SAND2019-6635C

Sandia National Laboratories

Physical processes of insulating liquid conduction in high DC electric field

Michael G. Mazarakis, Mark L. Kiefer, Joshua J. Leckbee,

Sandia National Laboratories

Albuquerque, NM 87185

Del H. Anderson, Frank L. Wilkins, Robert J. Obregon

National Security Technologies

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Abstract

- In the power grid transmission where a large amount of energy is transmitted to long distances, High Voltage DC (HVDC) transmission of up to 1MV becomes more attractive since it is more efficient than the counterpart AC. However, two of the most difficult problems to solve are the cable connections to the high voltage power sources and their insulation from the ground. The insulating systems are usually comprised of mineral oil and solid insulators. The oil behavior under HVDC is similar to that of a weak electrolyte. Its behavior under HVDC is more dominated by conductivity than dielectric constant. Space charge effects in the oil bulk and near high voltage electrodes and plastic insulators affect the voltage oil hold-off

Sandia National Laboratories

Experimental setup

- **We have constructed an experimental set-up to study the mineral oil and oil plastic interface behavior under high DC electric field stresses.**

Experimental set up

- The apparatus is composed of four oil cylinders. The #1 and # 2 contain one switch each. The third cylinder contains a resistive load.
- The fourth cylinder

(not shown in the photo) contains an isolation resistor to isolate the High Voltage DC power supply from the rest of the system.

- Two hydraulic tables

can move up and down the cylinders for system maintenance.

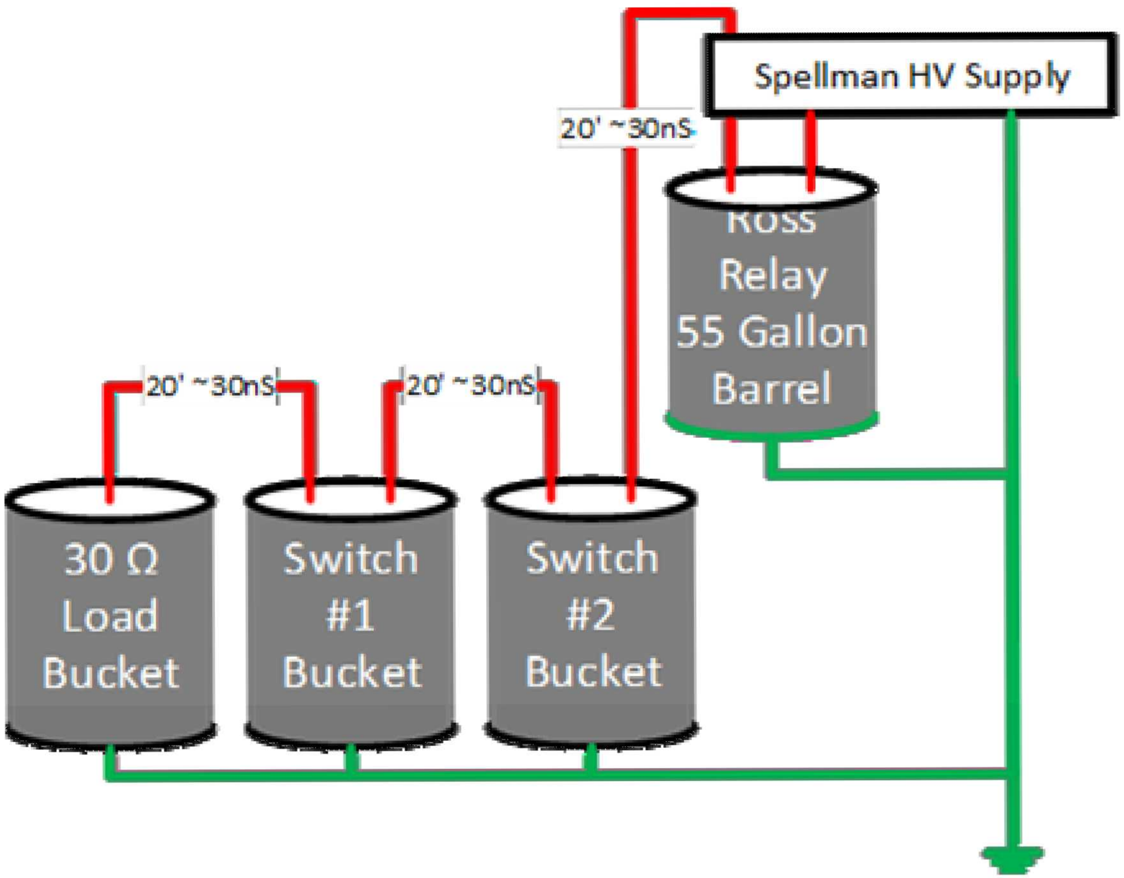
Set up top view

Sandia National Laboratories

CTS (cylinders lowered)

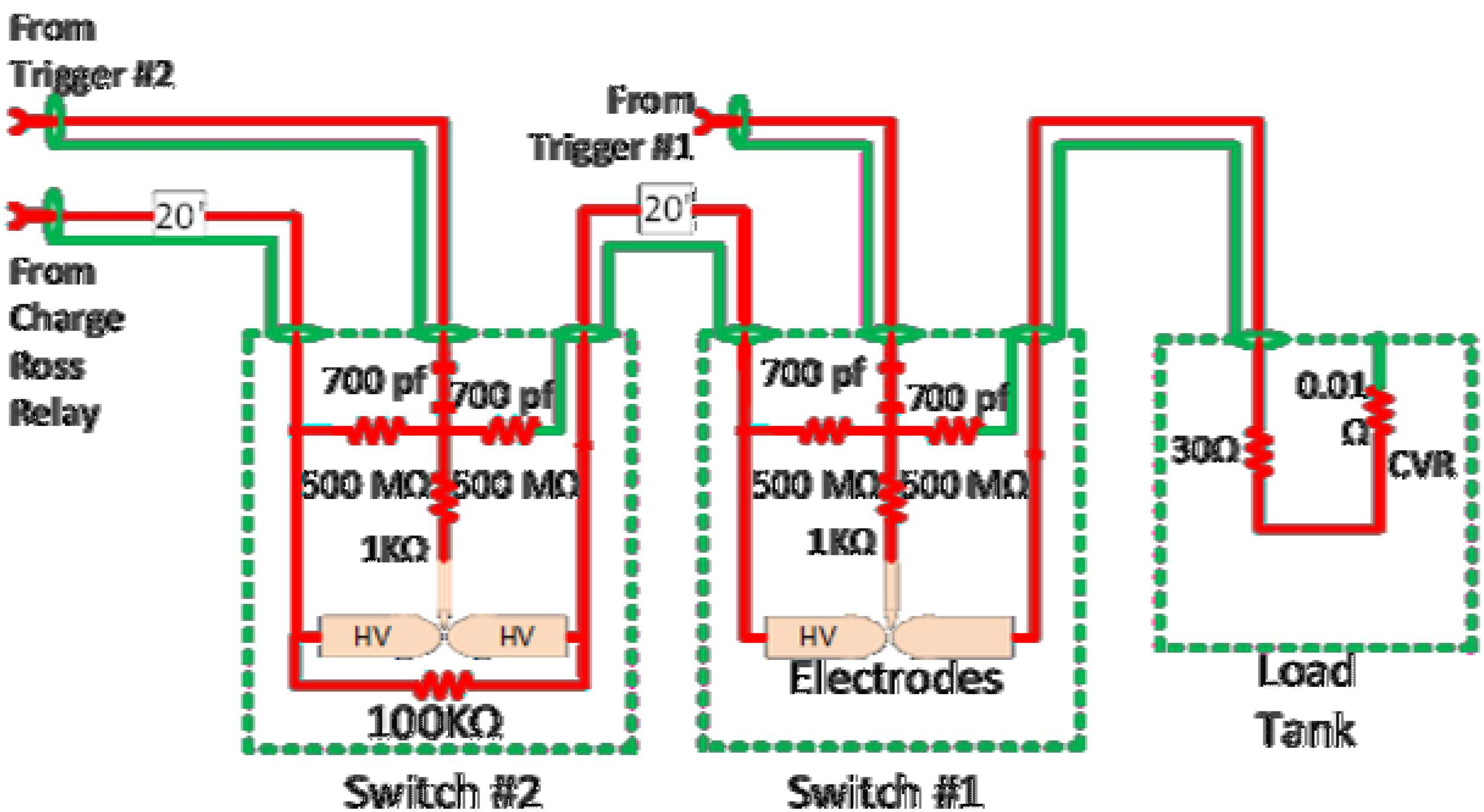
The switches and the cable feed-through are permanently attached to the top lids and immersed into the liquid insulator (mineral oil), high voltage of up to 200kV is applied across the switches. The electric fields across the switch is 160kV/cm and of the order of 20kV/cm between the high voltage cable guide and the can walls (ground). The switches when triggered help to discharge the cables. Thus we can vary the time that the cable guides and oil are under stress.

Block diagram of the high voltage set up.



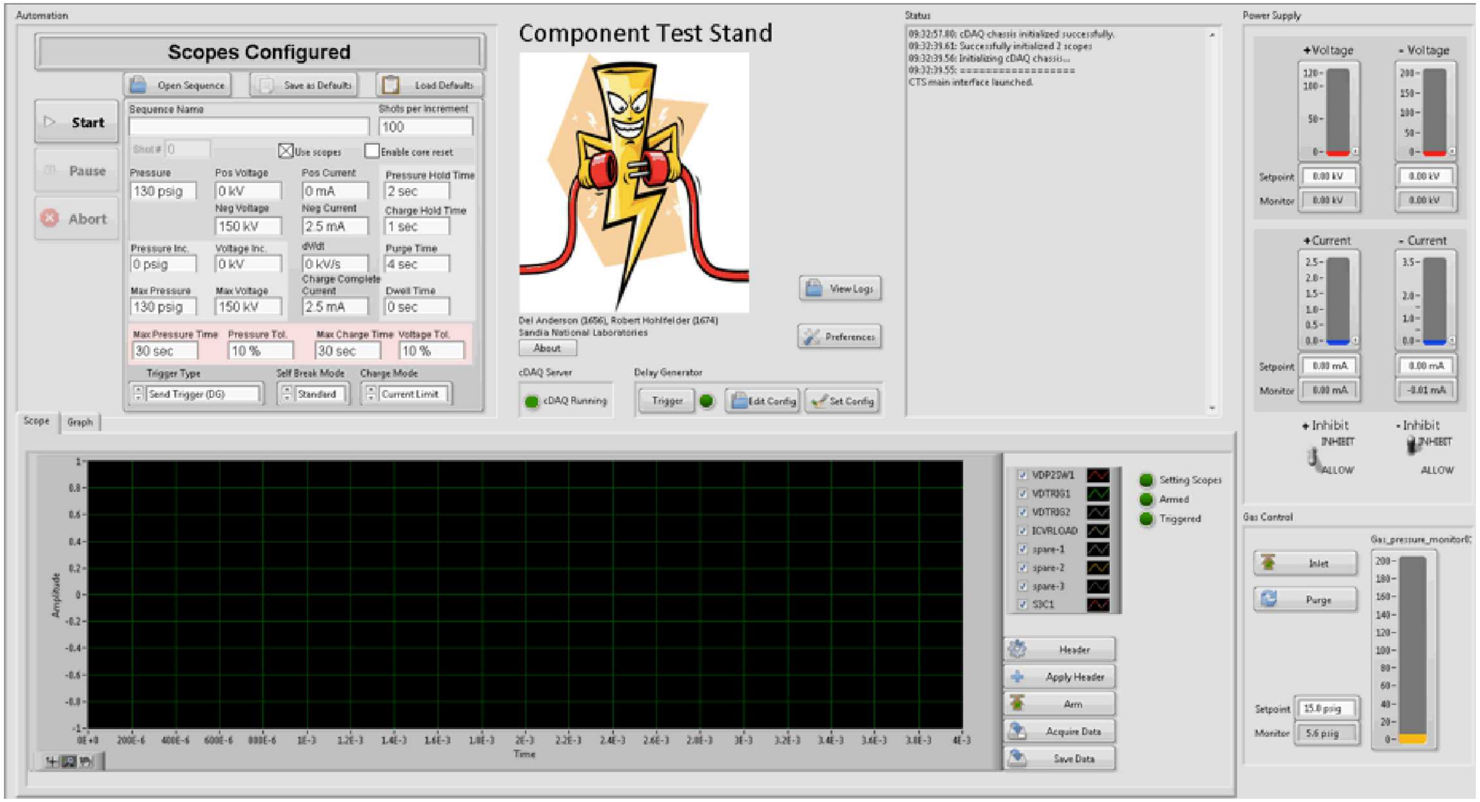
Sandia National Laboratories

Actual electric circuit of the high voltage set up.



Sandia National Laboratories

Automation control panel. We can fire the test stand with a rep rate of up to 6 shots per minute

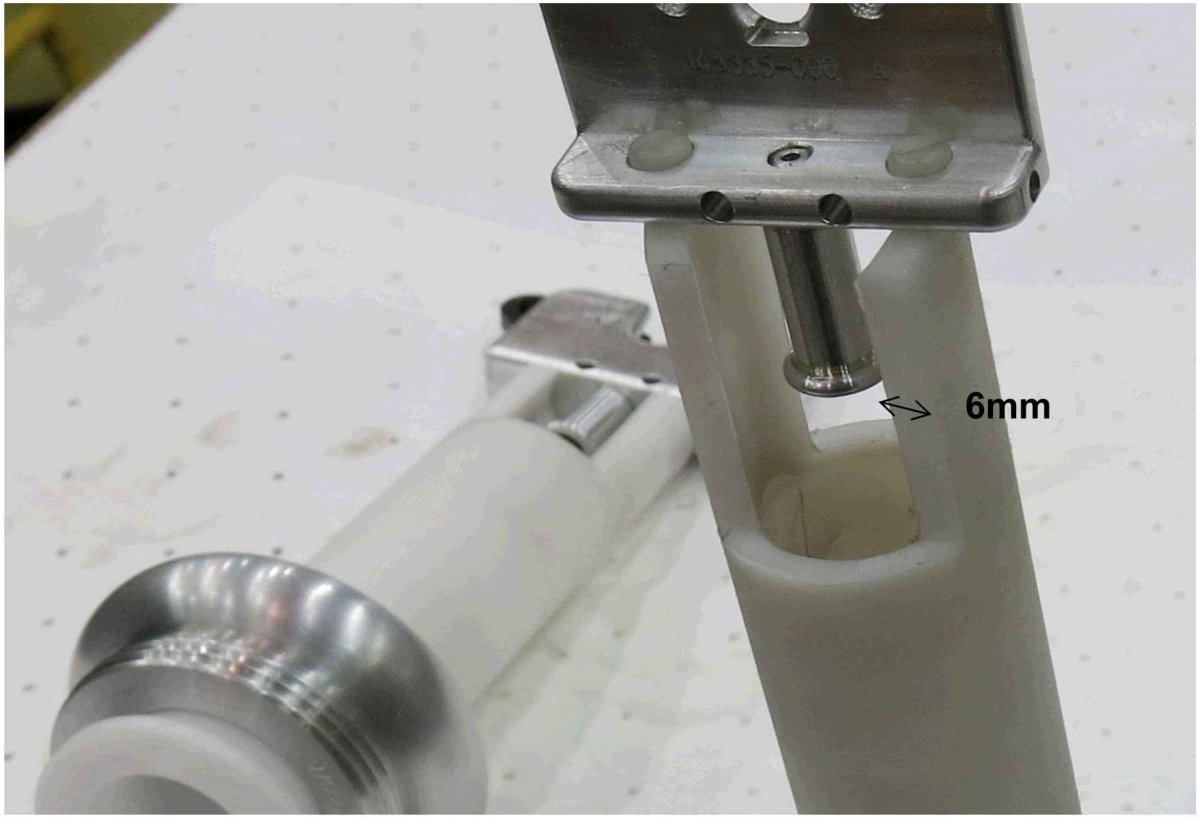


CTS (cylinders lowered)

At the beginning we used 6.12 mm thick polyethylene cylindrical cable guides. The guides were tracking at 170kV charging during 120 ns pulse duration and 1 second inter-pulse separation. We increased the inter-pulse separation to 10 s, and we succeeded into firing 1,500 shots at 170 kV without any arcing through the cable guide or the oil (space charge effect ?).

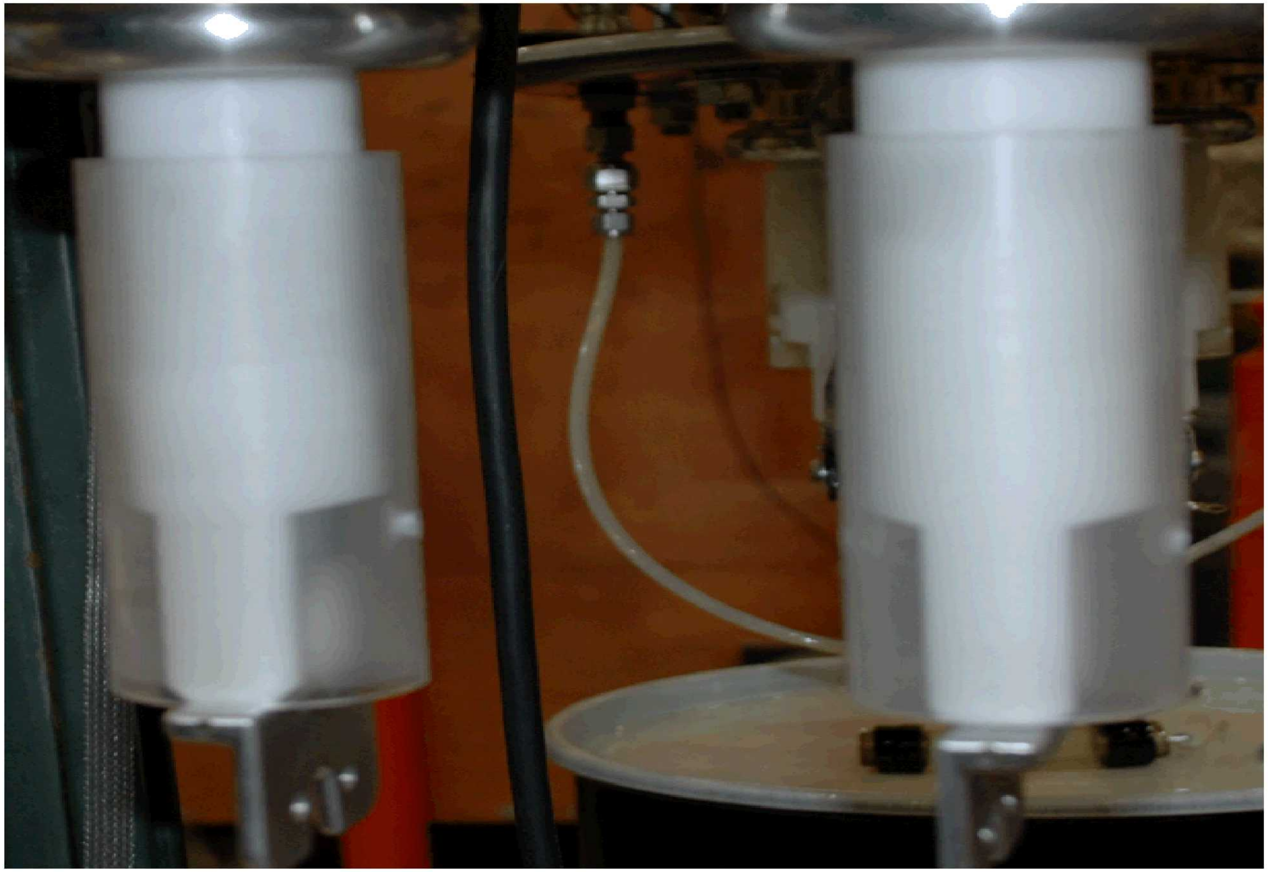
Sandia National Laboratories

First 6mm thick cable guide utilized



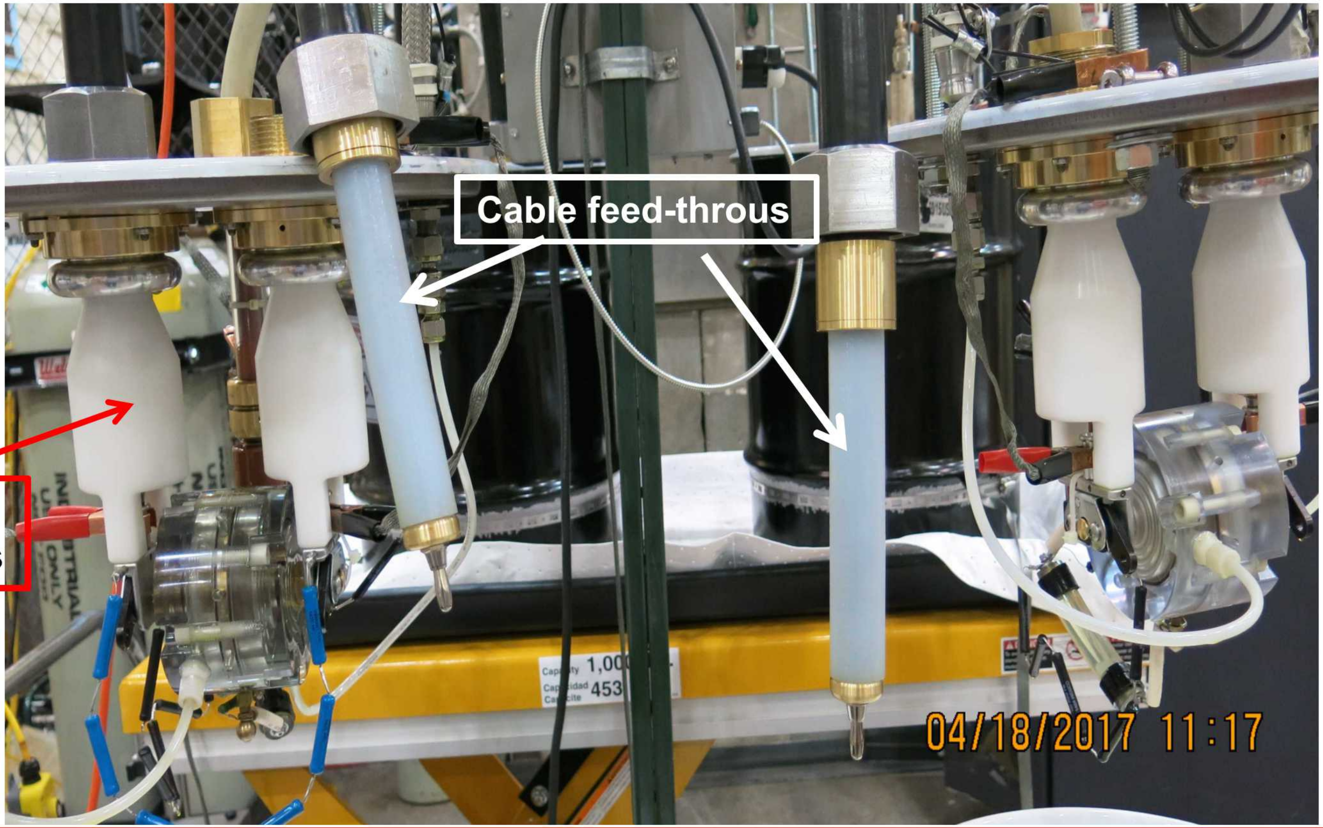
There was a ~3mm gap filled with oil between the plastic insulation of the cable and the cable guide.

A 4.30 mm acrylic sleeve was added to the previous cable guide to strengthen it electrically.



However, now we were arcing and punching holes through the sleeve instead of the cable guides.
Again an oil gap was between the cable guide and the sleeve.

This is the newest design that was proven very successful in holding 200kV without arcing.



Increasing the thickness of the cable guide to 17.51 mm enable charging to 200kV without cable or guide insulation damage . We fired ~ 400 shots at 200kV (10kV/cm) without arcing.

Sandia National Laboratories

One of the new cable guide design

- **With this cable guide we successfully fired four cable guides, (two switches) for 714 shots at 170kV, 550 shots at 180 kV, 528 shots at 190kV and 408 shots at 200kV with no arcing problem.**

Sandia National Laboratories

Experimental observations

- Our observations are suggestive and consistent with the following assumptions:
- 1- While solid insulators have, at room temperature, a negligible conductivity for most practical purposes, dielectric liquids always retain a considerable one [1].
- 2- Because of the oil conductivity, charge carriers accelerated by the electric field pile up close to the metal or solid insulators and generate space charge areas of opposite than the applied electric field polarity, which effectively cancelling the electric field inside the oil

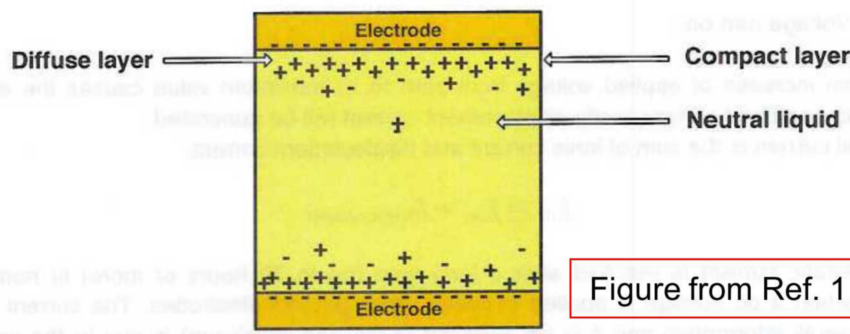
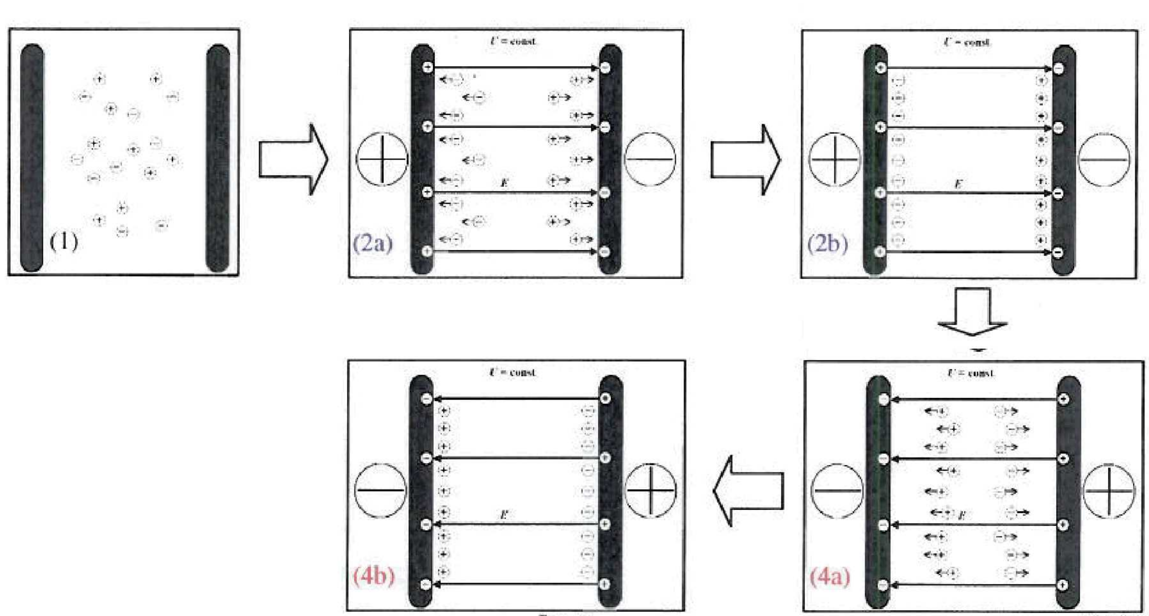


Figure from Ref. 1

In our applied field strengths the carriers remain close to the electrodes and do not get neutralized.



Polarity reversal experiments demonstrated that the charge carriers in insulating oil drift and form space charge zones adjacent to the electrodes. (Ref.2)

An immersed solid insulator in the oil must be thick enough to withstand the entire applied field.

- **In a DC situation the entire applied electric field is concentrated inside the plastic insulator wetted from both sides of its surfaces by oil. This is why we tracked the thinner cable guides and the thin sleeves. Hence, any plastic insulator immersed in a insulating mineral oil (transformer) must be thick enough to withstand the entire applied DC electrical field without arcing through its volume.**

Thin wall plastic tracked

Thicker wall plastic survived

Sandia National Laboratories

Source of conductivity of an insulating liquid

- The conductivity of the insulating oil has being studied for many years. The present understanding is as follows:
- The conduction of the weak electrolytes, like oil, is due to two physical processes: a) electrolytic dissociation of the liquid itself and b) carrier injection at liquid - electrode interface. The conductivity also strongly depends on the mobility and diffusion of the generated charge carrier species. It is non linear and varies with the applied electric field.

  Space charge in the bulk and also near the electrodes affects the conductivity.
  - a) Charge carriers in low permittivity liquids are produced from the neutral molecules M of the liquid bulk in two step process: ionic dipole formation C^+A^- and then dissociation:

$$M \rightleftarrows C^+A^- \rightleftarrows C^+ + A^-$$

Free ions are continuously being generated from the dissociation of the ionic pairs,

and conversely , ionic pairs are formed by the recombination of ions.

Neglecting diffusion, the conductivity can be expressed by the equation:

$$\sigma = \Sigma_i (\mu_i . q_i)$$

where q_i is the charge density of the ionic species and μ_i their mobility.

Sandia National Laboratories

Negative and positive electrode-liquid injection

- b) When a negative ion is injected, an electron- accepting species must be present and should first get adsorbed on the cathode surface. Then an electron can tunnel to the adsorbed molecule, converting it to negative ion. This ion, however, is not free to escape into the bulk of the liquid since it is strongly bound by the image force. So a Helmholtz charge double layer is created.
- The electric field inside the double layer could be much higher than the externally applied field, causing tracking of the insulator surface. Thus carrier injection obeys Boltzmann' statistics.
- Therefore there is not direct electron emission into the oil. Namely at the cathode, a molecular species M could undergo the simplest reduction process : $M + e \rightarrow M^-$ giving rise to a negative radical ion. This process should not be confused with electron emission since positive injection is as frequent as negative one:

$$C_n(OH_2)_m \rightarrow e + H^+ + C_n(OH_2)_{m-1} + OH^-$$

Sandia National Laboratories

Summary

- We have extensively utilized the CTS to investigate the solid plastic insulators behavior while immersed in an HVDC stressed oil.
- It appears that the entire applied electric field is concentrated inside the plastic.
- The oil charge carriers concentrate near the plastic surfaces, generating space charge domains which cancel to a certain degree the electric field in the oil bulk.

Sandia National Laboratories

References

1.-Measurement of ion mobility in dielectric liquids, Mohsen S. Zadeh. Sciences Thesis Chalmers University of Technology, Goteborg, Sweeden, 2011.

2.-Interaction of Oil Ducts and solid Insulation in HVDC Barrier Systems. M. Liebschner, A. Kuchler, Ch. Krause, B. Heinrich, C. Leu and F. Berger. In Proceeding of the 16th Symposium on High Voltage, ISBN 978-0-620-44584-9.

3.-Oil Conductivity-An Important Quantity for the Design and the Condition Assessment of HVD Insulation Systems. Fabian Schober, Andreas Kuchler and Christoph Krause, in FHWS SCIENCE JOURNAL, VOL1, No 2, 2013.

Sandia National Laboratories