end of branch
  - Middle of branch

# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience - Wisconsin Electric Power:***

- Location of connector in circuit
  - Line side
  - Load side
- Switching speeds
  - Normal - quick
  - Slow - teasing

# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience - Wisconsin Electric Power:***

- Special conditions
  - Caps without ground leads
  - Insulated vs. semiconductive cap cuffs
  - Vacuum pulled on injection port elbow
  - Cable charged with DC voltage
  - Dirt on interface
  - Splice grease as lubricant to promote adhesion

# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience - Wisconsin Electric Power:***

- Cable training
  - Laid out on ground
- Energization History before switching
  - Immediate - same day
- Voltage (nominal 14.4 kV to ground)
  - Maximum measured transient (35.6 kV; 1.75 p.u.)
- Switching done at 60° to 75°F, indoors

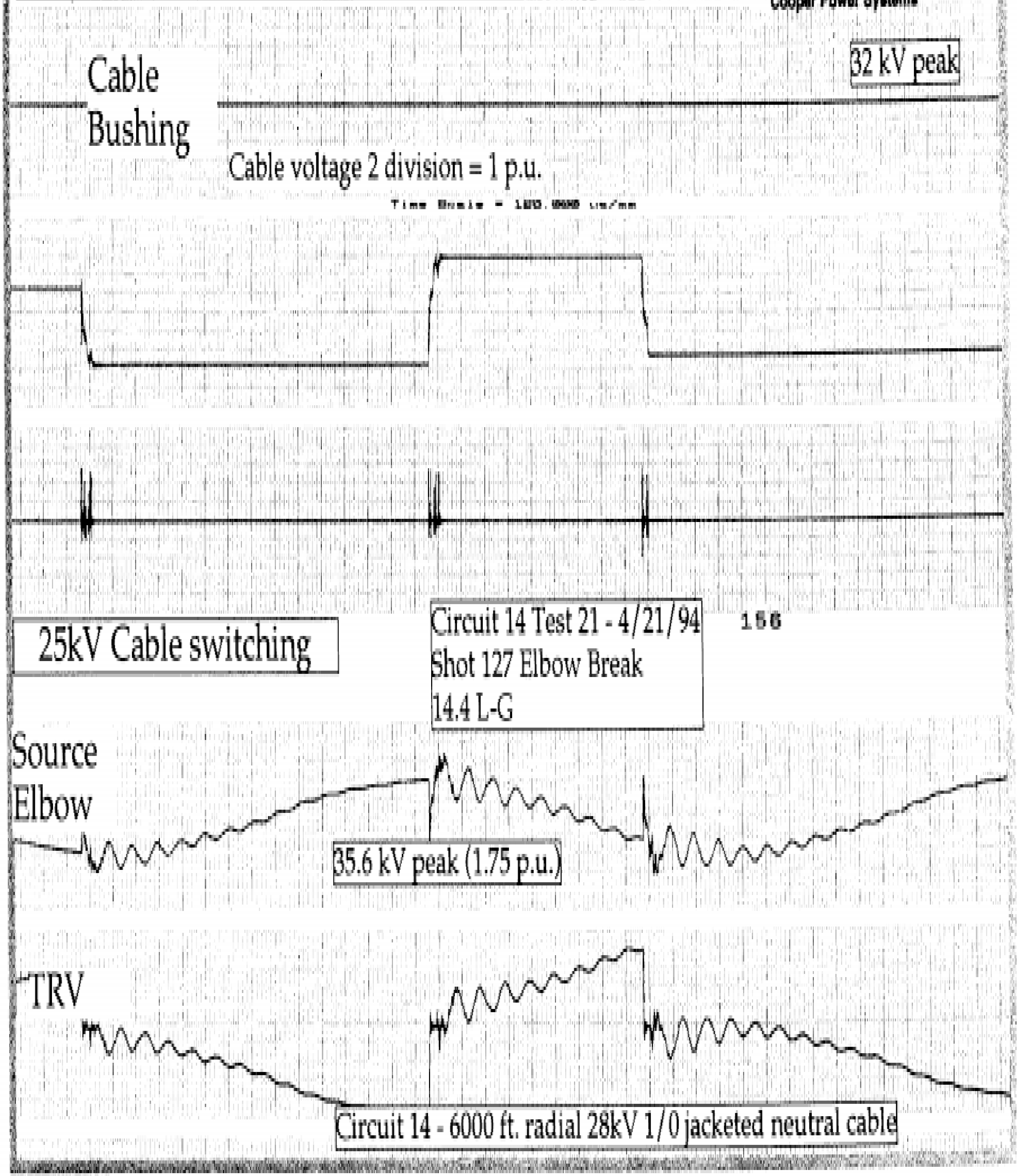
# *LOW CURRENT SWITCHING PHENOMENA*

## ***Test Experience - Wisconsin Electric Power:***

- Instrumentation
  - With and without dividers and recorders
  - High speed video
  - Standard VHS video
- Tests done through 11/94

# Low Current Switching Phenomena

COOPER
Cooper Power Systems



# *LOW CURRENT SWITCHING PHENOMENA*

## *Test Experience - Wisconsin Electric Power:*

- WEPCO provides cable, connections to system
- Cooper provides manpower and site

Conditions: Indoors (60 to 75°F); multiple operations on unaged parts

# *LOW CURRENT SWITCHING PHENOMENA*

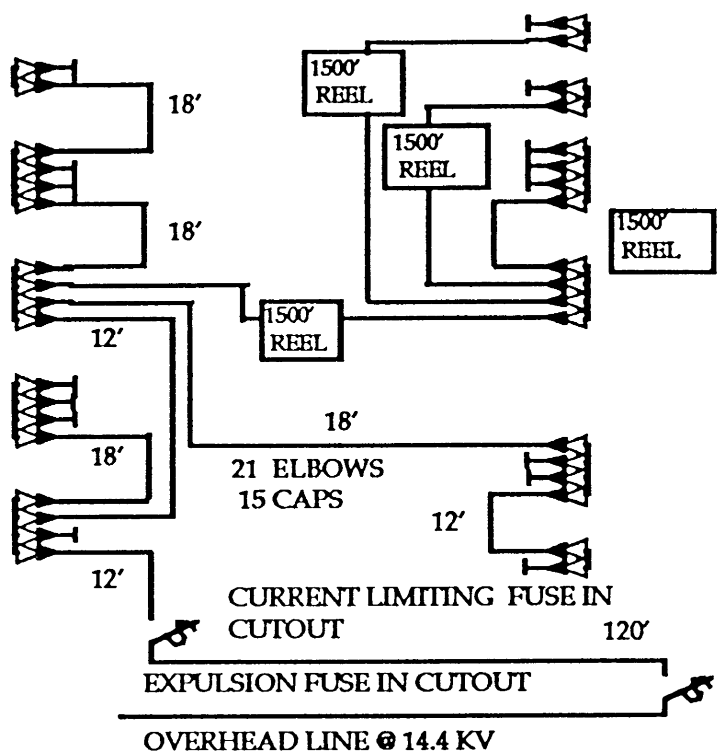
## ***Test Experience - Wisconsin Electric Power:***

- Outdoor Test Circuits
  - Switching done outside
  - Parts continuously held at 14.4 kV LG between tests
  - Cables were left on reels
  - Tests run with and without instrumentation
  - Images captured on both high speed and normal VHS videotape
  - Tests run on junctions only

# LOW CURRENT SWITCHING PHENOMENA

**25 kV Low Current Test Circuit**

**CPS and WEPCO**



# LOW CURRENT SWITCHING PHENOMENA

**25 kV Cable Switching Test at Cooper**
**Conducted Outdoors @ 14.4 lg; 28 kV 1/0 Solid Stranded Jacketed Neutral Cable**

| Date | Ambient Conditions | | Products Tested | |
|---|---|---|---|---|
| | Temp-°F | Relative Humidity | Elbows Flashed/Total | Caps Flashed/Total |
| 11/2/94 | 60 | - | 0/3 | 0/1 |
| 12/15/94 | 35 | 86% | 0/2 | 1/6 |
| 1/18/95 | 28 | 69% | 0/11 | 1/10 |
| 4/4/95 | 20 | 28% | 0/16 | 3/12 |
| 8/22/95 | 75 | 60% | 0/13 | 0/9 |
| 10/31/95 | 41 | 78% | 0/17 | 0/12 |
| 4/4/96 | 33 | 86% | 0/20 | 1/16 |
| 5/31/96 | 66 | 46% | 0/19 | 0/13 |
| Summary-Temperature >35°F | | | 0/52 | 0/55 |
| -Temperature ≤35°F | | | 0/49 | 6/44 |

***INSERT SCAN***

# *LOW CURRENT SWITCHING PHENOMENA*

***Test Experience - Wisconsin Electric Power:***

- Comparison between field and test experience
  - Flash occurs during removal
  - No or low current flow in most cases
  - Tick mark locations on probes are the same
  - Overcurrent protection may or may not operate
  - Temperatures of 35°F or lower tends to increase incidence
  - Stuck products experience a higher incidence rate

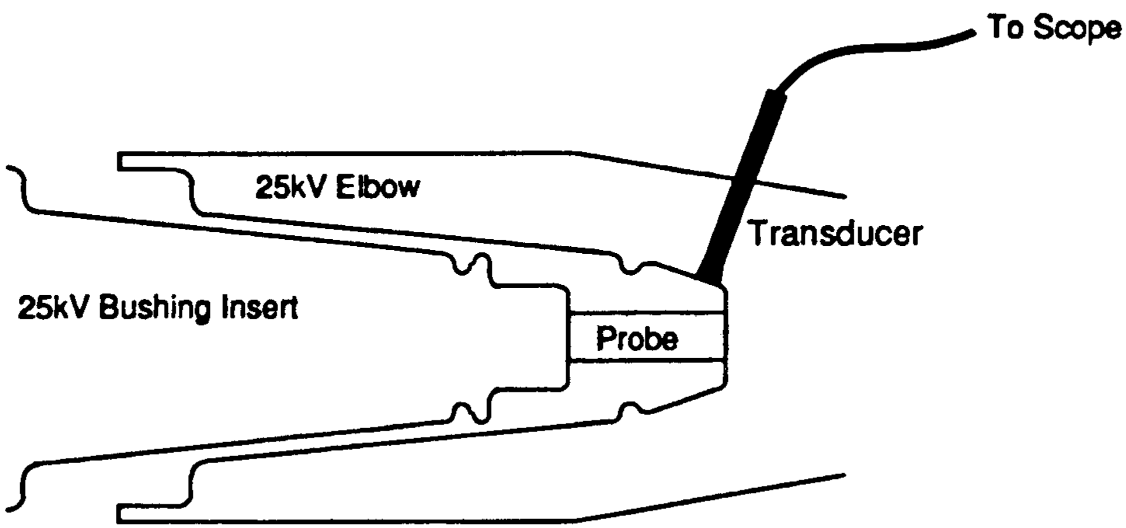
# *LOW CURRENT SWITCHING PHENOMENA*

## *Test Experience - Pressure Measurements:*

- Earlier tests show a reduction in pressure occurring during separation; discounted because switching does not start until after vacuum is dissipated
- Wish to know what level of vacuum occurs as elbows separate from mating bushings

# *LOW CURRENT SWITCHING PHENOMENA*

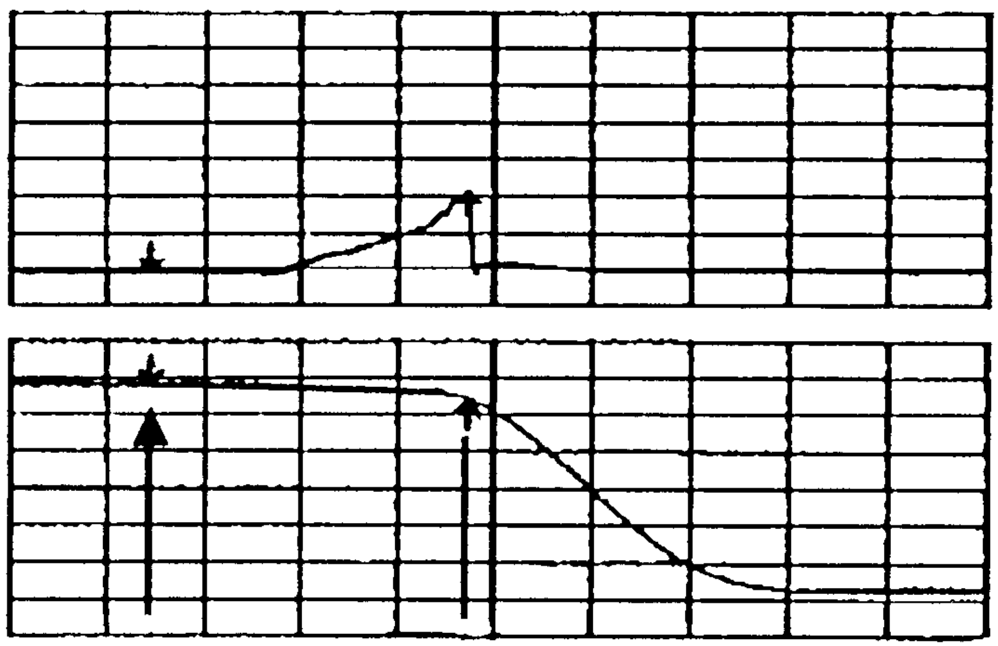
## *Pressure Measurement - Test Modifications*



# *LOW CURRENT SWITCHING PHENOMENA*

Test 65 -Cooper Cap and Insert - Break Operation

Internal Pressure Trace



Deflection=.438V @ 20 PSI per Volt

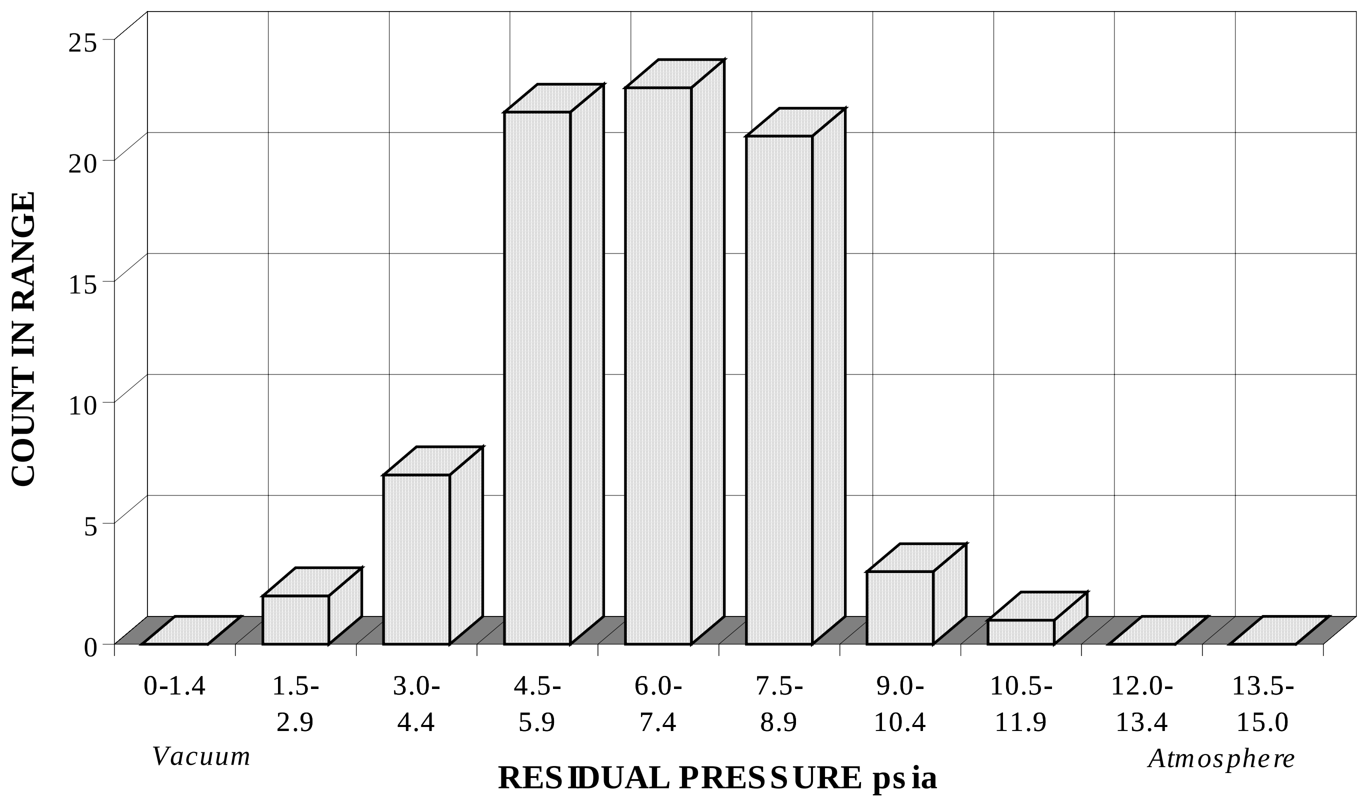
Therefore, peak= 8.76 PSI

Elbow Stretch and Movement Trace

Net Pressure = 5.94 PSI

Stretch before break = .38”; time/division = 50 mS

# LOW CURRENT SWITCHING PHENOMENA



# *LOW CURRENT SWITCHING PHENOMENA*



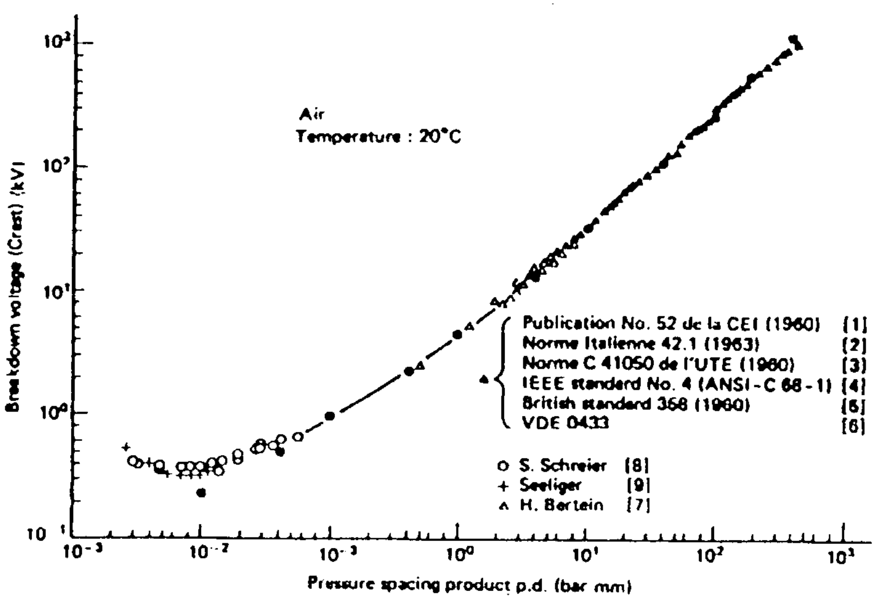



FIG. 5.23. Paschen curve for air in log-log scale. Temperature 20°C. (● calculated $V_s = 6.72\sqrt{pd} + 24.4(pd)$).[74] **Note formula in bar-cm**

Paschen's Curve

Taken from the book "High Voltage Engineering Fundamentals

by E. Kuffel and W. S. Zaengl
Published by Pergamon Press
New York, 1992
Printing, Page 360

**Printing, Page 360**

# *LOW CURRENT SWITCHING PHENOMENA*

***Primary Failure Mode:***

- Flashover along the 200A interface, immediately after separation of the interfaces. This will occur even before the contacts separate!
- Occurs before actual switching begins.

# ***LOW CURRENT SWITCHING PHENOMENA***

## ***Hypothesis***

- During separation, a partial vacuum is created, reducing the air pressure in the interface region.  This reduced pressure lowers the dielectric strength along the interface, increasing the probability of a flashover, as system transients increase the stress.

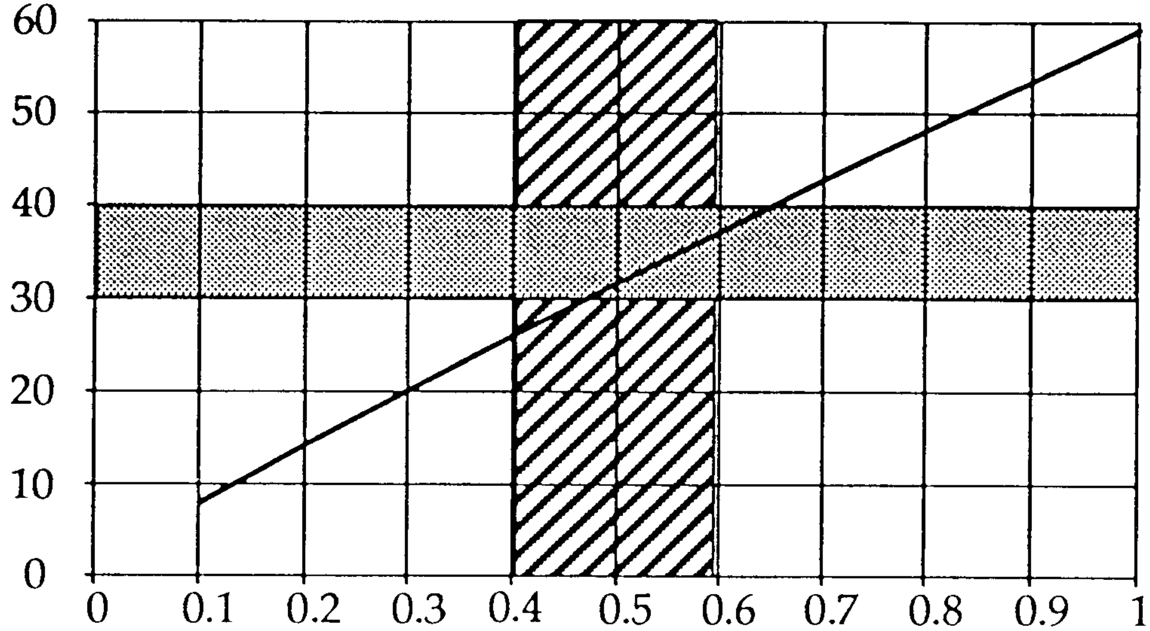
# *LOW CURRENT SWITCHING PHENOMENA*

***Hypothesis comments:***

- There are two probabilistic inputs:
  - The pressure/dielectric withstand
  - The peak voltage occurring in the system

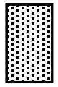
# *LOW CURRENT SWITCHING PHENOMENA*

Voltage withstand vs. pressure during elbow separation




NOTE: 59 kV is minimum withstand kV measured in air at 20°C and 1 atmosphere

Typical Peak Voltage Measured



Typical Pressures Measured

# *LOW CURRENT SWITCHING PHENOMENA*

***Possible solution areas:***

- Keep product same size/fit with existing bushings
- Heat elbows before operating (WEPCO experience)
- Maintain fresh lubrication
- Eliminate vacuum
- Increase creepage
- Increase dielectric withstand base level

# *LOW CURRENT SWITCHING PHENOMENA*

***Insert Scan***

Cooper Power Systems

# *THE SOLUTION TO LOW CURRENT SWITCHING FLASHOVER PROBLEMS*

By: John M. Makal
Staff Engineer
Nov. 4, 1997
ICC Project 10-50

***THE SOLUTION TO***

***LOW CURRENT SWITCHING***

***FLASHOVER PROBLEMS***

***25 kV 200A Loadbreak Connectors***

The Problem

Primary Cause

The Solution

- Insulated Insert & Probe

Switching Test Protocol

Test Results

Field Trials

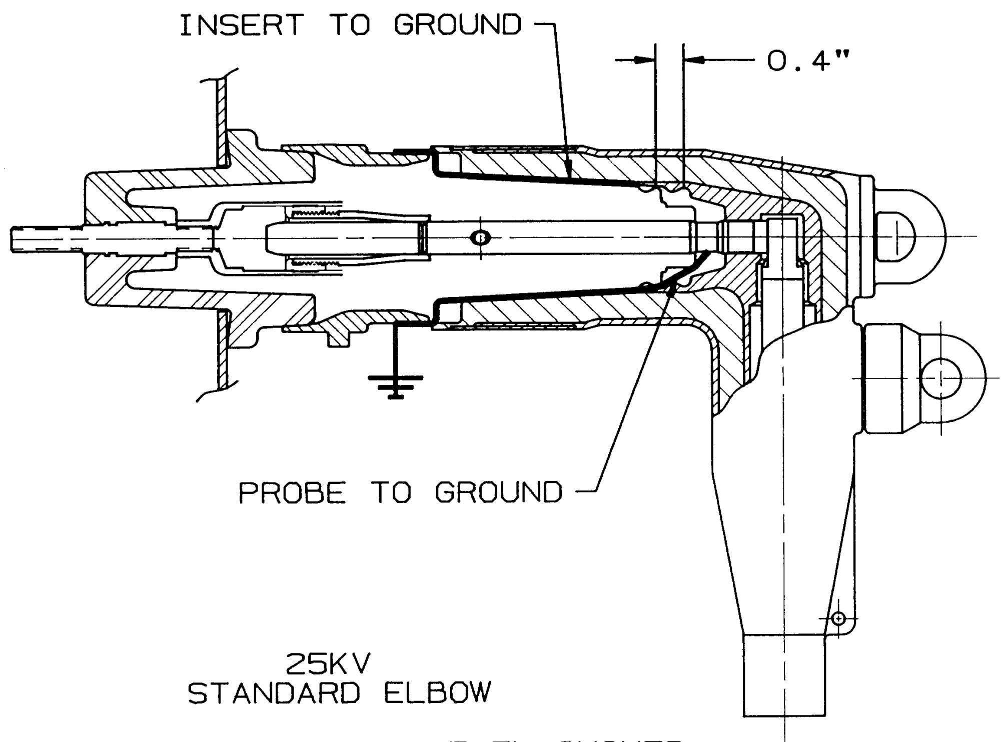
Features & Benefits

## 25 kV 200A LOADBREAK
# ***"ENHANCED SWITCHING"***

***PROBLEM:***

- Line-to-ground flashover when removing elbows and caps on lightly loaded or no load circuits.

# PARTIAL VACUUM
# FLASHOVER PATH




25KV
STANDARD ELBOW

TYPICAL ELBOW TRAVEL AT FLASHOVER
0.4 INCHES

## 25 kV 200A LOADBREAK

## ***"ENHANCED SWITCHING"***

*PRODUCTS INVOLVED:*

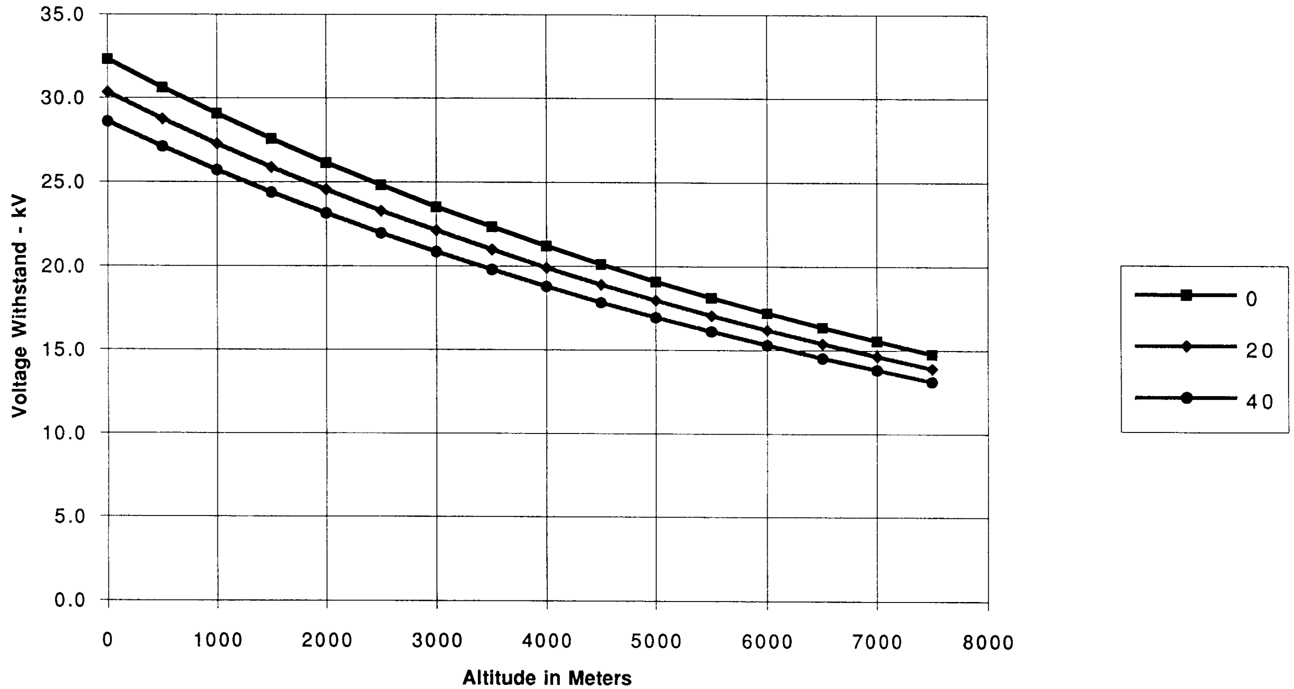
- Elbows and Caps
- Bushing Inserts, Junctions and Feedthru Insert
- All manufacturers
- All combinations

## 25 kV 200A LOADBREAK
# ***"ENHANCED SWITCHING"***

*CONTRIBUTING FACTORS:*

- Temperature below 40°F (5°C)
- Stuck or seized
- Low or no load current
- High altitude

# Voltage withstand versus Altitude at Various Temperatures (°C)




Based on relationship - Air density = Air Density Original * Exp^-0.00018*Altitude in meters, and Paschen's Law

## 25 kV 200A LOADBREAK
## *"ENHANCED SWITCHING"*

# PARTIAL VACUUM EFFECT

***Action:***

- Pulling elbow creates partial vacuum

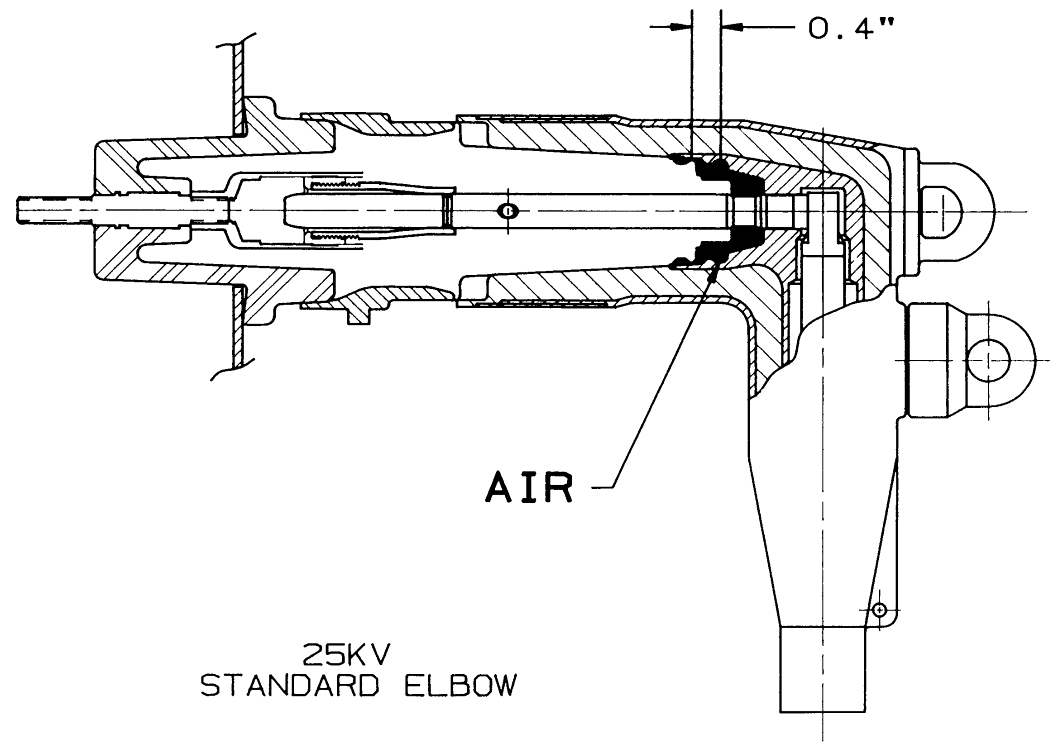
***Reaction:***

- Reduction in dielectric breakdown level of air along interface

***Physics:***

- Per Paschen's Law

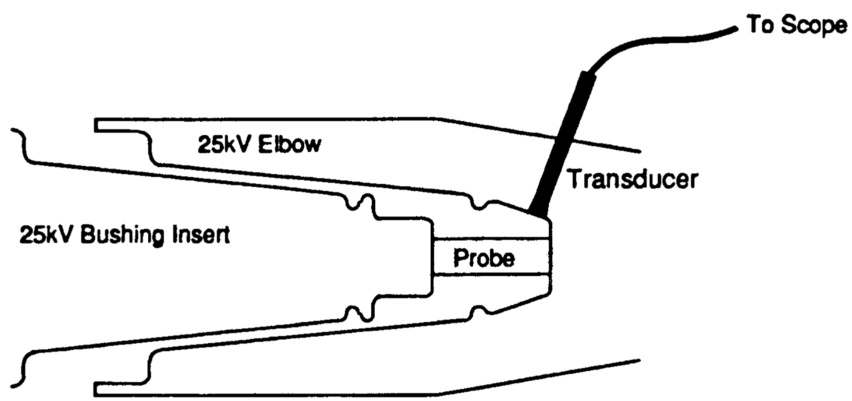
# INTERNAL AIR SPACE INSIDE ELBOW



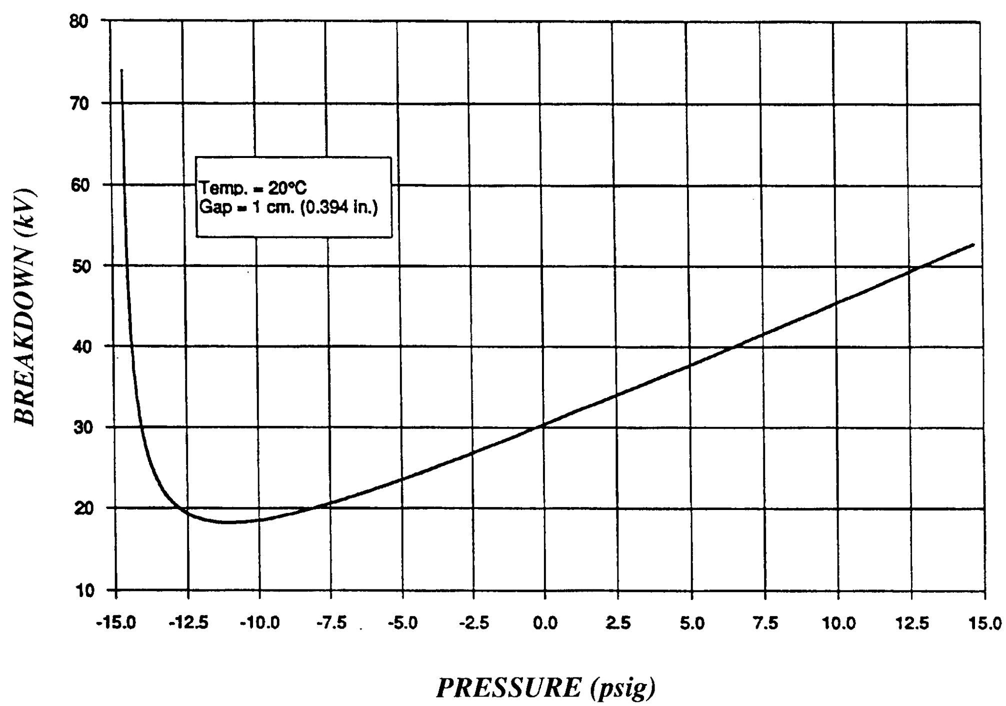

TYPICAL ELBOW TRAVEL AT FLASHOVER
0.4 INCHES

# 25 kV 200A LOADBREAK
# *“ENHANCED SWITCHING”*

## *PARTIAL VACUUM PRESSURE MEASUREMENT*



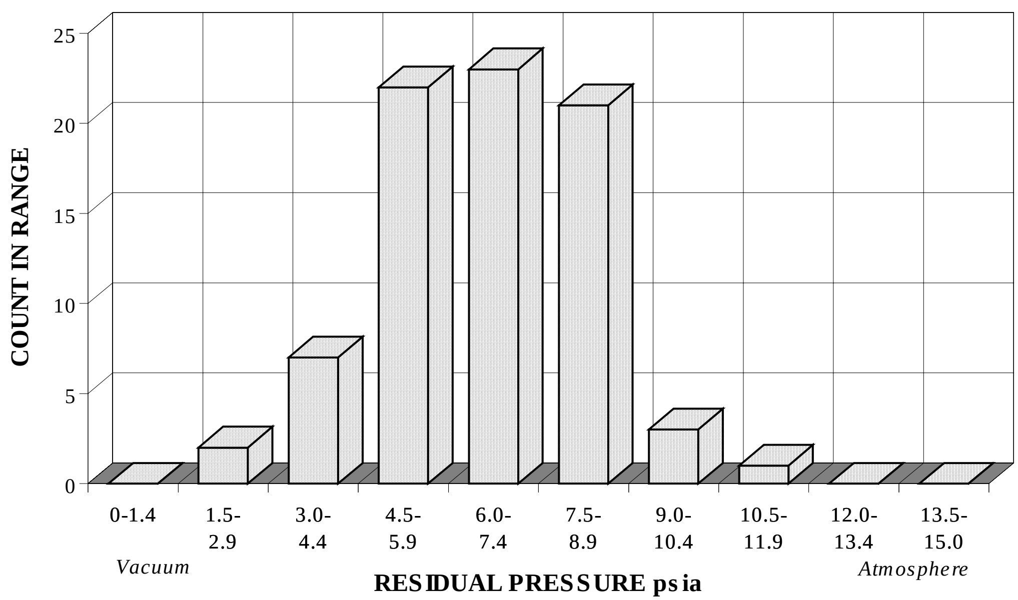
# PASCHEN'S LAW



# 25 kV 200A LOADBREAK
# *“ENHANCED SWITCHING”*

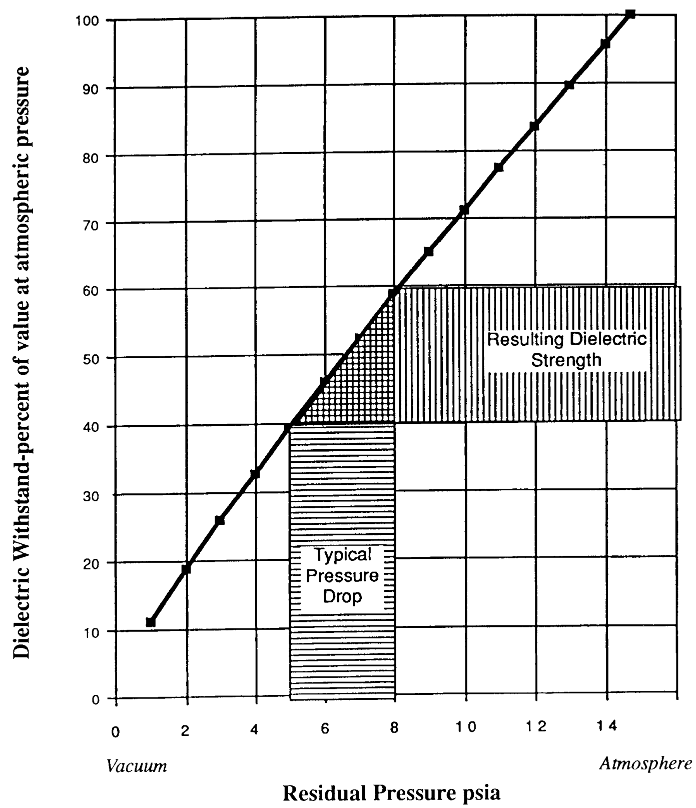
## *MINIMUM INTERNAL PRESSURE DURING REMOVAL OPERATION*

Elbows and Caps (‘96 data)



# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## *AIR DIELECTRIC STRENGTH VS. PRESSURE*



## 25 kV 200A LOADBREAK
## *"ENHANCED SWITCHING"*

*PRIMARY CAUSE:*

- Reduction of dielectric strength along interface due to creation of partial vacuum while pulling off elbow or cap (Paschen's Law).

## 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

*'96 PROPOSAL*

## INCREASED VOLUME INSERT

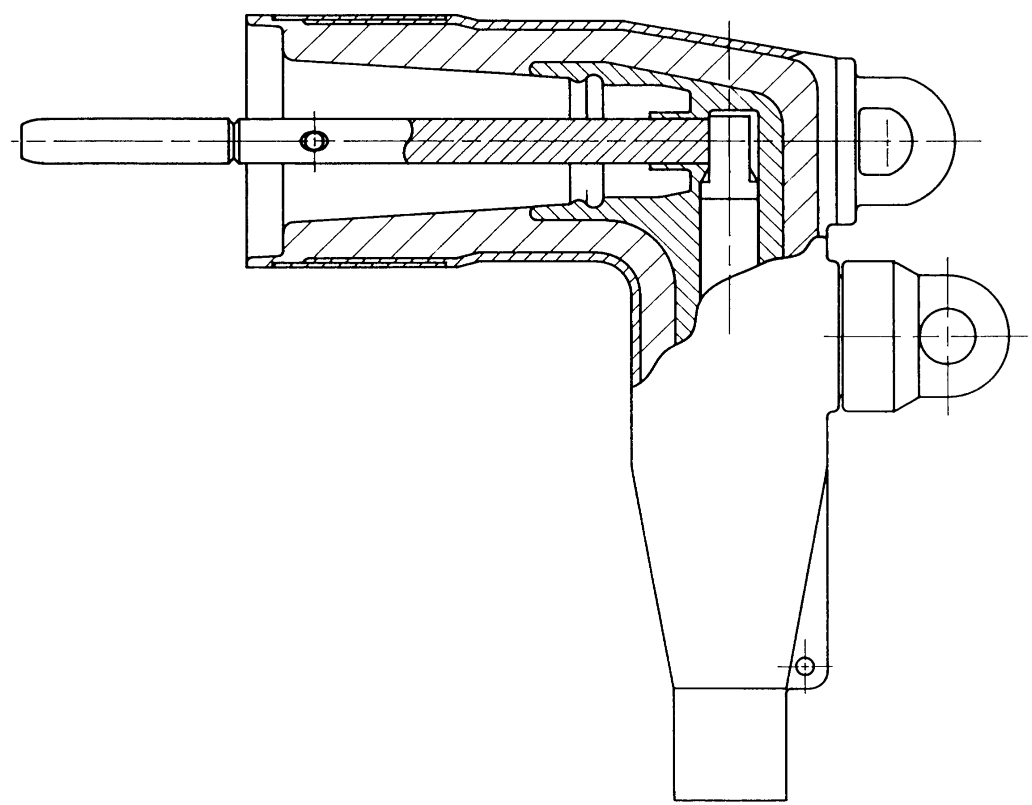
*WHAT:*

- Increase Air Volume of Semiconductive Insert

*WHY:*

- Reduces Partial Vacuum
- Increases Dielectric Breakdown Level

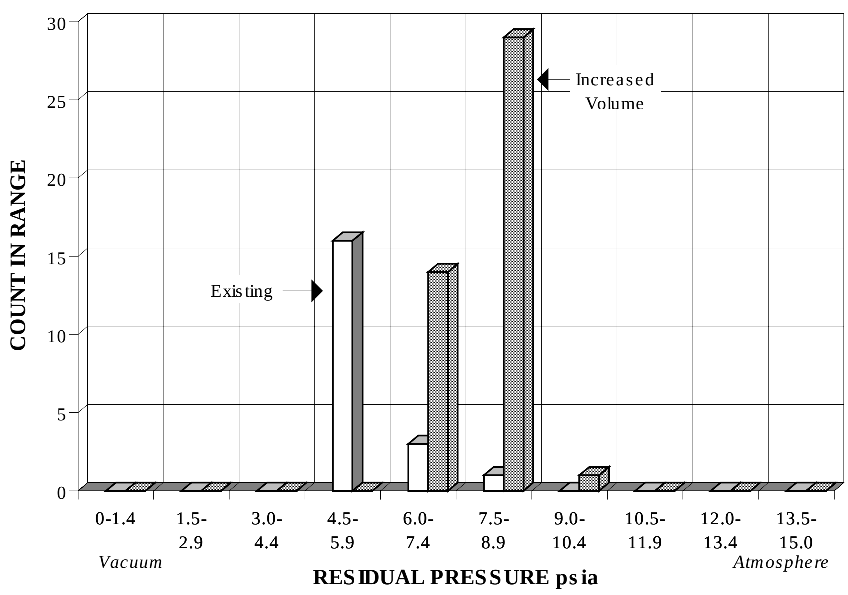
# 25 kV 200A ELBOW WITH INCREASED VOLUME INSERT



# 25 kV 200A LOADBREAK
# *“ENHANCED SWITCHING”*

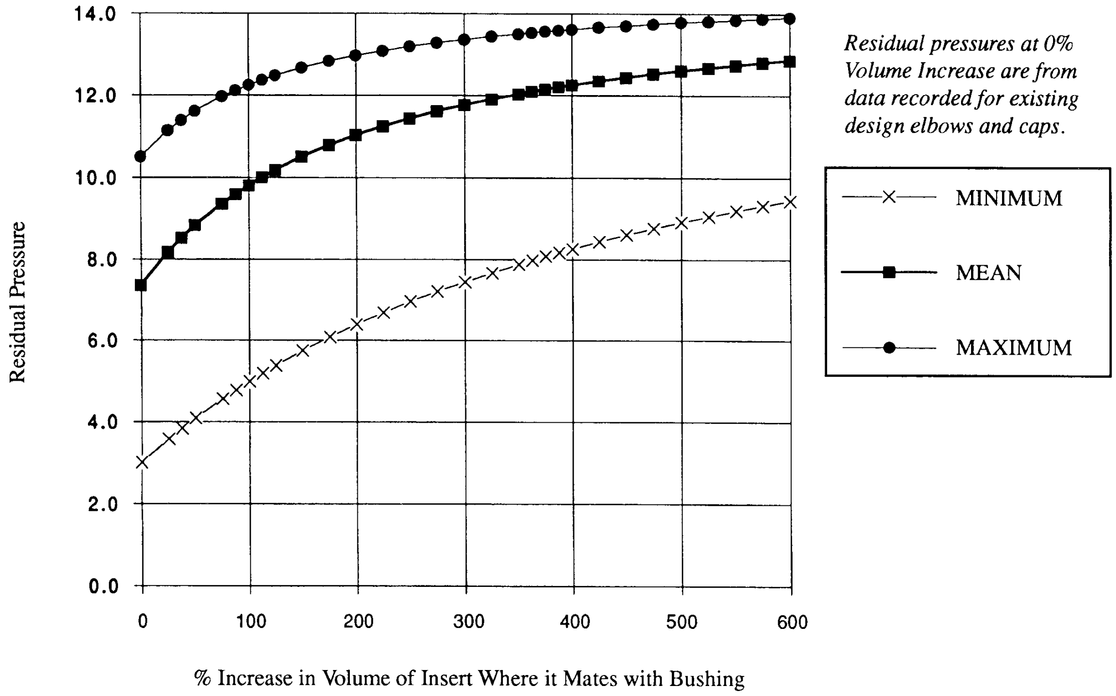
## *MINIMUM INTERNAL PRESSURE DURING REMOVAL OPERATION*

Existing vs. Increased Volume Cap (‘97 data)



# INCREASED VOLUME INSERT DESIGN

## Residual Pressure vs. Increase in Volume of Insert



## 25 kV 200A LOADBREAK
# ***"ENHANCED SWITCHING"***

*COOPER'S '97 SOLUTION*

**INSULATED INSERT & PROBE**

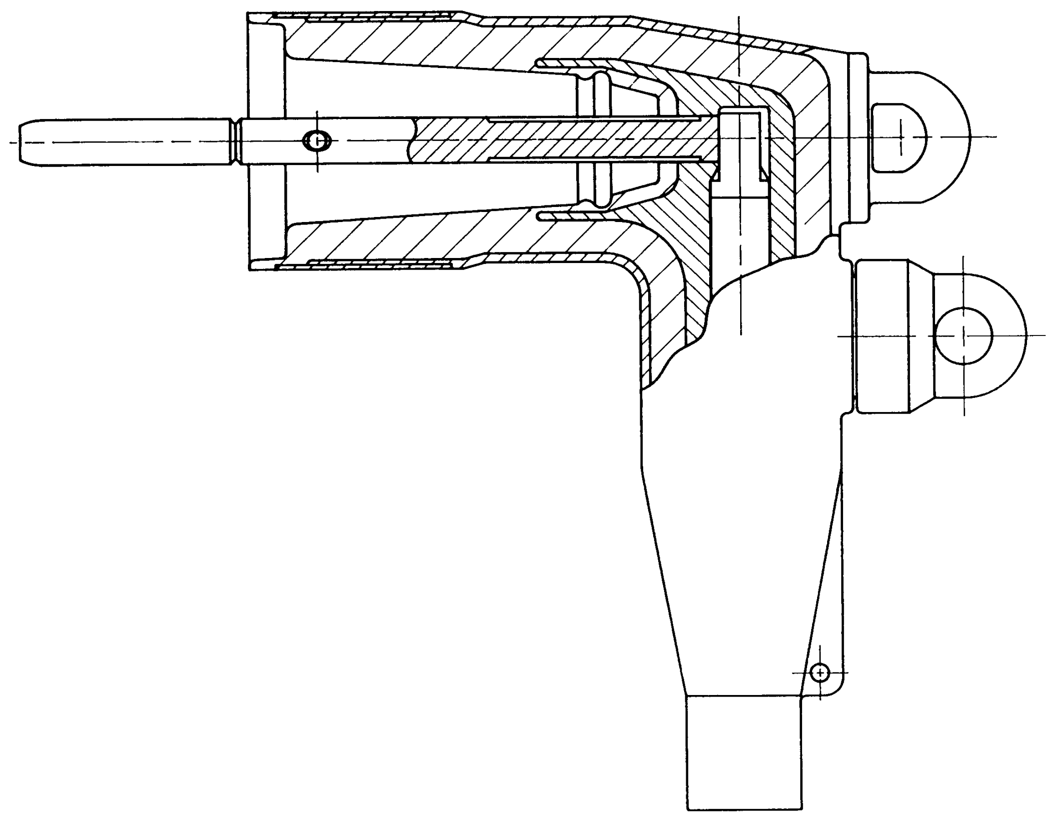
*WHAT:*

- Increase strike distance from live components to nearest ground plane

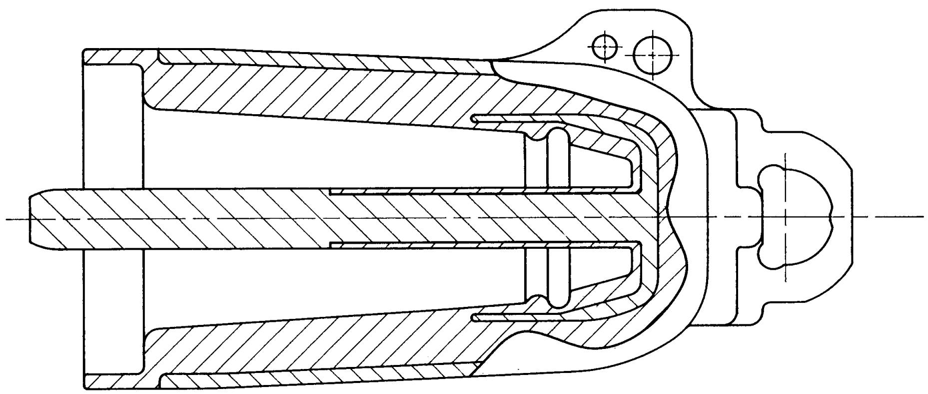
*HOW:*

- Cover semiconductive insert (faraday cage) and probe with insulation

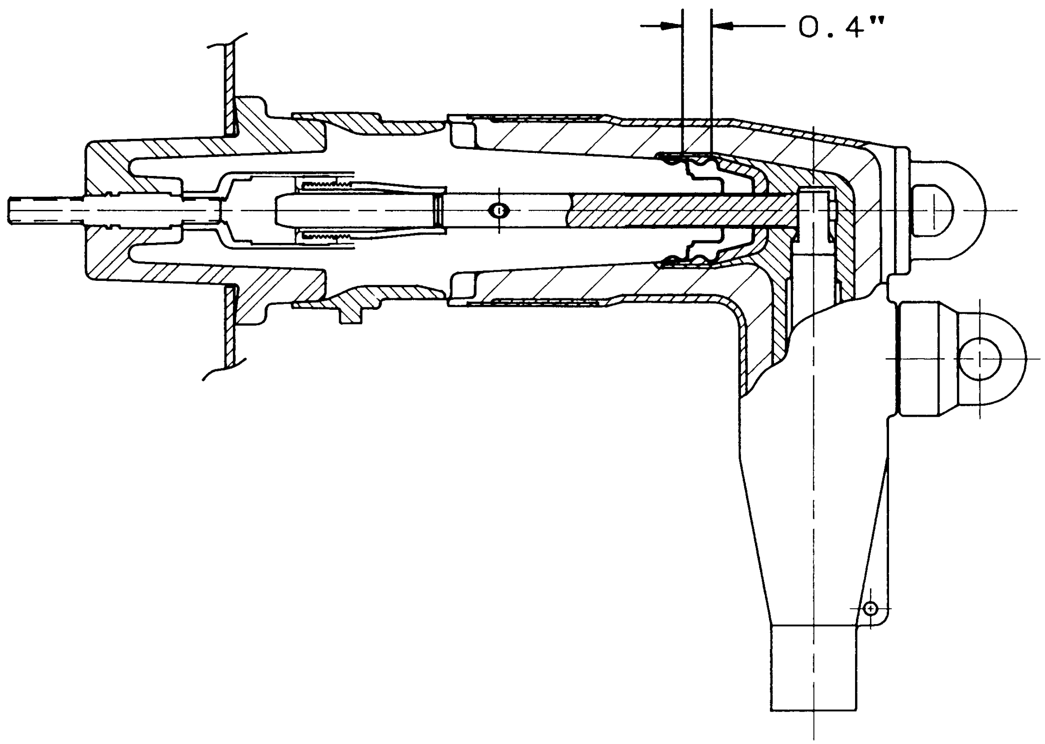
# 25 kV 200A ELBOW WITH INSULATED INSERT & PROBE



# 25 kV 200A CAP WITH
# INSULATED INSERT & PROBE



# 25 kV 200A ELBOW WITH INSULATED INSERT & PROBE




TYPICAL ELBOW TRAVEL AT FLASHOVER
0.4 INCHES

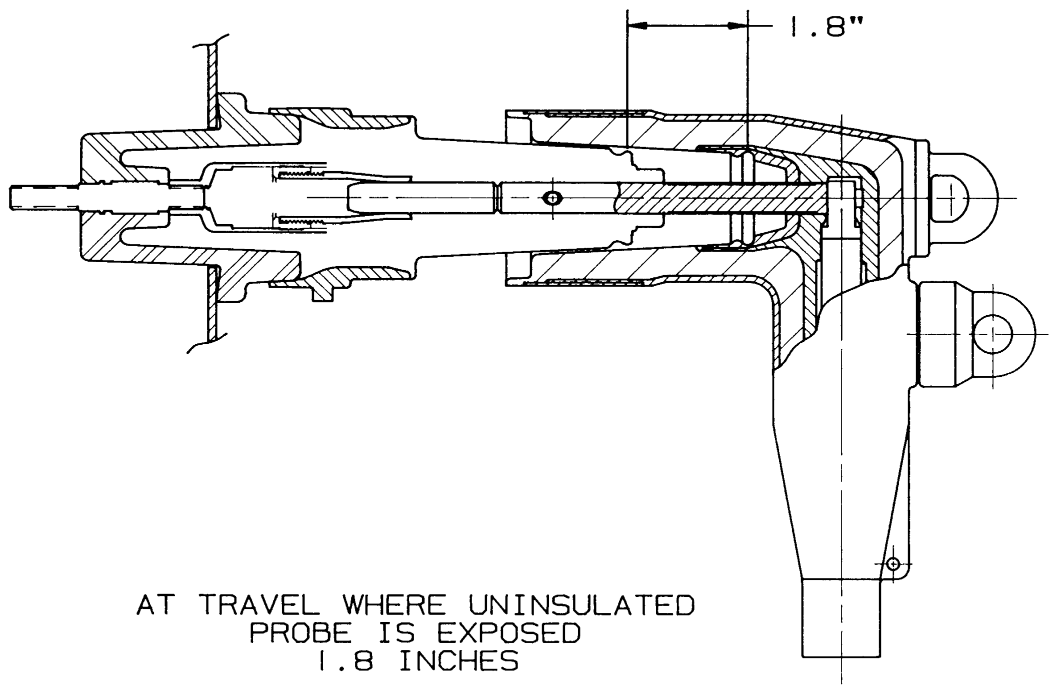
## 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## ELBOW

## *"STRIKE DISTANCE"*
After .4" of Travel

| | |
|---|---|
| Existing Design | 3.4" |
| Enhanced Switching | 5.6" |
| % Increase | 65% |

# 25 kV 200A ELBOW WITH INSULATED INSERT & PROBE



## 25 kV 200A LOADBREAK

# ***"ENHANCED SWITCHING"***

## *Design Qualification Tests*

| TEST | LEVEL | IEEE 386 SECTION | RESULTS PASS/TOTAL |
|---|---|---|---|
| Partial Discharge | 19 kV | 7.4 | 10/10 |
| AC 1 minute Withstand | 40 kV | 7.5.1 | 10/10 |
| Impulse Withstand | 125 kV | 7.5.3 | 10/10 |

# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## LAB SWITCHING TEST PROTOCOL

*PROCEDURE:*

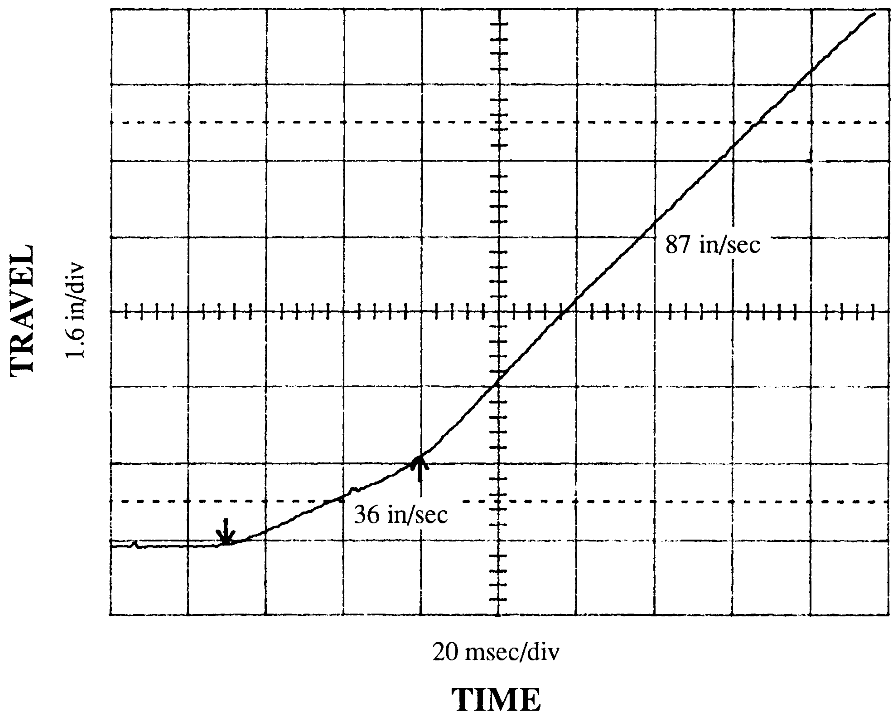
- Assemble elbow/cap to bushing insert without grease
- Chill parts for a minimum of 16 hours at -20°C (-4°F)
- Mount and switch elbow/bushing assembly within 5 minutes after withdrawal from chiller
- Circuits shall be:
  - 27.5 kV line-to-ground
  - No load current
  - No adjacent ground
- Perform one seapration each on 12 samples assemblies

*CRITERIA:*

- 12 samples shall be operated without a flashover

# 25 kV 200A SEPARABLE CONNECTOR

# TRAVEL TRACE




Robot actuator travel profile
for elbows and caps @ -20°C

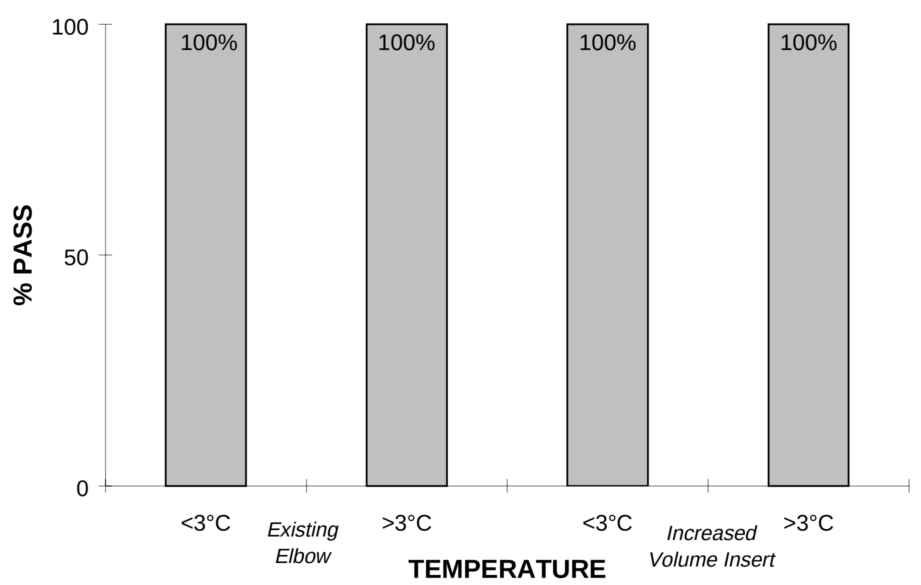
# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## *ELBOW*

*Switching Success Rate*

*vs. Design and Temperature*

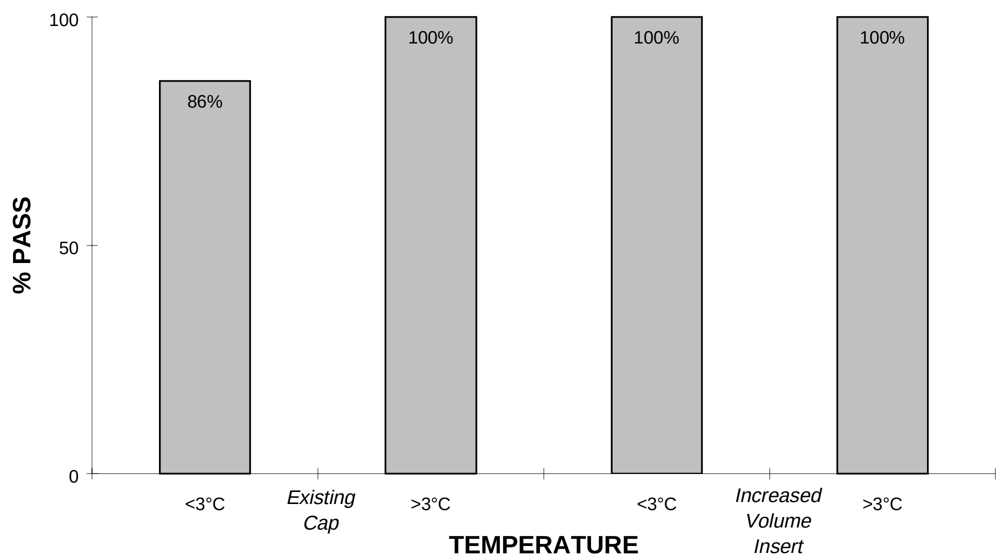
*(14.4 kV)*



# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## *CAP*

*Switching Success Rate*
*vs. Design and Temperature*
*(14.4 kV)*



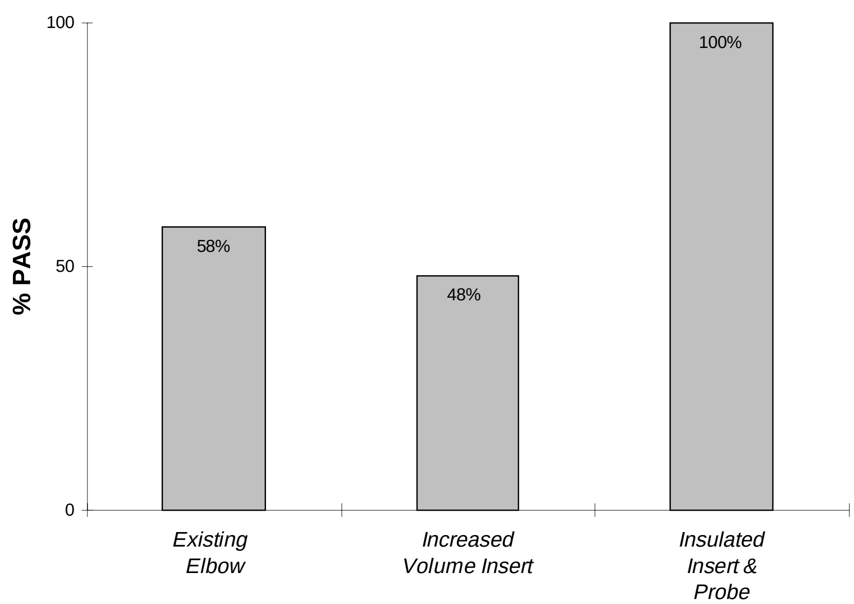
# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## *ELBOW*

*Switching Success Rate*

*vs. Design*

*( 27.5 kV @ -20°C)*



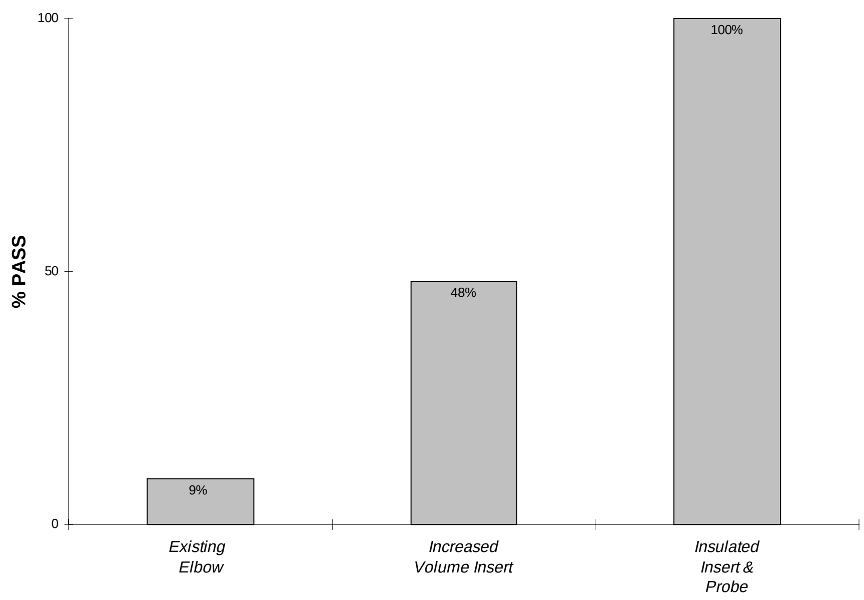
# 25 kV 200A LOADBREAK
# *“ENHANCED SWITCHING”*

## ***CAP***

*Switching Success Rate*

*vs. Design*

*( 27.5 kV @ -20°C)*



## 25 kV 200A LOADBREAK
# ***"ENHANCED SWITCHING"***

## ***CAP***

## ***"ENHANCED SWITCHING DESIGN"***

| INTERCHANGEABILITY<br>LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Teste d | Pass | % Pass |
| 27.5 | -20 | 10 | 10 | 100 |

*CAPS tested on competitor's 25 kV 200A loadbreak bushing insert*

## 25 kV 200A LOADBREAK

## *“ENHANCED SWITCHING”*

*INSULATED INSERT & PROBE DESIGN*

*“VALIDATION”*

**FIELD TRIALS**

Voltage: 14.4 kV L-G

Temperature: <40°F

Intervals: Between 1 and 4 weeks

Operations: >200

# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## *FEATURES AND BENEFITS OF THE "ENHANCED SWITCHING" ELBOW AND CAP*

- Interchangeable with all new and installed bushings
- Field retrofittable without dropping load
- Retains the stress control provided by the faraday cage
- Requires no change in standard operating practices
- No flashovers due to partial vacuum effect

*The following tables contain the raw data that the previous bar graphs were based on.*

## 25 kV 200A LOADBREAK
# *“ENHANCED SWITCHING”*

### *ELBOW*

### *“STANDARD EXISTING DESIGN”*

| LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Tested | Pass | % Pass |
| 14.4 | <3 | 49 | 49 | 100 |
| 14.4 | >3 | 52 | 52 | 100 |
| 27.5 | -20 | 24 | 14 | 58 |
| 27.5 | +20 | 12 | 12 | 100 |

## 25 kV 200A LOADBREAK

# *“ENHANCED SWITCHING”*

### *CAP*

### *“STANDARD EXISTING DESIGN”*

| LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Tested | Pass | % Pass |
| 14.4 | <3 | 44 | 38 | 86 |
| 14.4 | >3 | 55 | 55 | 100 |
| 27.5 | -20 | 11 | 1 | 9 |

## 25 kV 200A LOADBREAK

# *"ENHANCED SWITCHING"*

***ELBOW***

***"INCREASED VOLUME DESIGN"***

| LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Tested | Pass | % Pass |
| 14.4 | <3 | 95 | 95 | 100 |
| 14.4 | >3 | 57 | 57 | 100 |
| 27.5 | -20 | 21 | 10 | 48 |

# 25 kV 200A LOADBREAK
# *"ENHANCED SWITCHING"*

## *CAP*

## *"INCREASED VOLUME DESIGN"*

| LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Tested | Pass | % Pass |
| 14.4 | <3 | 74 | 74 | 100 |
| 14.4 | >3 | 45 | 45 | 100 |
| 27.5 | -20 | 20 | 8 | 40 |

## 25 kV 200A LOADBREAK

# *“ENHANCED SWITCHING”*

### *ELBOW*

### *“ENHANCED SWITCHING DESIGN”*

| LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Tested | Pass | % Pass |
| 27.5 | -20 | 20 | 20 | 100 |
| 27.5 | +20 | 12 | 12 | 100 |

## 25 kV 200A LOADBREAK

# *"ENHANCED SWITCHING"*

### *CAP*

### *"ENHANCED SWITCHING DESIGN"*

| LOW CURRENT SWITCHING RESULTS | | | | |
|---|---|---|---|---|
| Test Voltage Line-to-Ground kV | Test Temperature °F/°C | Tested | Pass | % Pass |
| 27.5 | -20 | 12 | 12 | 100 |
| 27.5 | +20 | 12 | 12 | 100 |

## 25 kV 200A LOADBREAK
## *“ENHANCED SWITCHING”*

*PROBLEM:*

- The IEEE 386 200A load switching test does not detect the partial vacuum failure mode.

*WHY:*

- Freshly lubricated interfaces
- Trapped pressure inside elbow on Make operation
- Break operation performed within minutes after Make

# 25 kV 200A LOADBREAK ELBOW
# and
# INSULATED PROTECTIVE CAP

***TRAPPED AIR PRESSURE (psig)***

***MAKE OPERATION***

| | MEAN | MIN | MAX |
|---|---|---|---|
| Elbow | 10.7 | 9.4 | 13.8 |
| Cap | 10.5 | 9.6 | 13.4 |

***PRESSURE DECAY RATE***

%Initial Pressure = 100% e (.0075$^t$)

$^t$=time after installation

# 25 kV 200A LOADBREAK
# *“ENHANCED SWITCHING”*

## *INSULATED INSERT & PROBE DESIGN*

## *“QUALIFICATION”*

| • IEEE 386-1995 TESTS | SECTION |
|---|---|
| *DIELECTRICS* | |
| Corona | 7.4 |
| AC Withstand | 7.5.1 |
| DC Withstand | 7.5.2 |
| Impulse Withstand | 7.5.3 |
| *THERMAL* | |
| Short-time Current | 7.6 |
| Current Cycling-Accelerated | 7.10.1 |
| Current Cycling-Off Axis | 7.10.2 |
| *MECHANICAL* | |
| Operating Force | 7.14 |
| Pulling Eye | 7.15 |
| *OPERATING* | |
| Switching | 7.7 |
| Fault Close | 7.8 |