Characterization of the Electrical Properties of Contaminated Dielectric Oils for Pulsed Power Research

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1. Abstract

The Z-machine at Sandia National Laboratory uses pulsed power to study magnetized inertial confinement fusion. In the Energy Storage Section of this apparatus, the high-voltage capacitors that store electrical charge are submerged in an insulating oil (Shell Diala S2 ZX-A) to minimize thermal and electric losses before and during system operation. Shell Diala S2 ZX-A has a density of 890 kg/m^3 and is classified as a mineral oil. [1] Over time this oil becomes contaminated with both dielectric breakdown byproducts resulting from high-voltage "flash-over" discharges and extrinsic contaminants (atmospheric moisture and dust particles) introduced into the oil during maintenance and cleaning activities. The effect of these contaminants on the electrical properties of Shell Diala S2 ZX-A was evaluated using impedance spectroscopy measurements over a frequency range of 50 μHz – 5 MHz along with DC-regime measurements of resistivity and current flow. Oil samples exposed to electrical arc discharges were treated with either activated carbon or molecular sieve (13X) to remove dielectric breakdown contaminants; the absorbents in turn were removed by centrifugation followed by syringe-filtration through a submicron particle membrane filter. The electrical properties and transmittance spectra of both the contaminated and purified oil samples were analyzed and compared to similar data collected on pure oil samples that had never been subjected to arc discharge. The impedance spectroscopy results show that the oils contaminated with breakdown byproducts have both a higher dielectric constant and a higher loss factor across a wide frequency range, which suggests significant degradation in the insulating property of the oil. Both the DC resistivity measurements and the transmission spectra of the oil samples purified with absorbents showed recovery of the samples' dielectric and spectroscopic properties to values roughly equivalent to those of the original pure material. Molecular sieve showed superior efficiency to activated carbon in purifying the oil,

suggesting that the contaminants are primarily charged particles. This work will provide the framework for future studies on characterizing the electrical properties of insulating oil directly from the Z-machine and on developing *in-situ* continuous purification systems for contaminated insulating oil.

2. Introduction

The Z-machine is a pulsed power machine at Sandia National Laboratory in Albuquerque, New Mexico (Fig. 1). This powerful machine is being used to study the uses of pulsed power, such as nuclear weapons research and fusion energy. Pulsed power is the intense release of electrical energy over an extremely short period of time.

Each pulse generated by the Z-machine lasts 100-300 nanoseconds, and produces more than 80 trillion Watts of power. Before the apparatus fires, its capacitors charge to store around 20 Megajoules of energy [Fig. 1(a)]. These capacitors are submerged in 540,000 gallons of Shell Diala S2-ZX-A insulating oil in order to minimize thermal and electrical losses before the machine is fired [Fig. 1(b)].

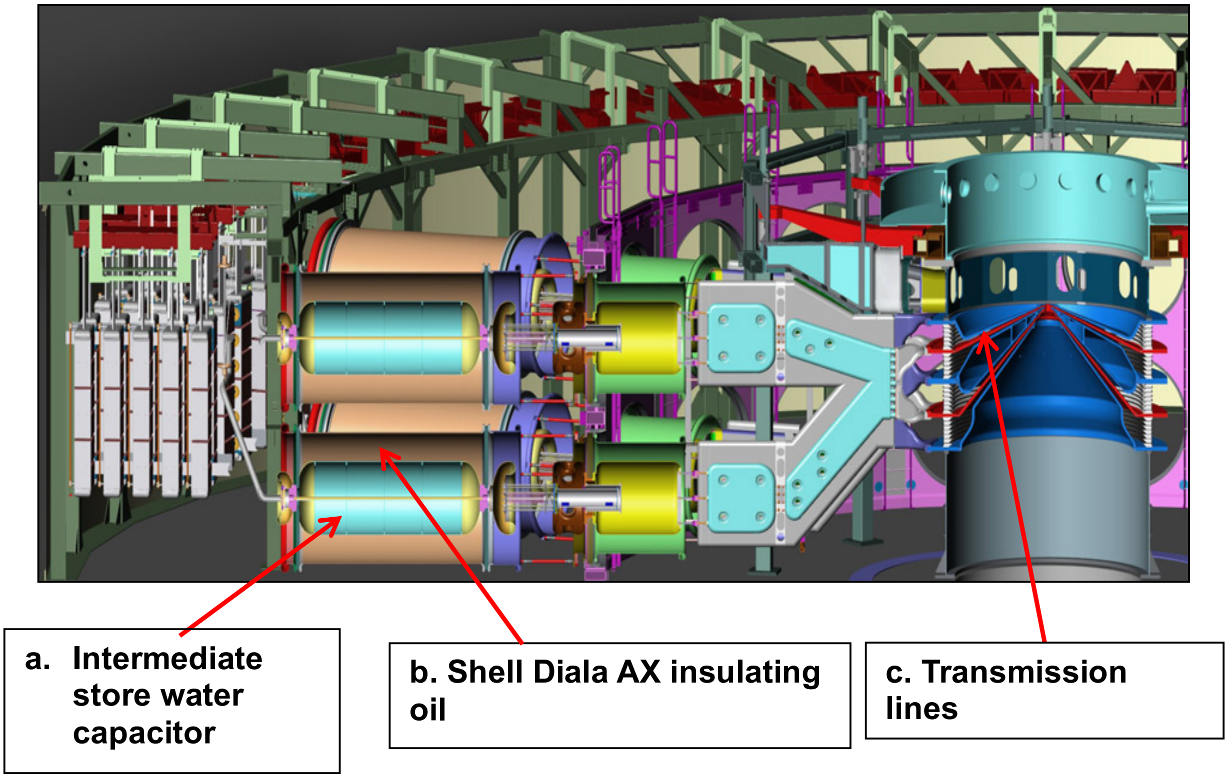


Fig. 1: A cross-sectional diagram of the Z-machine. The total diameter of the apparatus is 34 meters. [2]

Inside the vacuum chamber of the Z-machine, the electrical pulse is discharged through hundreds of parallel tungsten wires that transform into a plasma once the pulse arrives, creating a strong magnetic field that implodes the wire particles. These particles collide on the z-axis (which is where the instrument gets its name), producing intense amounts of radiation, pressure, and heat (up to 1.8 million degrees Celsius). As the collisions of the wire particles slow down, 2.7 million joules of x-rays are produced. [2]

The insulating oil used in the Z-machine becomes contaminated over time from both intrinsic and extrinsic sources. The 540,000-gallon insulating oil reservoir in the Z-machine is an uncovered tank and is susceptible to contamination through atmospheric moisture and dust from building access doors. Moisture can provide a low-resistance pathway for electricity through the oil, thus deteriorating the quality of the insulating oil. The cleaning process for the transmission lines [Fig. 1(c)] involves physical grinding, and occurs only 30 feet away from the oil tank, resulting in metal particles becoming airborne and landing in the oil tank, producing another low resistance avenue for electricity to take when escaping from the oil. [3]

Figure 2 shows a photograph of the Z-machine while in operation. Significant arcing, called "flash-over" discharge or breakdown, occurs in the insulation oil due to the sheer magnitude of current that is trying to escape (26 million amps). [2]

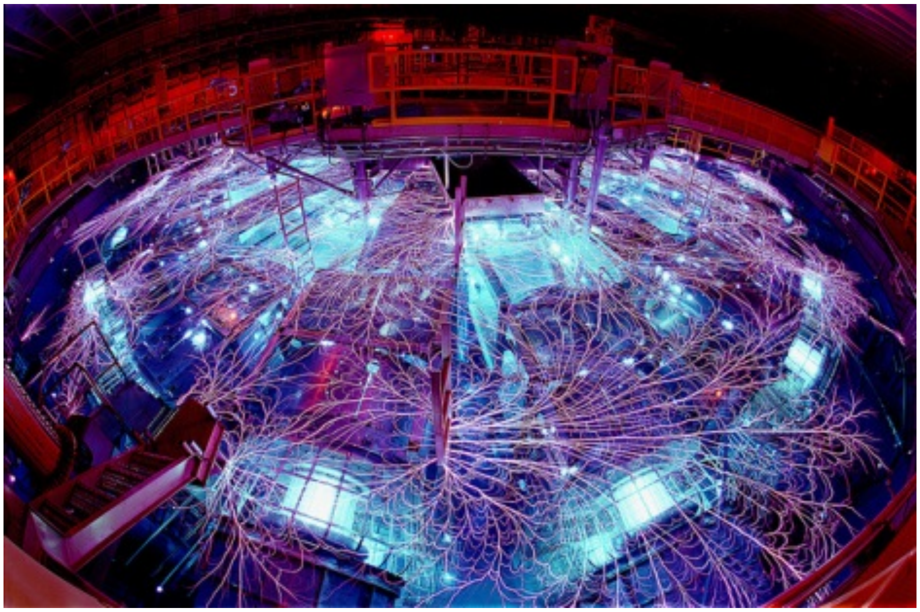


Fig. 2: An image of "flash-over" discharges in the Z-machine insulating oil. [2]

The goals of this work were to characterize the impact of breakdown products generated by dielectric discharge in the oil on the electrical properties of the oil and develop a scalable process suitable for *in-situ* continuous purification of the insulating oil for use in LLE's own pulsed power laboratory.

3. Theory

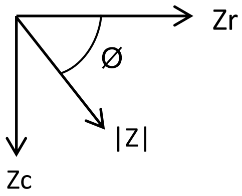
The process of dielectric breakdown produces various byproducts in the insulating oil, including hydrocarbon gases and polar compounds. When arcing occurs, a huge amount of energy is released and the hydrocarbon chains that make up the oil molecules are broken to produces gases such as hydrogen, methane, ethane, acetylene, and free carbon. Other breakdown contaminants include oxidation products, which pose a big problem to the function of the oil. Oxidation products can include organic carboxylic acids and formic acid, which decrease the surface tension of the oil and increase the number of bubbles. These bubbles can align between metal fragments and ionized particles to create a conductive bridge. Other common contaminants include dimethyl sulfide and ozone. All of these dielectric breakdown products that contaminate the oil have various impacts on the electrical properties of the oil such as resistivity, impedance, permittivity, dissipation factor, and dielectric constant. [4]

Resistivity (ρ) is a fundamental property of a material that describes its resistance to current flow (**Eq.1**). Unlike resistance, resistivity takes into account the properties of the material. [5]

$$\rho = \frac{AR}{l} \qquad \textbf{Eq. 1}$$

where *A* is the cross sectional area, *l* is the length and *R* is the resistance.

Impedance (***Z***) is the complex form of resistance that applies to AC circuits.[5] Impedance includes an imaginary component on the y-axis, a real component on the x-axis, and a phase angle. Ohm's law still applies to AC circuits, but resistance is replaced by impedance (**Eq. 2**). In order to find the magnitude of impedance, one can simply use the Pythagorean theorem (**Eq. 3**).



$$\boldsymbol{Z} = \frac{V}{I}$$ **Eq. 2**

$$|\boldsymbol{Z}| = \sqrt{{Z_r}^2 + {Z_c}^2}$$ **Eq. 3**

where V= voltage, I= current, |$\boldsymbol{Z}$|= magnitude of impedance, Z_r= real impedance (resistive), and Z_c= imaginary impedance (capacitive).

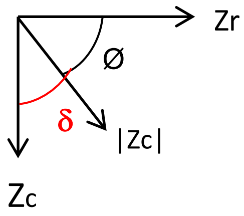
Capacitance (C) is the ability to store charge. A simple parallel plate capacitor contains two conductive parallel plates with a dielectric, or insulating material between the plates. The dielectric material polarizes when a voltage (V) is applied between the plates, pushing the positive charges (Q) to one plate and the negative charges (-Q) to the other (**Eq. 4**). The capacitor holds charge effectively when the dielectric material between the plates is a good insulator and doesn't allow the charges to migrate towards each other.[4] The capacitance of a parallel plate capacitor is shown in **Eq. 5**, where ε is the permittivity of the dielectric, A is the cross sectional area of the capacitor and d is the distance between the conductive plates. The extent to which the dielectric is a good insulator is given by its permittivity.

$$C = \frac{Q}{V}$$ **Eq. 4**

$$C_{parallel\ plate} = \varepsilon\frac{A}{d}$$ **Eq. 5**

The *dielectric constant* (K) of a material is the extent to which it concentrates electrical flux. A material with a higher dielectric constant can concentrate more charge. However, it is more likely to break down and thus is a poorer insulator than a material with a lower dielectric constant. The dielectric constant of a material can be calculated by dividing the capacitance of a parallel-plate capacitor containing the material by the capacitance of a capacitor with the same plate area and gap spacing but filled with air, with both measurements conducted at the same voltage and frequency.[5]

The *loss factor* (tan δ) is calculated using the complement of the phase angle of the impedance (**Eq. 6**). This value is commonly used in industry to characterize the condition of transformer oil. Usually, the tan δ of the oil is measured before use, and the deviation from this value is tracked and compared between batches to ensure that the oil has not deteriorated. In this experiment, impedance phase data was used to calculate and compare the tan δ values of the oil samples. The higher the tan δ of a material, the more energy loss occurs when a voltage is applied to the material, and the less effective is the material as an insulator.[5]



$$\text{Loss Factor} = \frac{Z_r}{Z_c} = tan\delta$$

Eq. 6

where δ = complementary angle to phase angle ϕ.

In theory, the electrical properties of the oil responsible for its insulating ability should change measurably as the oil becomes contaminated with breakdown contaminants. Measuring these properties will corroborate the widely held view that breakdown products are indeed responsible for deterioration of the oil's insulating capability with time.

4. Experimental Methods

All experiments were conducted on three samples of Shell Diala S2-ZX-A insulating oil [Fig. 3(a)] that were subjected to a high voltage discharge using a 50 kV Tesla coil with a 1mm spark gap for 0, 5, and 20 minutes [Fig. 3 (b)]. A pure sample of the oil that had not been subjected to dielectric discharge was used as a control sample.

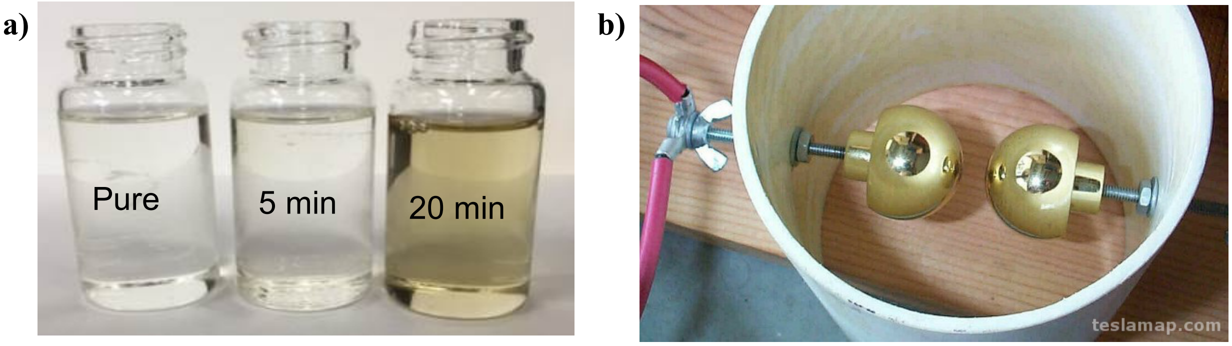


Fig. 3: (a) Two Shell Diala S2-ZX-A oil samples subjected to dielectric discharge for 5 min and 20 min compared to a sample of the pure material; darkening of the oil due to contamination is clearly evident. (b) Tesla coil setup that was used for the dielectric breakdown experiments; the spark gap is the distance between the two plates. [6]

4 (a) Impedance spectroscopy measurements

A Solartron 1260 Impedance/Gain-Phase analyzer with a Solartron 1296 Dielectric Interface and Solartron 12962 sample holder (Fig. 4) was used to collect impedance spectroscopy data on both the pure oil and the samples exposed to high voltage arc-discharge (5 min and 20 min) to determine a relationship between various electrical properties (dielectric constant and tan δ) and level of dielectric breakdown products. Both instruments were connected to a computer that used the SMaRT impedance software package from Ametek for data collection and processing. The measurement time was dependent on the range of frequencies over which the instrument was programmed to sweep; the lower the minimum frequency and the larger the range, the longer the measurement duration. Typical impedance spectroscopy scans for the oil samples were collected over a frequency range of 50 μHz to 5 MHz; each measurement took ~44 hours to complete.

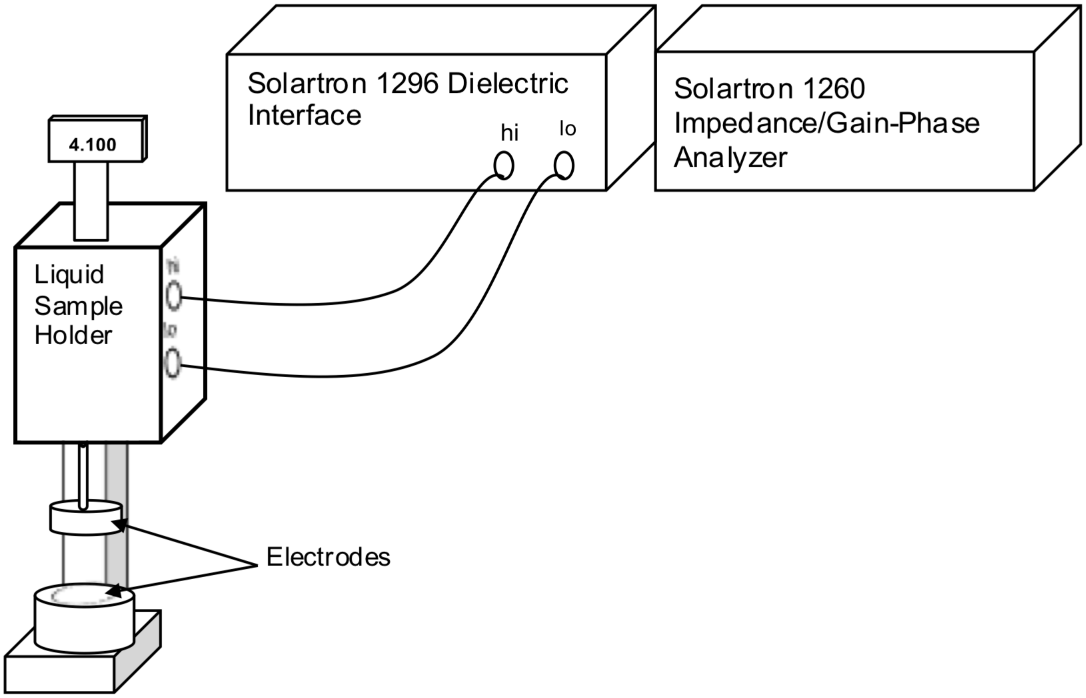


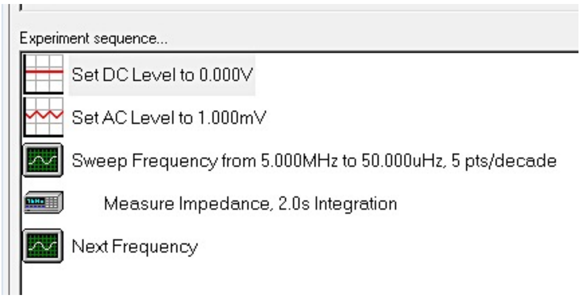
Fig. 4: Setup of the impedance spectroscopy instrumentation experiments. The instrument can sweep a maximum frequency range of 10 μHz to 5 MHz, measure impedance values from 100 Ω to 100 TΩ, and measure capacitance values from 1 pF to 0.1 F.

The instrument was checked for proper functionality by conducting frequency response analysis on a sample of deionized water, calculating its dielectric constant, and comparing the result to published literature values. The dielectric constant was determined by dividing the measured capacitance of deionized water at 100 KHz by the capacitance of the empty sample holder (air) determined at the same frequency and electrode gap setting. The accepted value for water at 100 kHz is 78 and the calculated value from the measurements was 76, which implies that the apparatus was working correctly.[7]

Prior to conducting measurements on the oil samples, the sample chamber and components (bottom electrode, guard ring, top and bottom surface of the mobile high electrode) were carefully wiped several times with methanol. The sample chamber was then wiped down with detergent, rinsed with deionized water and allowed to dry for two hours inside an incubator (Fig. 5) set to 40 ^{O}C.

Fig. 5: Incubator used to dry the Solartron sample holder assembly at 40 ^{O}C.

After removing the sample holder from the incubator and allowing it to cool to room temperature, ~3 mL of the oil sample was transferred to the sample cell using a pipette. The mobile high electrode was lowered down towards the sample until the cell gap distance displayed on the sample holder scale was 4.100 mm. After allowing the sample to equilibrate in the sample holder for 0.5 to 0.75 hrs for temperature stabilization and to ensure the removal of any trapped air bubbles, the sample holder's high and low electrode ports were connected to the corresponding ports on the impedance analyzer, using the shortest possible wires to avoid stray impedance contributions. Figure 6 shows a screen shot of the measurement sequence used in the SMaRT software to acquire the impedance data.



Experiment sequence...

Set DC Level to 0.000V

Set AC Level to 1.000mV

Sweep Frequency from 5.000MHz to 50.000uHz, 5 pts/decade

Measure Impedance, 2.0s Integration

Next Frequency

Fig. 6: Screen capture of the experiment sequence programmed with SMaRT for impedance data acquisition. The two-second integration period refers to the amount of time the instrument took to normalize the data for each measurement.

4(b) DC resistivity measurements

A Keithley Electrometer model 619 connected to a Yellow Springs Instruments Model 3403 conductivity probe with a cell constant of 100/m was used to determine the DC resistivity (Fig. 7). The electrometer measurement range is from 0.1 Ω to 200 GΩ. The probe leads were connected to the electrometer leads and secured with insulating tape. The instrument's functionality was verified by measuring the resistivity values for isopropyl alcohol and acetone (Table 1). The probe was cleaned using methanol and deionized water, followed by drying in the incubator for 1-2 hours. The resistivity of the sample was calculated by dividing the measured resistance by the cell constant.

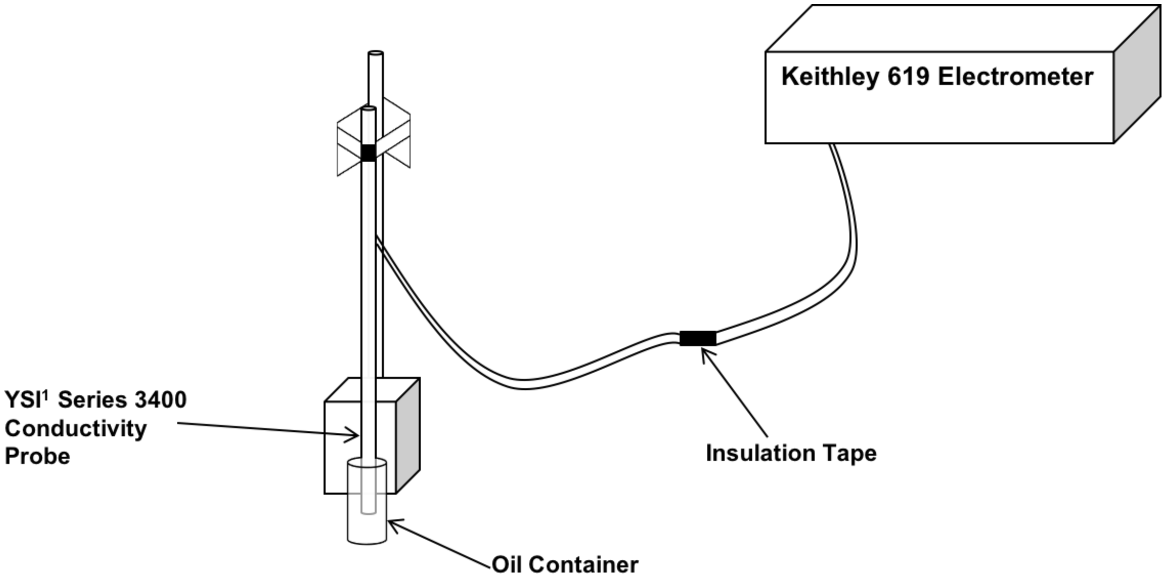


Fig. 7: Setup used to measure the resistivity of the various oil samples.

Data Source	**Acetone**	**Isopropyl Alcohol**
Measured	7.65 X 10^6 Ω-m	1.50 X 10^5 Ω-m
Literature	5.00 X 10^6 Ω-m	1.67 X 10^5 Ω-m

Table 1: Verification testing of the resistivity setup. Literature data was taken from material data sheets. [8] [9]

To minimize sensitivity of the probe and electrometer to vibrations, foam squares were cut and put under the four corners of the electrometer housing, the probe holder stand and the lead connections. For each measurement, ~16 ml of sample was used in a 25 ml glass vial. The probe was immersed in the sample until the bottom of the probe was ~ 3.5 cm above the bottom of the sample vial. A metal stand with a clamp was used to secure the probe in position during the measurement.

4(c) Transmittance measurements

An Agilent 8452 diode array spectrophotometer was used to measure the transmittance spectra of the oil samples. Sample measurements were conducted using a 1 cm path length fused silica cuvette.

4 (d) Purification process

Shell Diala S2 ZX-A oil samples exposed to high voltage discharge for 20 min were used for all of the purification process testing and development. Type 13X molecular sieve was used without activation as supplied by Chemicals Dynamics Corporation; Norit activated carbon was obtained from the University of Rochester Chemistry Department. Test samples were prepared by dispersing ~10 wt % of either molecular sieve or Norit in ~20 ml of oil in a Teflon beaker. The initial dispersion was conducted by hand using a spatula, followed by high-shear mixing using a Dremel Moto Tool equipped with a saw-tooth dispersion blade at 4000 rpm for 1 min. (Fig. 8).

Fig. 8: Dremel Moto tool setup used for high-shear dispersion of absorbents into the oil samples.

Following high-shear dispersion, the absorbent was separated from the oil sample by centrifugation at 3300 rpm for 4 min using a Fisher Scientific Centrific Model 228 centrifuge [Fig. 9(a)]. An identical weight of sample was transferred to each tube and the two tubes were placed opposite each other in the centrifuge rotor to eliminate vibration during the centrifuging process. For Norit-containing samples, it became necessary to centrifuge the sample an additional 2 min at 3300 rpm to eliminate the very fine black particles that remained suspended in the oil sample [Fig. 9(b)]. Remaining ultrafine suspended particles were removed by filtration of the oil sample through a 0.2 μm disposable PTFE membrane syringe filter (0.2 μm pore size) fitted to a glass syringe [Fig. 10].

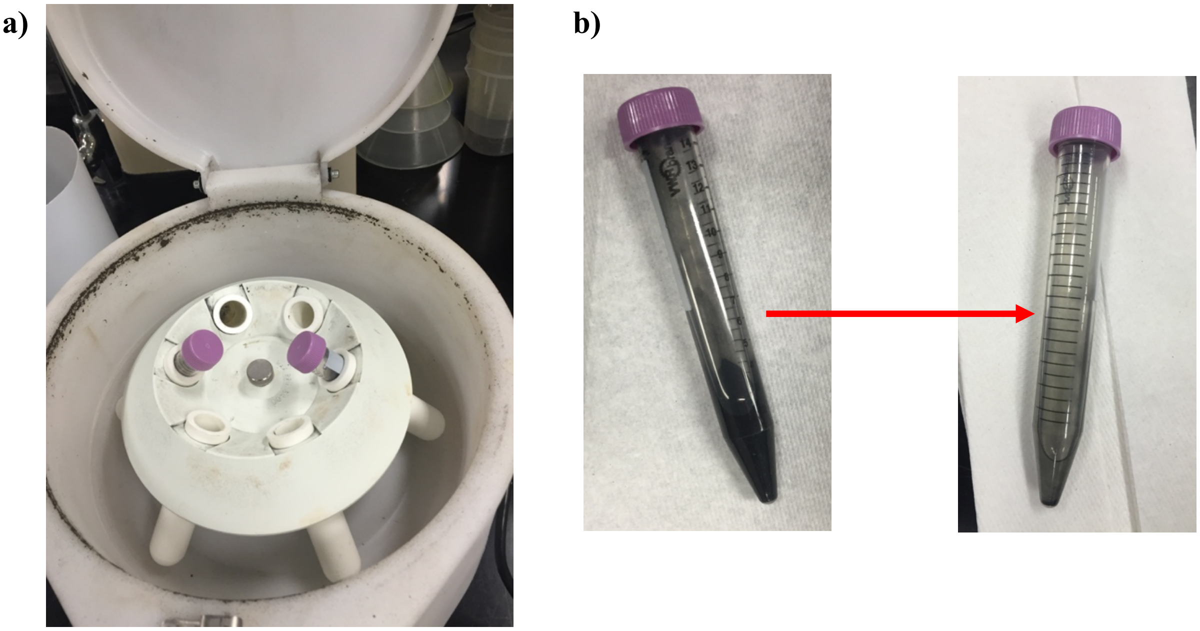


Fig. 9: Centrifuge used for bulk removal of absorbent from the oil samples. (a) Centrifuge rotor showing two centrifuge tubes containing identical weights of sample; (b) *Left:* Norit/oil sample after the first centrifugation step; note the large mass of Norit at the bottom of the tube. *Right:* centrifuge tube shown on the left after the oil sample was poured out. Fine particles of Norit such as those clinging to the walls still remained dispersed in the oil, requiring a second centrifugation step.

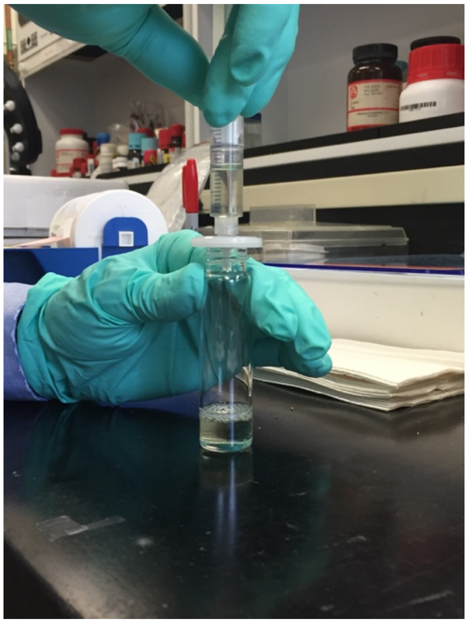
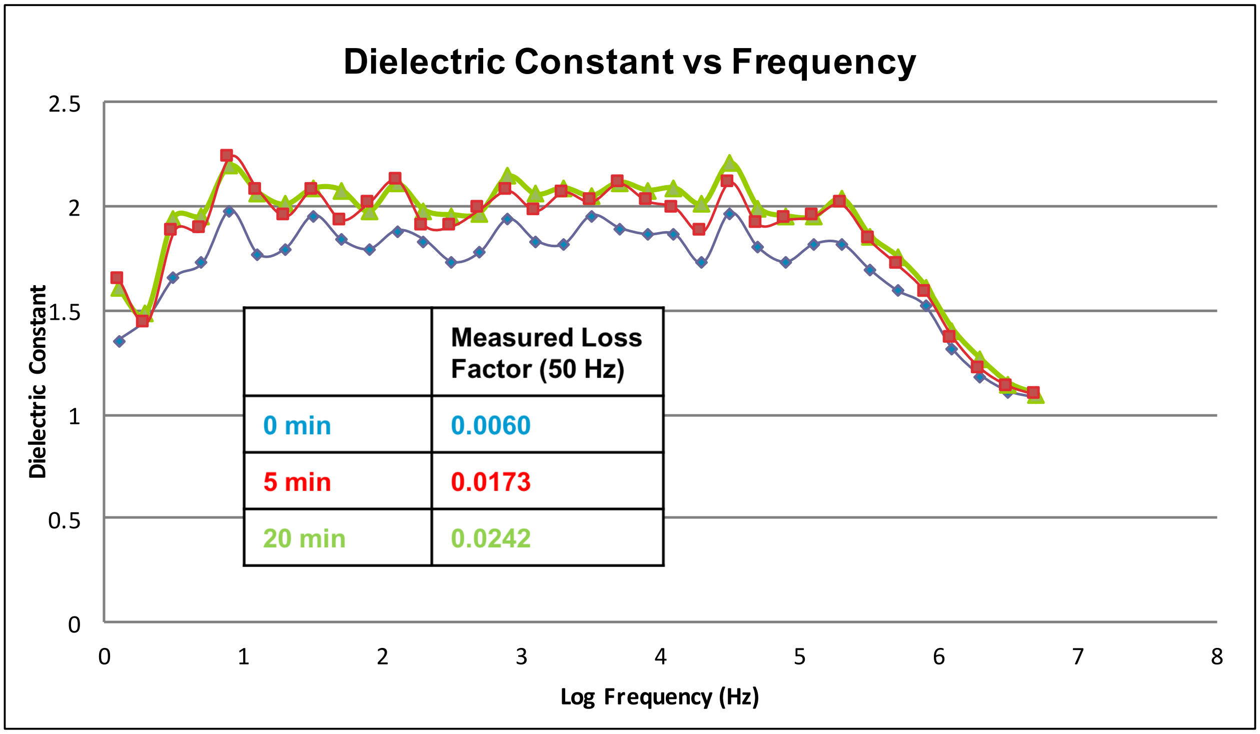


Fig. 10: Syringe filtration of a molecular sieve/oil dispersion through a disposable 0.2 μm Teflon membrane filter.

5. Results and Discussion

5 (a) Impedance measurements

Figures 11 and 12 present electrical properties data obtained from impedance spectroscopy measurements taken on the contaminated insulating oil samples over a frequency range of 50 μHz to 5 MHz. The presence of dielectric breakdown products in the Shell Diala S2-ZX-A oil increases its dielectric constant in the high frequency range (from 1 Hz to 5 MHz); the presence of these dielectric breakdown products increases the loss factor (tan δ) of the oil at 50 Hz (Fig. 11).



	Measured Loss Factor (50 Hz)
0 min	0.0060
5 min	0.0173
20 min	0.0242

Fig. 11: The dielectric constant vs log of the frequency and the loss factor (tan δ) data collected by impedance spectroscopy for samples exposed to dielectric discharge for 0, 5, and 20 min.

An analysis of the results in Fig. 11 shows that the dielectric constant of the contaminated insulating oil is increased at high frequencies, which indicates that dielectric breakdown products increase the conductive nature of the insulating oil. For the low frequency range (<10 Hz, Fig. 12), no significant trends are discernible due to noise in the data. The higher tan δ of the contaminated oil indicates that breakdown products increase the amount of energy loss in the oil. The corroboration between both these trends confirms that dielectric breakdown products decrease the functionality of insulating oil.

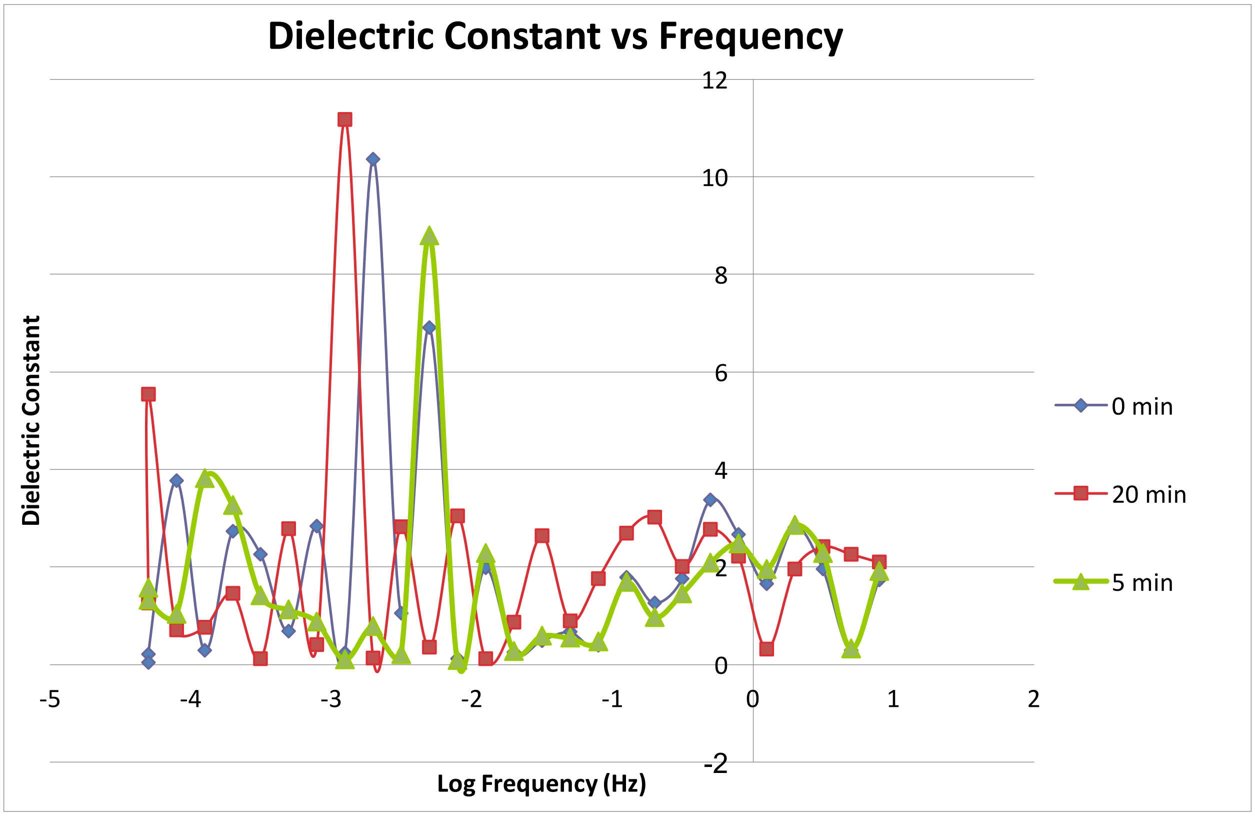


Fig. 12: Dielectric constant versus Log Frequency in the low frequency range (<10 Hz). No consistent trend is observed when compared to the high frequency range data in Fig. 11.

Impedance spectroscopy is also useful in obtaining the complex impedance plot (Fig.13), where the real impedance component of the sample is plotted on the x-axis and the imaginary impedance component is on the y-axis. Each curve in Fig. 13 represents a locus of impedance values for each of the three oil samples obtained during the frequency sweep. The positive x-axis represents positive resistive impedance (analogous to resistance in a DC circuit), while the negative x-axis represents negative resistive impedance. A material with a degree of positive resistive impedance will lose some of the electricity applied to it in the form of heat. The positive y-axis represents inductive impedance while the negative y-axis represents capacitive impedance, both of which are shown by the circuit symbols in the right side of Fig. 13. A material with a degree of inductive impedance will store some of the electricity applied to it in the form of a magnetic field. Conversely, a material with capacitive impedance will store some of the electricity applied to it in the form of an electric field in a similar manner to a parallel plate capacitor. An ideal insulator would have a higher imaginary impedance, as this implies that it is storing electricity rather than losing it as heat [5].

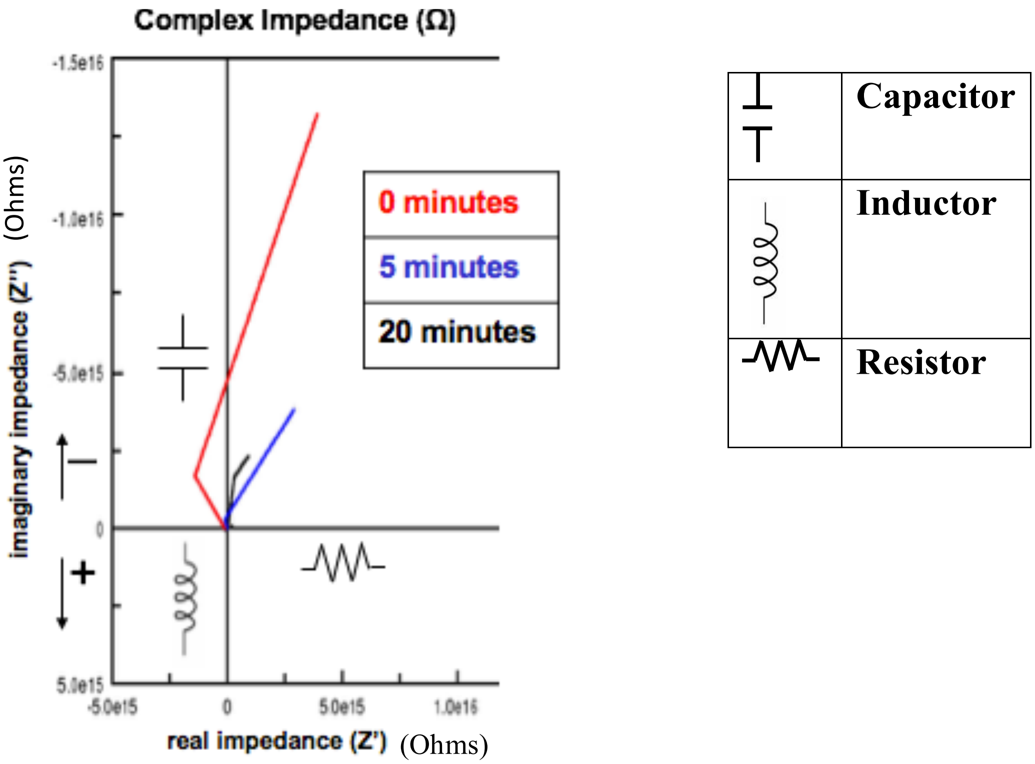


Fig. 13: Complex impedance plot with an inverted y-axis; the circuit symbols are identified on the right. The plot displays impedance spectroscopy data taken over a frequency range of 50 µHz to 5 MHz.

The complex impedance data collected in the experiment indicate that dielectric breakdown contaminants lower the imaginary (specifically, the capacitive) impedance because in Fig. 13, the capacitive impedance of the contaminated oil is lower than that of the pure oil. Dielectric breakdown products will therefore render the oil less functional. The small degree of negative resistance observed for the pure oil indicates that during some of the measurement, the pure oil exhibited a current-voltage relationship that was inverted; i.e., the current increased when the voltage decreased. This effect can also occur in certain electronic devices and under certain conditions when an arc discharge (and resultant current flow) occurs in a gas [10].

5(b) Purification process evaluation

Optical spectroscopy and DC resistivity measurements were conducted to quantify the effectiveness of both molecular sieve and Norit absorbents in removing dielectric breakdown products from Shell Diala S2-ZX-A oil subjected to a high voltage arc discharge for 20 min. Figure 14 shows photographs of the original 20 min arc-discharged sample [Fig. 14(a)] and the same material after purification using molecular sieve [Fig. 14(b)] and Norit [Fig. 14(c)] absorbents. There is a visibly noticeable reduction in color in the purified samples, regardless of the absorbent used.

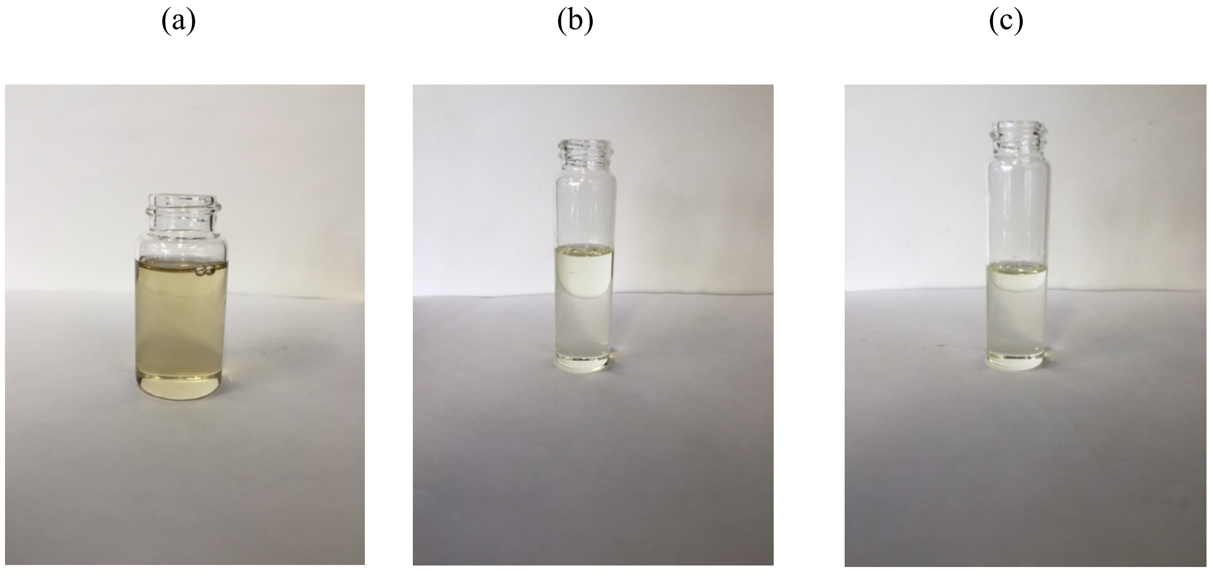


Fig. 14: (a) A sample of Shell Diala S2-ZX-A oil subjected to 20 min of high voltage discharge; (b) the same material shown in (a) after purification with molecular sieve; (c) the same material shown in (a) after purification with Norit.

Transmittance spectra for the three oil samples in Fig. 14 are compared in Fig. 15 along with the transmittance spectrum for a pure oil sample at the same optical path length. The pure oil has the highest transmission, while the sample subjected to 20 min of high voltage discharge has the lowest transmission. Both purified oil samples show significantly improved transmission, approaching that of the pure oil.

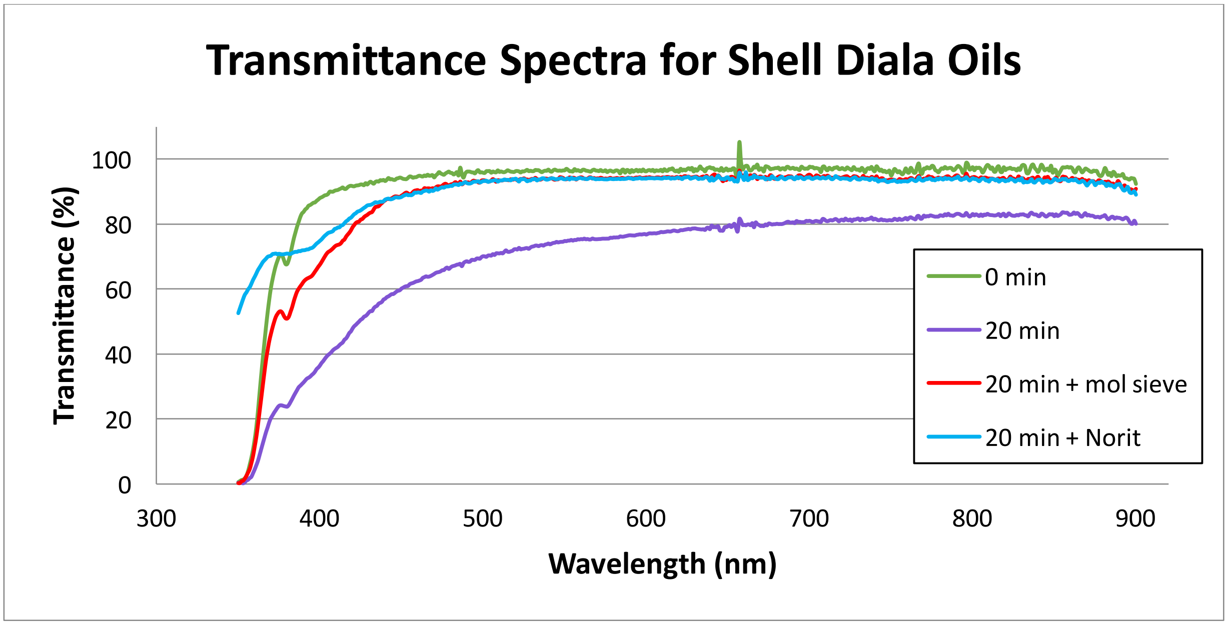
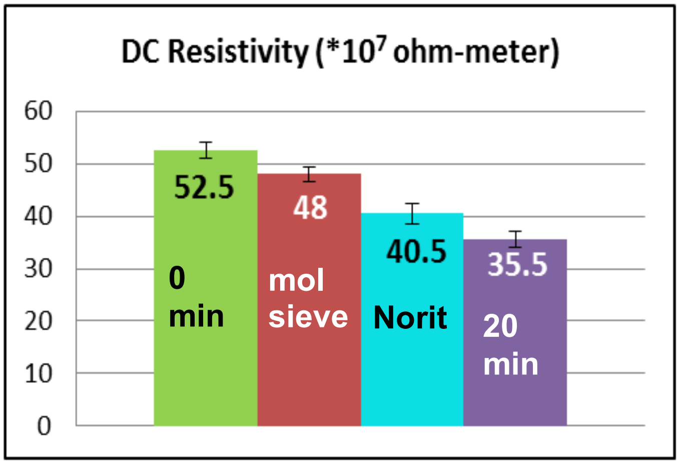


Fig. 15: Transmittance spectra from 350 nm to 900 nm of the four oil samples obtained in a 1 cm path length quartz cell.

DC resistivity data collected for the samples shown in Fig. 14 and the pure sample using the electrometer setup described in Section 4(b) are shown in Fig. 16. The resistivity data in Fig. 16 follow the same trend seen in the transmittance data in Fig. 15; the pure oil has both the highest resistivity and highest transmission, while the contaminated oil has the lowest resistivity and transmission. These results imply that the dielectric breakdown products responsible for the loss in resistivity are highly colored, and establish a direct correlation between the degree of coloration and resistivity, suggesting that optical spectroscopy may be an alternate and convenient method for monitoring the loss of the oil’s insulating ability. In Fig. 15, the spectral curve shape of the sample purified with molecular sieve more closely matches that of the pure oil sample than does the Norit-purified sample. This observation, together with the resistivity data of Fig. 16, demonstrates that molecular sieve absorbent is more effective than Norit in removing dielectric breakdown contaminants from the insulating oil and restoring its resistivity.



Sample (AD= arc discharge)	**Temp (°C)**	**Humidity**
0 min AD (Pure)	22.5	42%
20 min AD: mol sieve	23.1	40%
20 min AD: Norit	21.9	44%
20 min AD	22.7	41%

Fig. 16: DC resistivity data measured on the three oil samples shown in Fig. 14 plus the pure sample. Temperature and humidity were also monitored during each measurement and are shown in the table on the right. Because the electrometer is highly sensitive to vibration, the data is reported as a range of values.

The relative effectiveness of the two absorbents in removing dielectric breakdown products from the insulating oil as shown in Fig. 16 provides some insights into the chemical nature of these contaminants. Molecular sieve is a zeolite-based absorbent with a cage-like, highly porous structure and an alumino-silicate composition. The pore size of molecular sieves are precisely defined, and molecular sieves with different pore sizes can be used to selectively trap and absorb a wide variety of liquids and gases. The Type 13X molecular sieve used in the purification process described in this work has a pore diameter of 10 Å. Pore size can be altered by changing the cation in the negatively charged structure of the molecule. Type 13X has sodium cations in its structure (Fig. 17). A typical formula for Type 13X molecular sieve is $Na_{86}[(AlO_2)_{86}(SiO_2)_{106}] \cdot nH_2O$. In industry, Type 13X molecular sieve is normally used to absorb CO_2, H_2O, H_2S, and other compounds, from gaseous and liquid process streams. Due to their highly charged internal field made of AlO_4 and SiO_4 tetrahedrons, zeolite materials are very effective at absorbing highly polar and charged particles. [11]

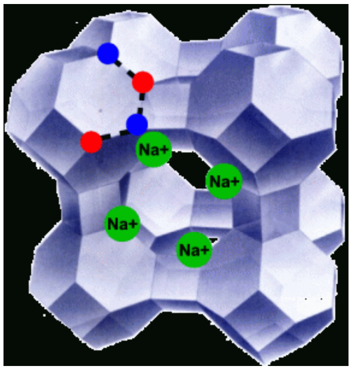


Fig. 17: Structure of Type 13X molecular sieve. Sodium cations contained inside the pores determine the pore size and attract charged particles. [12]

The molecular sieve used in this work was not activated; “activation” involves heating the material to very high temperatures (> 250 °C) in order to rid its structure of any water. This process maximizes the amount of material that the zeolite structure can absorb, because water molecules occupy space inside the pores.

Norit (activated carbon) is a common absorbent that has a high surface area and micro-porosity, which allows it to absorb very large amounts of materials (Fig. 18). This absorbent functions by binding to molecules that come into contact with its surface by means of van der Waals intermolecular forces. Because it is carbon-based, it does not have the capability to bind to inorganic materials, metals, strong acids and bases, and alcohols. [13]

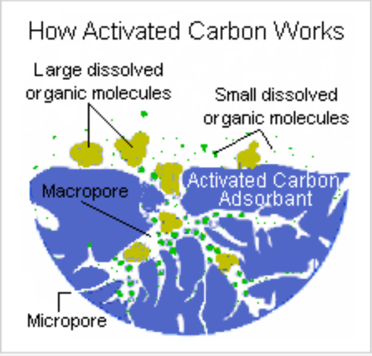


Fig 18: Structure of Norit, showing the presence of both macro and micropores. [14]

The finding that molecular sieves are more effective than Norit at removing dielectric breakdown contaminants from the insulating oil suggests that these contaminants may be small-to-medium molecular weight organic materials that bear a strong charge, as molecular sieve has a much higher affinity for such charged species than does Norit.

6. Future Work

Future efforts should be focused on ways to further improve the speed and efficiency of the purification process using absorbents. A simple first step would be to repeat the process using activated Type 13X molecular sieve. Molecular sieve activation is achieved by heating the material at 250 – 315 °C under a nitrogen flow or under vacuum for several days. Other absorbents could also be explored to evaluate their affinity for removing dielectric breakdown products. Some well-known examples are shown in Table 2 along with a comparison of their relative cost to molecular sieve and Norit.

In addition to testing different absorbents, different oils can be tested in order to find which oil is least affected by dielectric breakdown contaminants, as evidenced by changes in resistivity, dielectric constant, loss factor, complex impedance, and transmittance spectra. Other formulations of insulating oils, both from Shell and other sources, are widely available in industry. Conducting experiments on samples of contaminated oil taken directly from the Z-machine could also lead to a more detailed understanding of all contaminants present and their individual roles in contributing to dielectric breakdown.

Absorbent	Cost per Kg
Molecular Sieve	$0.68
Norit	$0.58
Floridin Clay	$0.32
Alumina	$1.00
Silica Gel	$0.75

Table 2: Price comparison of absorbents. [15]

A key element of this project was developing a purification process for the oil that could be eventually applied to large-scale, continuous processing of oil in LLE's Pulsed Power laboratory that is currently under construction. Figure 19 shows a schematic diagram for a cartridge-based absorption/filtration set-up that could be run continuously so that the oil would never be overly contaminated during the operation of the pulsed-power apparatus. Submicron particle cartridge filters are installed after the absorption beds to capture fine particles, followed by a resistivity monitor to measure *in-situ* the effectiveness of the purification process and monitor oil quality. Because of the relationship established between optical transmission and resistivity, monitoring of the transmission of the oil in real-time is also an option.

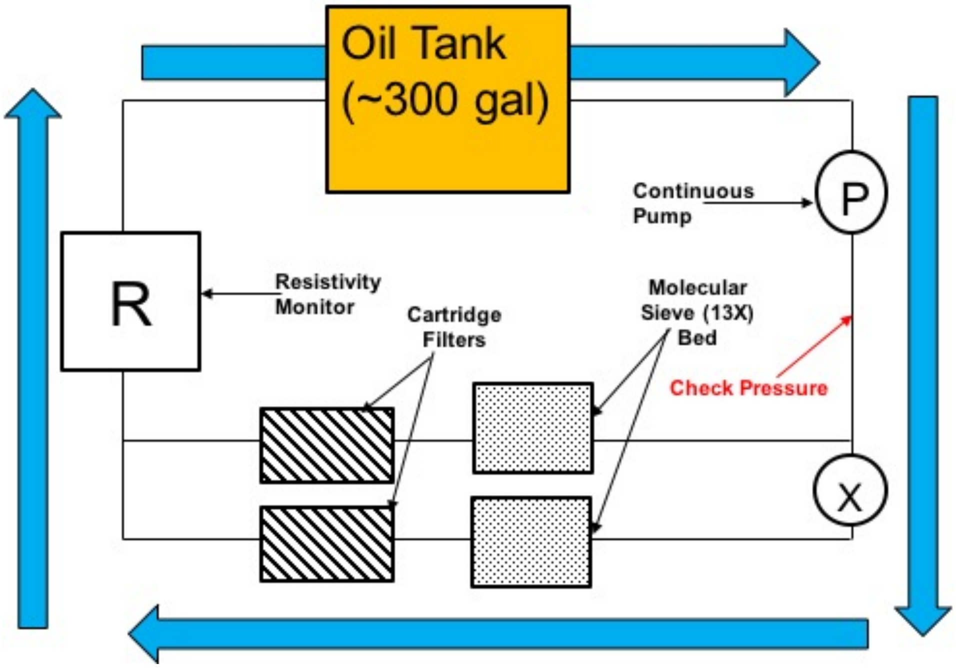


Fig 19: Schematic for a continuous absorption/filtration system for the purification of insulating oil in the pulsed-power systems. Flow through the purification system would be constant when the pulsed-power system is in an idle state.

7. Conclusion

An absorption-based purification process was developed to remove dielectric breakdown contaminants from insulating oils used in pulsed power research. The presence of dielectric breakdown products was shown to both increase the dielectric constant of the oil in the high frequency range, and decrease the complex component of the oil's impedance. Both of these values are indicators of a loss of insulating oil's functionality. DC resistivity measurements and transmittance spectra were used to evaluate the effectiveness of the purification process. Molecular sieve was shown to be very effective in restoring the contaminated oil's resistivity. Experiments on contaminated oil directly from the Z-machine could lead to further insights before a similar pulsed power apparatus is constructed at LLE.

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