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Current requirements by electro hydrodynamic filter systems under shipboard operation conditions

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ABSTRACT

CURRENT REQUIREMENTS BY ELECTRO HYDRODYNAMIC FILTER SYSTEM UNDER SHIPBOARD OPERATION CONDITIONS

by
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An experimental study was performed to determine the current required by an Electro-Hydrodynamic (EHD) filter system to clean contaminants from Diesel Engine Lubrication Oil under normal shipboard operation conditions. The amount of current at a set predetermined voltage, which together means Power, was needed in order to anticipate the power required to perform a Shipboard Site Test Evaluation of the EHD filter.

The filter uses the effect of dielectrophoresis to separate contaminants from the lubrication oil. The filter operates at two thousand volts (2KV ac-rms) and thus requires substantial current to energize its electrodes. This type of Power is not normally readily available from typical power systems. In order to develop a power system for the filter, the required power, voltage and current needed to be determined. The laboratory experiments performed were conducted under typical operating conditions of the diesel lube oil. The normal operation temperature of diesel lube oil is 240 degrees Fahrenheit. Various parameters, which effect the current requirement, were examined in order to well define the current requirements for all the anticipated conditions. The parameters include temperature, voltage, frequency, flow rate, and contamination level of the oil.

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By
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CURRENT REQUIREMENTS BY ELECTRO HYDRODYNAMIC FILTER SYSTEM UNDER SHIPBOARD OPERATION CONDITIONS

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This thesis is dedicated to my Parents

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CHAPTER 1

INTRODUCTION

1.1 Background Information

This Master's thesis work relates to the engineering development of an Electro-Hydrodynamic Filter System. The filter will be used for the removal of particulate contaminants from in-service lubrication fluids. The most common causes of machine failure are caused by contamination of hydraulic fluids, gear oils, dielectric liquids, lubricants, coolants, brake fluids and other in-service fluids due to corrosion and wear of equipment, aging of these fluids etc. The EHD Filter uses the effect of dielectrophoresis, to separate and remove particulate contaminants i.e. soot, carbonaceous particles, wear metals, fibers, droplets, bubbles etc from the lubrication oils. Dielectrophoresis is the translational motion of neutral matter caused by polarization effects in a non-uniform electric field. It is a novel electro-hydrodynamic technology, which can be used to remove contaminants from in-service fluids to significantly extend the life of a wide range of machinery and equipment. Today's widely used in-service filtration technology (i.e. mechanical membrane filters) can only remove particles down to 5 microns and also replacement of clogged mechanical filters is a very labor consuming process and exposes personnel and equipment to hazardous material, while the EHD Filter can remove micron and sub-micron sized particles. Mechanical membrane

Filters eventually clog up and must be replaced, while the EHD filter has the possibility of utilizing an automated particle removal system, which could allow it to continuously operate in a closed system, offering obvious environmental advantages.

The EHD filter applies a high-gradient AC electric field (~several kV/mm) to the fluid by using an array of electrodes equally spaced apart. The electrodes and fluid between them offer a capacitive type impedance load to the Power Supply and draws a current from the Power Supply. The current drain by the impedance load of the filter is determined by the AC voltage applied, frequency of the applied voltage, surface area of the electrodes, conductivity of the fluid, temperature, contamination level and flow rate. Dielectrophoresis is able to separate two populations of particles, which exhibit +ve and –ve dielectrophoresis. In order to determine the Power requirement of the EHD Filter for Diesel Lube Oil, an experimental study was performed.

1.2 Mechanism of Electro Separation

Electro-separation is one of the techniques that have emerged in the post decade, which use a combination of electric and hydrodynamic effects to separate fine particles, droplets and bubbles from a fluid. Electro-separation uses Electro-magnetic fields to produce and enhance chemical or physical separation. Here, the electrical driving force combines with another chemical or physical driving force to create a synergism that is extremely beneficial.

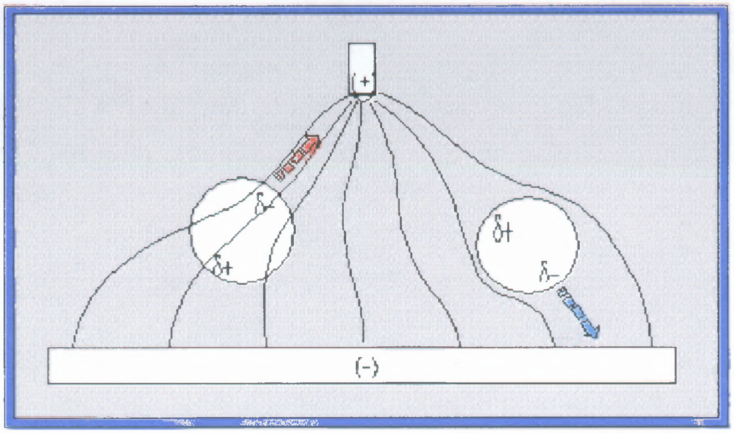


Figure 1.1 Two different particles in a non-uniform electric field. The particle on the left is more polarizable than the surrounding medium and is attracted towards the strong field at the pin electrode, whilst the particle of low polarizability on the right is directed away from the strong field region.

The net electric force (Fe) acting on a particle subject to a gradient electric field (i.e. a spatially non-uniform electric field) consists of two terms.

$$F_e = QE + \delta q(Er_+) - (\delta q Er_-) \quad (1.1)$$

$$F_e = QE + (P.\nabla)E \quad (1.2)$$

- The first term (referred to as electrophoretic force), is the product of the particle charge (Q) and the strength (E) of an applied electric field given in equation (1.1).
- Second term (referred to as dielectrophoretic force), equation (1.2), is proportional to dipole moment (P) and the gradient of the electric field (∇E). The electrophoretic force causes the particles to translate along the electric field lines whereas the dielectrophoretic force causes a particle to translate along the lines of the field strength gradient, which points towards high field regions. Since the particle polarization varies proportionally with the strength of an applied field the dielectrophoretic force is proportional to the square of the field strength. Therefore, the contribution of the

dielectrophoretic force to the net electric field Fe, equation prevails in the HIGH-GRADIENT STRONG ELECTRIC FIELDS.

Electro-separation is unique in that the electric forces are large and are applied solely to the particle and not to the total fluid as in typical centrifugal and mechanical filtration systems. For example, the electric force acting on a micron-sized particle may be as much as forty thousand times larger than the gravity forces. The use of Electro-hydrodynamics to derive a separation process has many advantages including:

- ✓ Low maintenance and economic price.
- ✓ Availability and flexibility.
- ✓ Benign Environment impact.

Many electro-separation devices such as electrostatic precipitators, electro-dialysis cells, electrophoresis units and electrically driven desalters, are already used industrially. Other technologies, like electro-kinetic liquid cleaning, electro-solvent extraction and dielectric filtration are now emerging.

1.3 Electro-Separation and underlying Phenomenon.

In 1995-96 Dr. Boris Khusid and others developed a new theory that delineates the conditions for the occurrence of electric-field-induced aggregation and dielectrophoresis in conducting colloids. [1], [2] Based on their theoretical predictions, they then proposed a new concept for a continuous electro-separation technique, which exploits the combined effects of electric-field-dielectrophoresis and aggregation of particles in a flowing fluid, subjected to a high gradient strong electric field.

The electric-field-induced aggregation in colloid is a reversible phase transition from a homogeneous random arrangement of particles into a variety of ordered aggregation patterns due to the electric-field-induced inter-particle interactions. The application of an electric field induces inter-particle interactions because each particle distorts the electric field in its vicinity, which leads to a dielectrophoretic force acting on another particle. The particles will return back to their initial state as soon as the electric field is removed. The response time is several milliseconds. The evolution of these aggregation structures can easily be manipulated by varying the frequency and the strength of the applied field.

Dielectrophoresis is a translation motion of an electrically uncharged particle under the action of a gradient electric field due to the particle polarization. The particle is attracted towards or repelled from the high electric-field region depending on the sign of its polarizability i.e. whether it is positive or negative, respectively. It is significant that the magnitude and moreover the sign of the polarizability can easily be varied by changing the frequency of the applied electric field.

The main advantage of dielectrophoresis in comparison with electrophoresis is that it eliminates undesirable electrolysis effects in the liquid. The electrophoresis pertains to the transitional motion of electrically charged particles under the action of only the DC field. Dielectrophoresis has become the most-used technique in electro-separation since the eighties when non-expensive portable high-voltage AC power supplies became commercially available.

1.4 Study Plan

The aim of this study was to select the optimum power source with which the diesel-lube oil could be filtered under the shipboard conditions of temperature of the order of 240 F. Conductivity of oil increases with temperature which further increases the power requirements on the power supply. The aim is to attain maximum voltage across the electrodes. In the present circumstances the maximum voltage was 2000V, but the current drawn puts limitations on the power source due to the prescribed power limits.

In the series of experiments conducted, the basic interest is to determine the current requirements by the EHD filter system in order to perform a site test evaluation on diesel Lube Oil under typical operating conditions. Various factors have been taken into consideration in order to satisfy the current requirements during the test like:

- ✓ The effect of applied voltage (V)
- ✓ Frequency (Hz)
- ✓ Temperature (F)
- ✓ Flow Rate &
- ✓ Contamination

So as to determine the relationship and to get the tentative values of currents at elevated temperatures in the range of 240F, the curves were extrapolated to that temperature. It has also been determined that there is a factor of two in current and voltage i.e. if the voltage is raised by a factor of two then there is a corresponding equivalent rise in the current. A linear relation between current and voltage has been determined.

During the first tests, the relation between voltages vs. current, frequency vs. current and temperature vs. current were sought. After the linear relation between voltage and current was established, another set of experiments was conducted and normalized to 2000V, as practically with the existing power supply this limit cannot be reached. This was done for rise in temperature as well as while cooling.

To make sure if the amount of contaminants in the oil affect the current-voltage relation in any way, the tests were conducted on oils with different contamination level. It was seen that the relation is similar and the relation holds good for any contamination level.

CHAPTER 2

EXPERIMENTAL SETUP

The system in which the experiments were performed consisted of the following equipment: -

1. Experimental Cell
2. Power Supply (TREK Amplifier 10/40)
3. Peristaltic Pump (Cole-Parmer)
4. Heat Source
5. Temperature Controller (OMEGA CN 3910JC)
6. Current-Voltage Meter (Fluke Model 8840 DMM)
7. Signal Generator (Wavetek Model FG2A)
8. Particle Counter (HIAC/ROYCO)
9. Logger (HIAC/ROYCO)
10. Stirrer. (STED FAST Model SL 600)

Each of the equipment has been explained briefly with the pictures. The basic schematic diagram of the setup is as shown in Figure 2.1

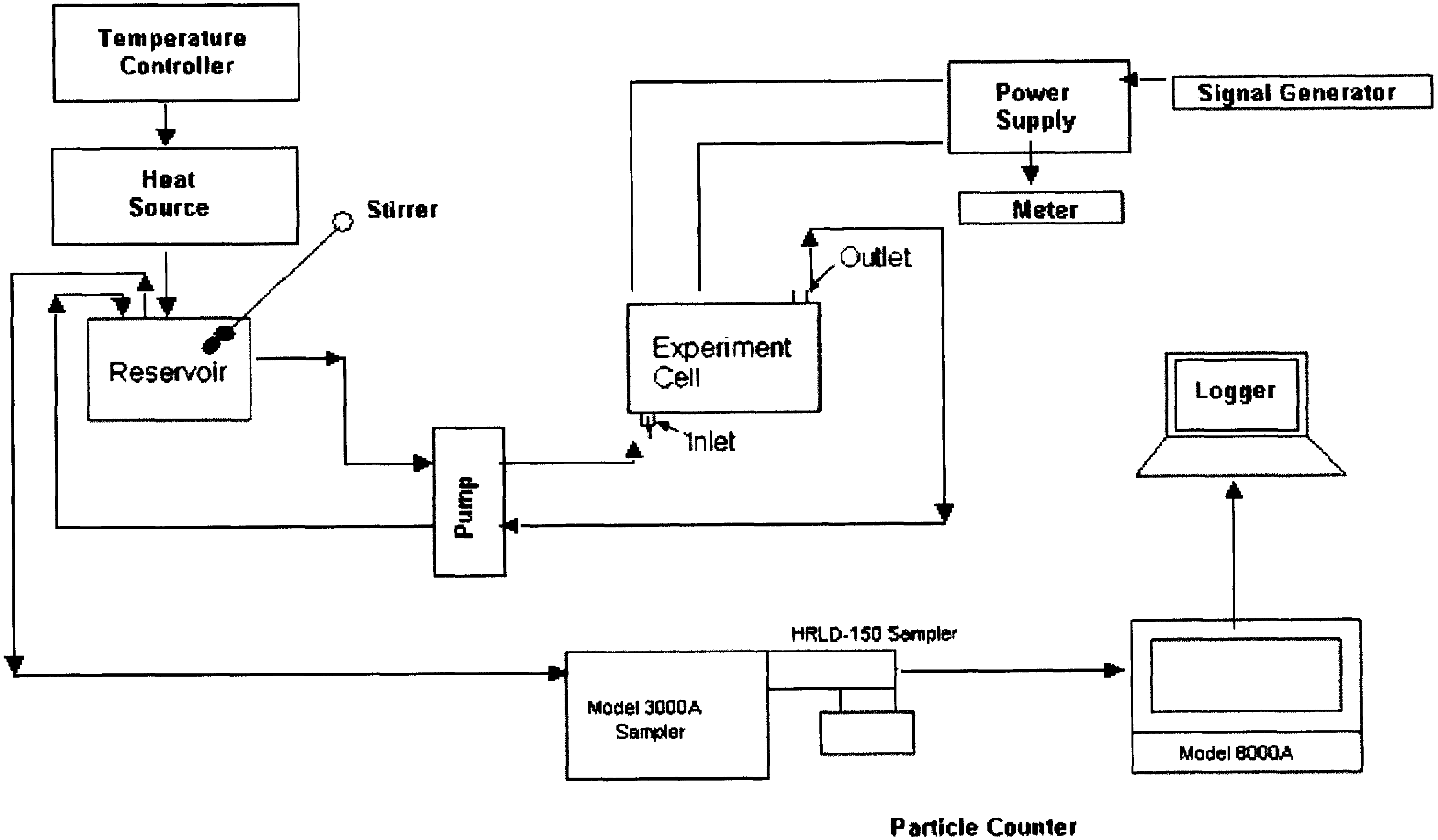


Figure 2.1 Schematic Diagram of the setup.

2.1 Experimental Cell

The cell housing on which the experiments were carried out was made out of polysulfone, polysulfone was chosen because it meets the operational requirements of Diesel Lube Oil. It is a high temperature material and can sustain temperatures in the range of -150^{O} F to 285^{O} F. Its properties include: high electrical breakdown strength, easy machinability, etc. The overall size of the cell was chosen to be ¼ the size of an existing test cell, which was used at a Navy test site to filter Diesel Lube Oil at room temperature, (68^{O} F). The polysulfone cell dimensions were 5" long, 2 ½" wide, and 3" high. Its cross-section is depicted in Figure 2.2 – 2.6 below. There were a total of 206 electrodes in the cell that were made of square brass tubes. The cross-section area of each electrode was 1.58 x 1.58 mm (1/16" X 1/16") and the length was 95mm.

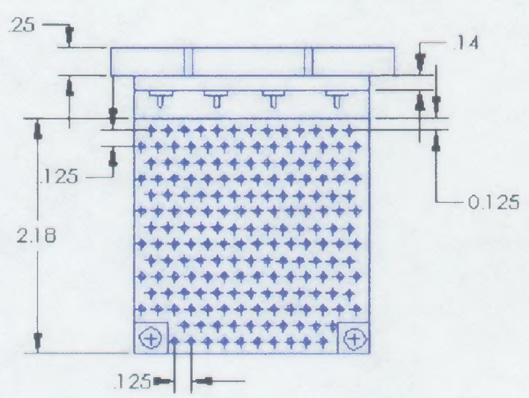


Figure 2.2 Side View of the cell.

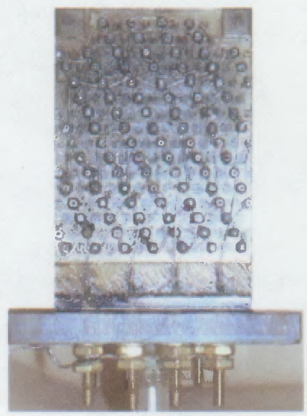


Figure 2.3 Picture of the side View.

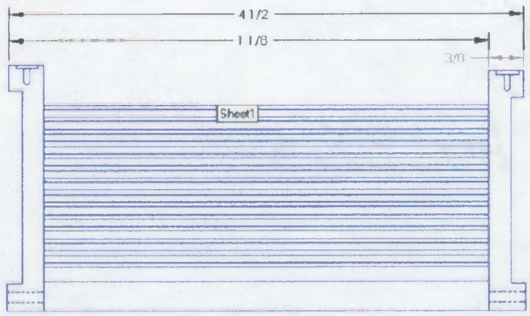


Figure 2.4 Front View of the cell.

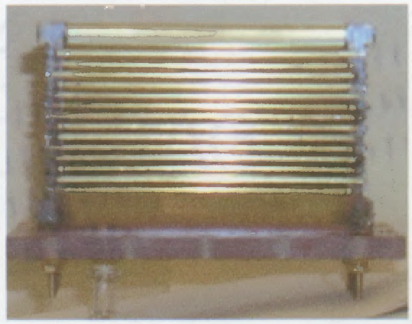


Figure 2.5 Picture of the cell.

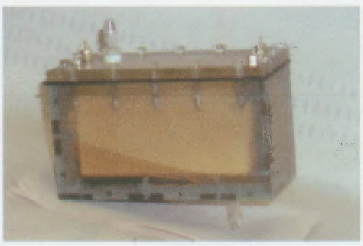


Figure 2.6 Picture of the front View.

An array of 206 linear, square in cross-section electrodes was embedded in the polysulfone plates in a staggered form. The electrodes were connected to the high voltage amplifier output via bolt/nut lug terminals, located on the exterior of the housing.

The electrodes were alternately connected to the positive terminal of the high-voltage amplifier and ground. (See Figure 2.7).

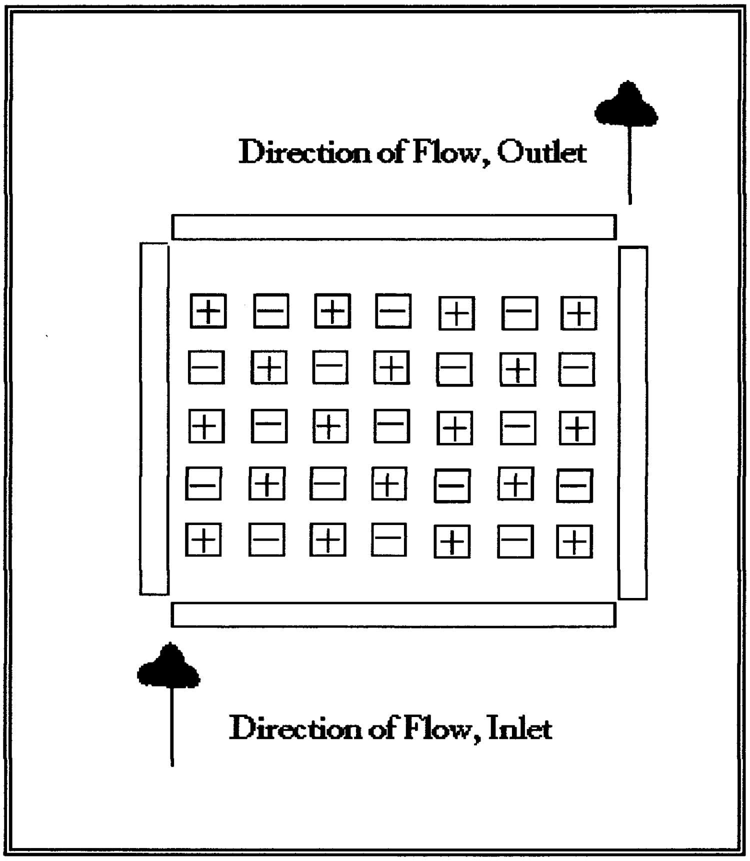


Figure 2.7 Direction of Flow of Lube Oil.

Edges of the electrodes were deburred and all residual small shavings of brass were removed to suppress sparking between the positive and grounded electrodes.

2.2 Power Supply

The applied AC electric field was produced with a TREK amplifier 10/40, with a WaveTek Function Generator to supply the signal to be amplified. The TREK model 10/40 was a DC stable, high voltage power amplifier. It gives precise control of output voltages in the range of 0 to +/- 10KV DC or peak AC with an output current range of 0 to +/-40mA DC or peak AC, over a frequency range of DC to greater than 25kHz. The amplifier provides scaled output voltages (1V/1000V and 0.1V/mA) for monitoring the voltage and current output of the amplifier. See Power System Figure 2.8, Figure 2.9 and Figure 2.10 below.

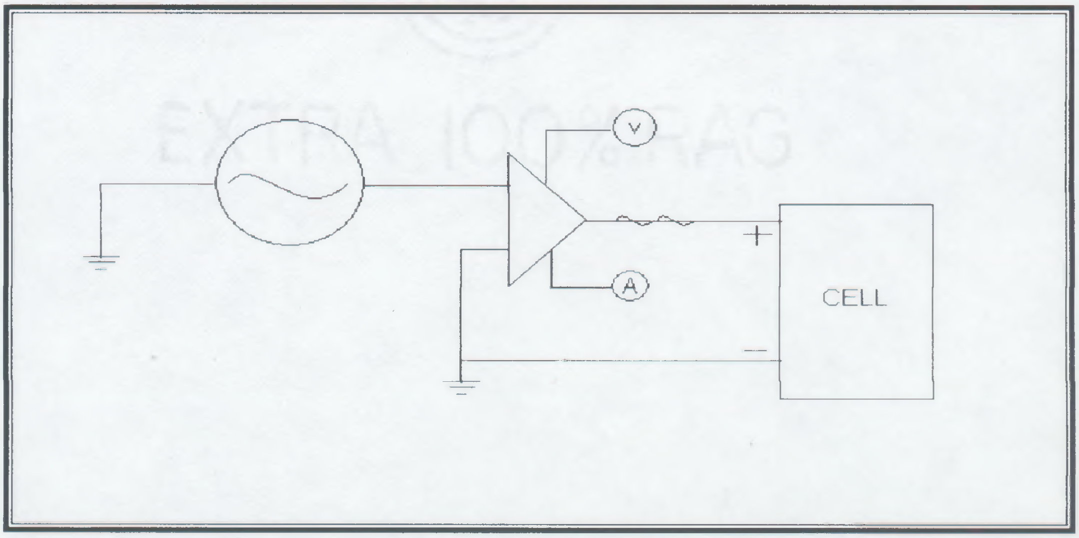


Figure 2.8 Power System.

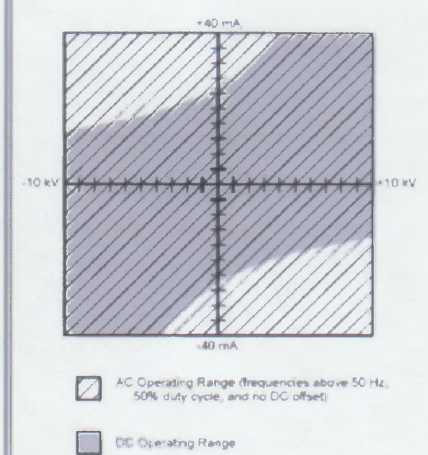


Figure 2.9 Trek Model 10/40 High Voltage Power Amplifier.

Figure 2.10 Model 10/40 Operating Range.

2.3 Pump

The lube oil flow was pumped through the electrodes under a flow rate controlled using a peristaltic Master flex pump (Cole-Parmer), see Figure 2.11. The range of speed of the pump is 0 - 100rpm. The operating temperature of the pump was 32F to 104F. The pump head accepts several different tubing sizes for a wide range of flow rates. (See Tubing Table 2.1 below) The over-center cam design and adjustable tubing retention allows quick tubing changes.

Table 2.1 Tubing sizes and flow rates, Master flex Easy-Load L/S pump head, 1- 100 rpm

Tubing	ml/ rev	ml/min
L/S 13	0.06	0.06 to 6.0
L/S 14	0.21	0.21 to 21
L/S 16	0.8	0.8 to 80
L/S 25	1.7	1.7 to 170
L/S 17	2.8	2.8 to 280
L/S 18	3.8	3.8 to 380

Figure 2.11 – Peristaltic Pump (Cole-Parmer).

The flow of lubrication through the system is depicted in Figure 2.12. The cell was made such that the flow of lubrication oil is streamlined from inlet to the outlet valve.

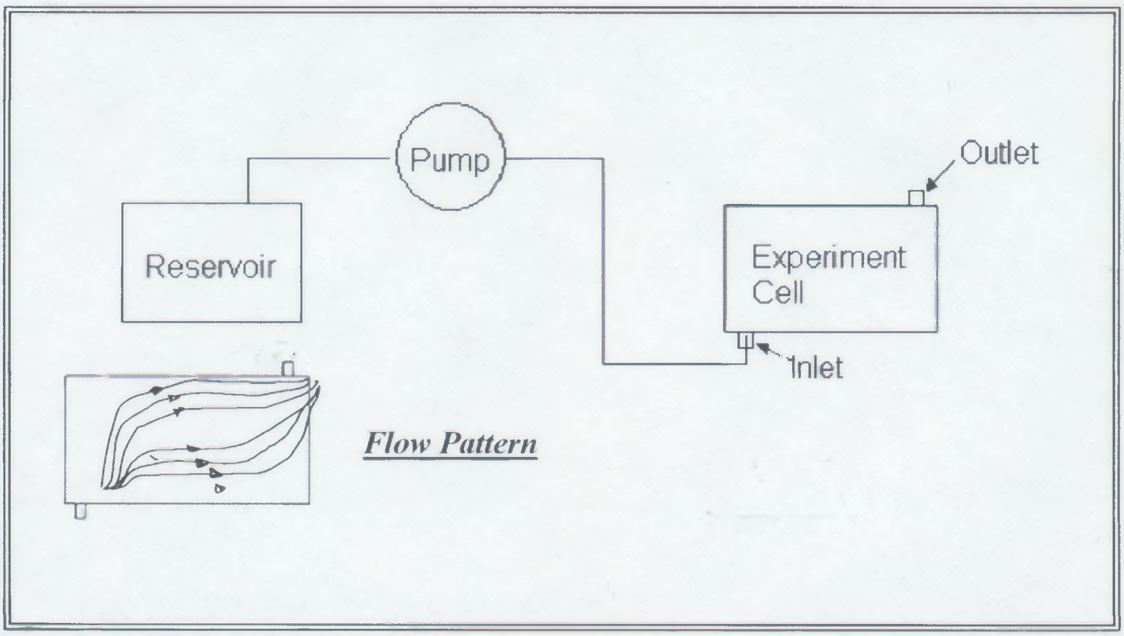


Figure 2.12 Lube Oil Flow in Peristaltic Pump with Flow Pattern.

The cell was carefully designed keeping in mind that the flow should not become turbulent even at the maximum flow rate that the pump provides. This was done so as to ensure that the particles captured might not be dislodged from the electrodes of the cell. The flow pattern is shown in the Figure 2.12 above.

2.4 Heat Source

The temperature of the oil was varied from as low as 75^O F to as high as 165^O F with the heat sources. The Heating Plate could raise the temperature to a maximum limit of 580^O C and the Heating Jacket was rated for a maximum temperature of 282^O C. Initially, the oil was raised to the desired temperature with the help of both Plate and the jacket. Later, it was noticed that the control for the plate is not very accurate and moreover that the temperature could be reached with the heat jacket alone, so for the experiments performed, only the heating blanket was used. The heat source along with the Viton tubing is shown in Figure 2.13, Figure 2.14 and 2.15.

Figure 2.13 Heating Plate.

Figure 2.14 Heating Jacket.

Figure 2.15 Viton Tubing.

The regular Tygon tubing (used for room temperature experiments) was not suitable for operation in Diesel Lube Oil to 240F. For this high temperature, viton tubing was used for the pump and other connections. The Viton tubing has ¼" internal diameter and ½" outer diameter equivalent to size LS-14, to achieve flow rates from 0.21 to 21 ml/min, corresponding to 0-100RPM of the pump.

2.5 Temperature Controller

The controller that was used with the heating jacket was an OMEGA CN 3910JC ON/OFF. Proportional controller with an adjustable proportional band control for temperature stabilization and minimum oscillation. This controller was J type, which indicates the type of the thermocouple (Iron /Constantan) the controller has in it. It has a temperature controlling range of 0-500° C. The Set Point temperature was set on the controller and it further controlled the temperature of the oil from there on. The thermocouple sensor was located between the heating jacket and oil reservoir, (and not in the Diesel Lube Oil). The temperature controller is shown below in Figure 2.16.

Figure 2.16 Controller: OMEGA CN 3910JC.

2.6 Current-Voltage Meter

The model of the meter is a Fluke model 8840 DMM (Figure 2.17). This is used for monitoring voltage and current output of amplifier. Monitor outputs are scaled 0-10V which represents 0-10KV output and 0-1V represents 0-10mA for current.

Figure 2.17 Current-Voltage Meter.

2.7 Signal Generator

The model of the Signal Generator is Wavetek model FG2A (Figure 2.18). It generates sine, square, and triangle waveform from 0.2 Hz-2.0 MHz. It is used to generate 0-2 V rms, 1000 Hz signal for the Trek amplifier.

Figure 2.18 Signal Generator.

2.8 Particle Counter

The particle counter was used to find the number of particle contaminants in different ranges of size in the Lube oil for the experiments performed. During the experiments conducted the contamination level of oil played an important role. It was also intended that the oil remains more or less consistently contaminated. The HIAC/ROYCO Model 8000A, Figure 2.19 counter was a digital counter that provided processing, control and flexibility for contamination analysis. The model 8000A included a 24-key Keypad for input, a 40 column 16-line LCD display and a 40 character per line graphics printer for output to operator. Basic configuration of Particle Counter is as shown in the Figure 2.20.

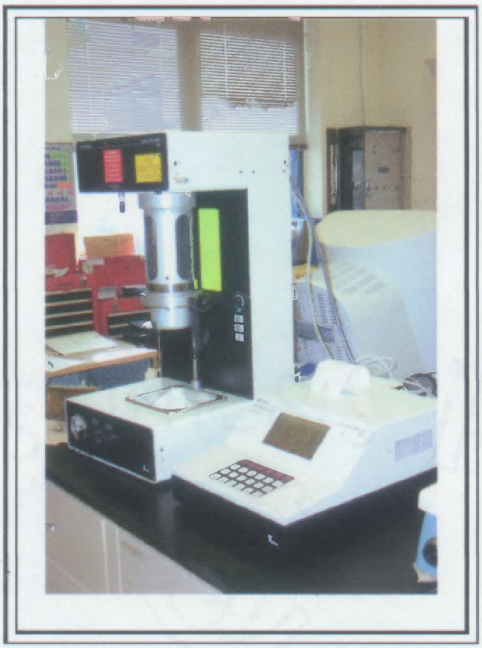


Figure 2.19 Particle Counter.

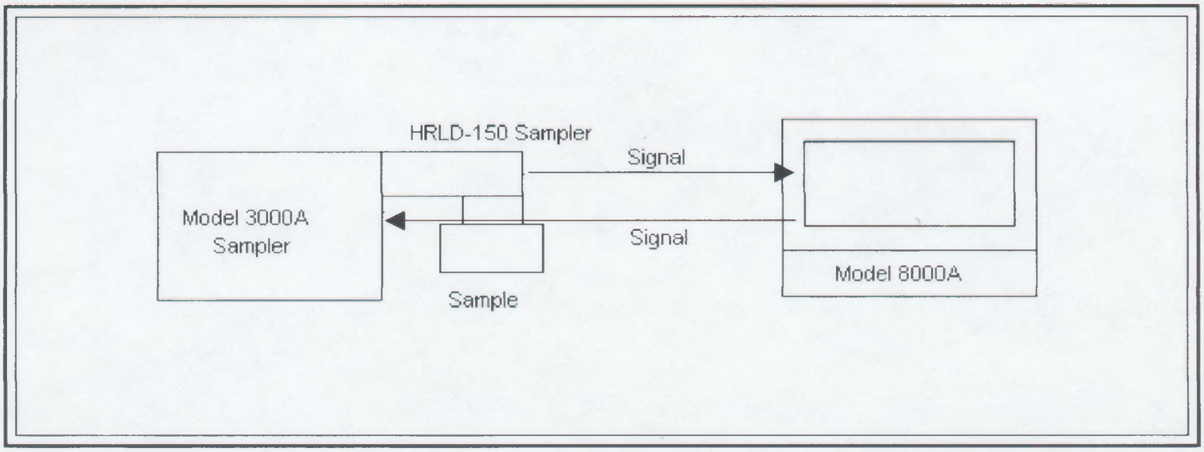


Figure 2.20 Model 8000A System.

2.9 Logger

The Hiac/Royco Logger (Figure 2.21) program is designed to collect data from a Hiac/Royco particle counter, optionally reformat the data to facilitate importation into a spreadsheet program, and save the data to a user-specified file. Logger can collect data from two counters simultaneously, one attached to the computers' COM1 Serial port, and the other attached to the COM2 port.

Figure 2.21 Logger Screen Snapshot.

2.10 Stirrer

The Lube oil was stirred during the filtration process so that the contaminants do not settle down and so that they are uniformly spread in the oil. Also, it was required to stir so as to have homogeneous temperature distribution through out the oil.

Figure 2.22 Stirrer.

The stirrer used was Fisher Scientific 'STED-FAST' model SL600 (Figure 2.22), which had the rpm in the range of 25-600 rpm.

CHAPTER 3

LUBE OIL TESTS

In order to determine the current requirements by the EHD Filter system to perform a site test evaluation on Diesel Lube Oil under typical operating conditions, a series of tests were performed. The following sections explain the tests performed and the results.

3.1 Test #1 Diesel Lube Oil Conductivity Test

The first experiment was conducted to determine the conductivity of Diesel Lube Oil.

The conductivity was determined by measuring the resultant current draw of the electrodes for various applied voltages. This was done in order to ensure adequate power was available from the power supply system for applied voltage levels other than the typical 2000Vacrms. The test was performed with fresh clean oil (supplied by Naval Sea Warfare Center, Carderock Division, Philadelphia, PA) at the operating condition of 1000Hz frequency and 75F temperature. The results of the tests are shown in the table on the next page; as voltage was varied from 200V to 2000V, Current increased from 1.18mA to 11.8mA.

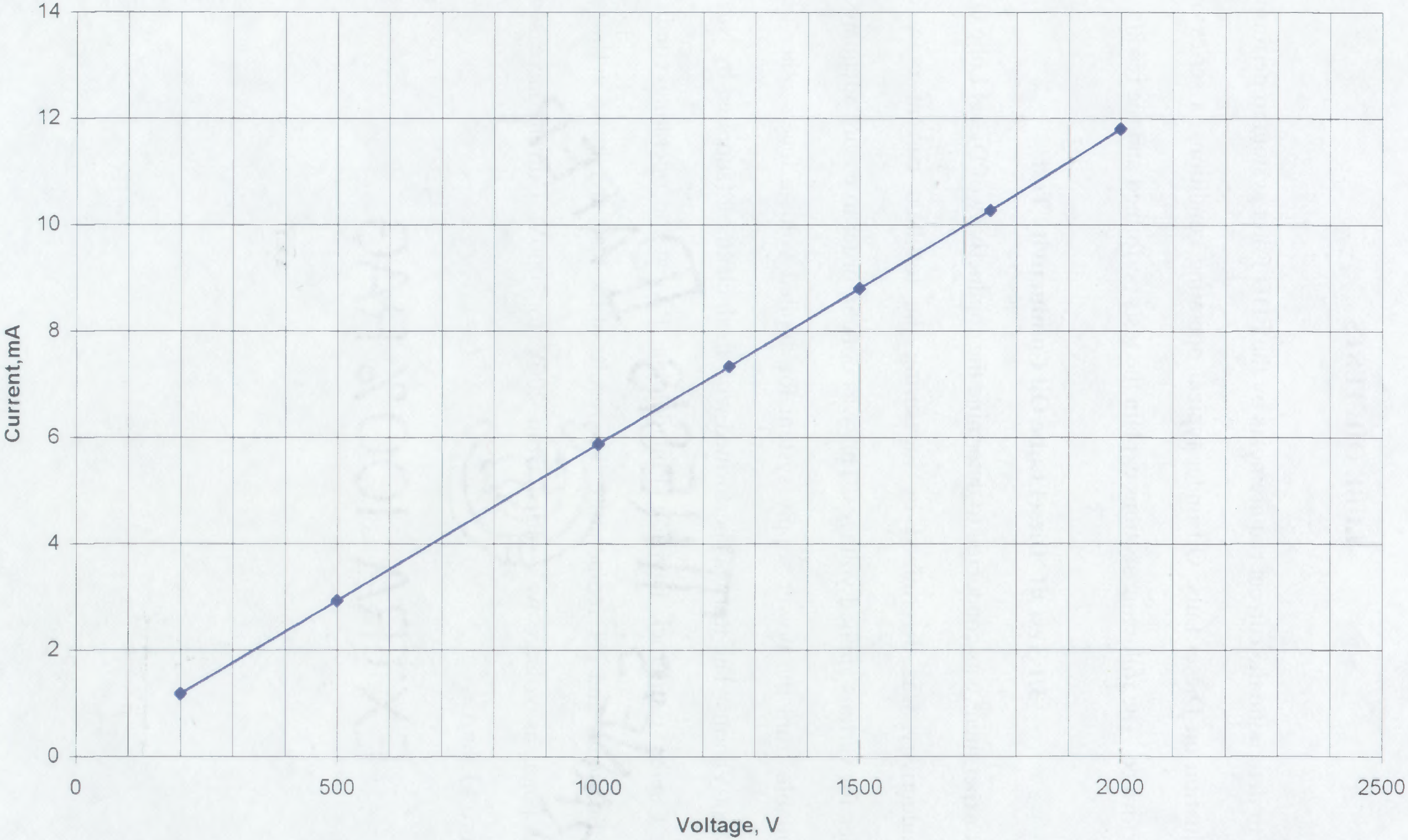


Figure 3.1 Voltage vs. Current at 1000Hz (Diesel Lube Oil)@75F.

Table 3.1 Voltage vs. Current, at 1000Hz & 75F

Voltage (V)	**Current (mA)**	
200	1.18	
500	2.93	
1000	5.87	
1250	7.33	
1500	8.8	
1750	10.27	
2000	11.8	

After plotting this data on a graph of Y axis (Current-mA) and X axis (Voltage- V), it was noticed that linear relation exists between the two. Refer Figure 3.1, Voltage vs. Current.

In order to determine the conductivity of Diesel Lube Oil, [4] that helps to get a better insight into the whole procedure, thus making the whole process cell independent or in other words non-dimensional, the following procedure was adopted. The various dimensions of the cell are as follows: -

Electrode Cross-section: -

$$\frac{1^{''}}{16} \times \frac{1^{''}}{16}$$

Cross-section Area of one Electrode: -

$$4 \times \frac{1^{''}}{16} = 6.35mm^2$$

Length of Electrode: - $95mm$

Surface Area of one electrode: - $603.25mm^2$

Total Number of electrodes: - 206

Effective Number of electrodes: - 103

(The electrodes were ground and energized as shown in the Figure 2.7, thus half of the electrodes were energized and the other half ground making the effective number of electrodes to be 103)

Total Surface Area: - $603.25 \text{ X } 103 = 62134.75mm^2$

Current Density: -

$$\rho = \frac{I}{A} = \frac{I}{62134.75} \text{ mA/mm}^2 \quad (3.1)$$

Conductivity: -

$$\sigma = \frac{L}{RA} = \frac{IL}{VA} = \frac{95I}{62134.75V} \text{ 1/ohm.mm} \quad (3.2)$$

Electric Field: -

$$\text{E} = \frac{V}{d} = \frac{V}{(2-1.875)25.4} = \frac{V}{3.175} \text{V/mm} \quad (3.3)$$

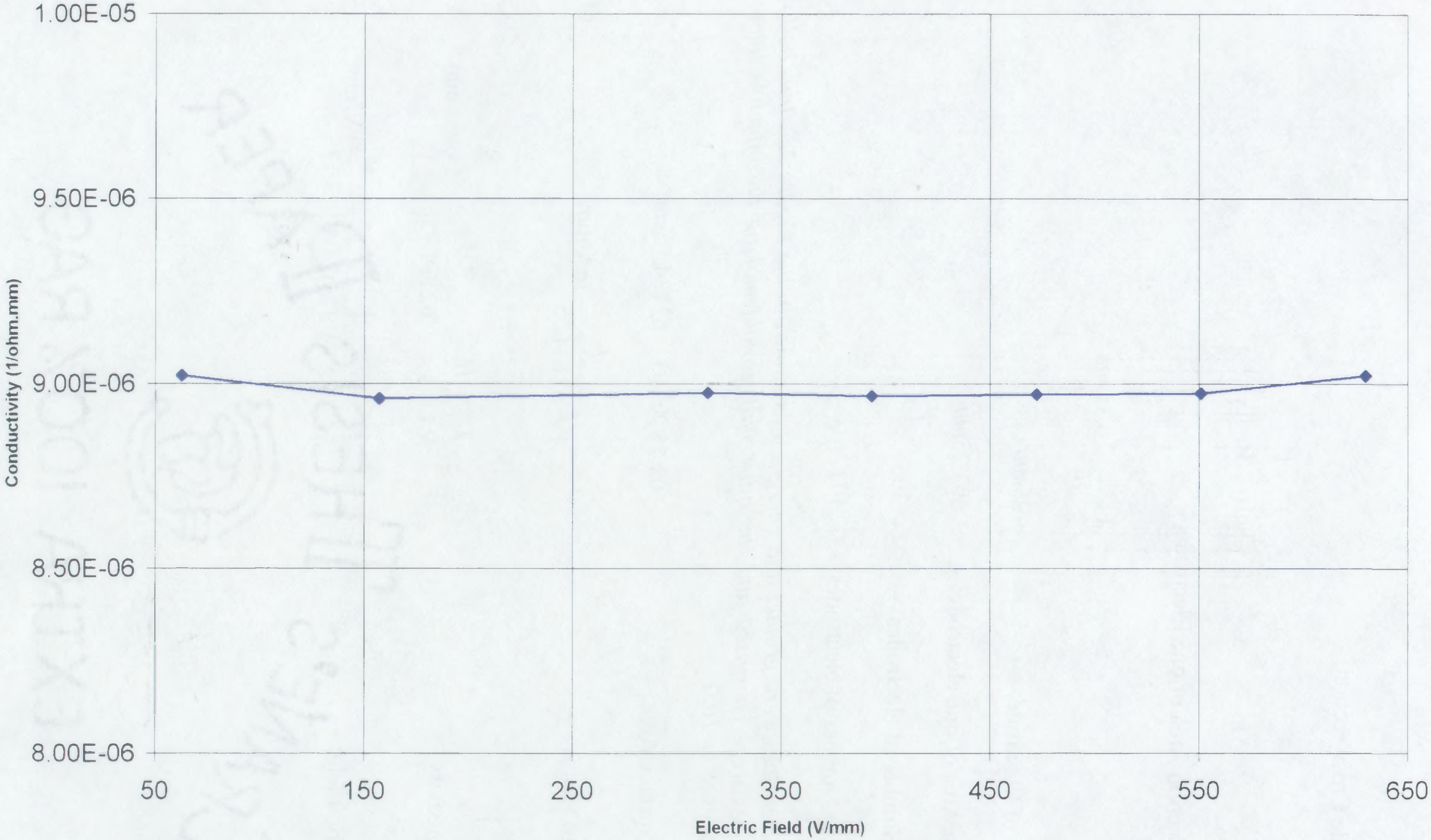


Figure 3.2 Electric Field vs. Conductivity.

The plot of conductivity (σ) vs. Electric Field (E) is hence shown.

Table 3.2 Electric field vs. Conductivity, at 1000Hz & 75F

Voltage (V)	**Current (mA)**	**Electric Field (V/mm)**	**Current Density (mA/mm^2)**	**Conductivity (1/ohm.mm)**
200	1.18	62.99	663389830.5	9.02E-06
500	2.93	157.48	667918088.7	8.96E-06
1000	5.87	314.96	666780238.5	8.97E-06
1250	7.33	393.70	667462482.9	8.97E-06
1500	8.8	472.44	667159090.9	8.97E-06
1750	10.27	551.18	666942551.1	8.97E-06
2000	11.8	629.92	663389830.5	9.02E-06

Note: Refer to Figure 3.2 Electric Field (E) vs. Conductivity (σ)

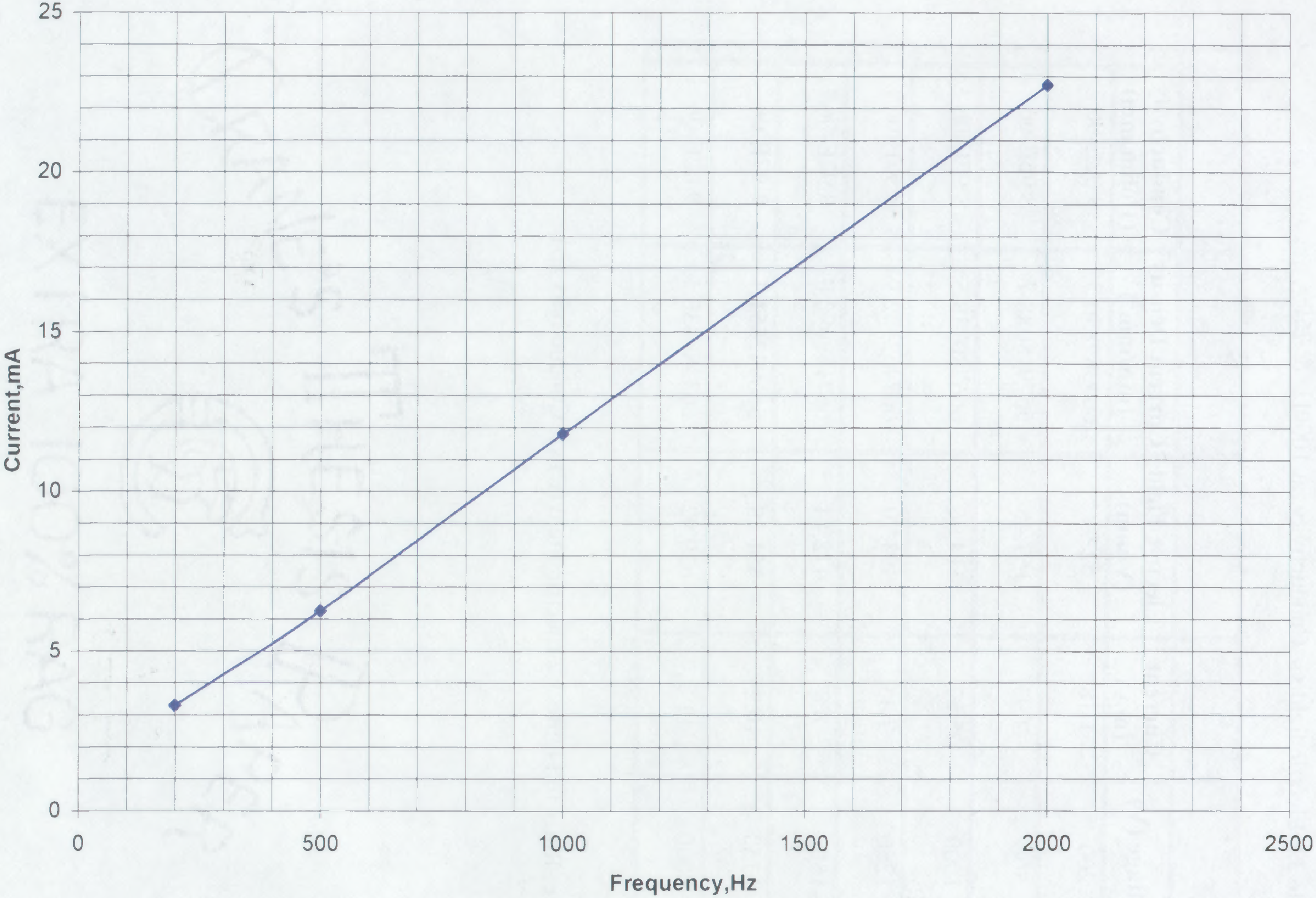


Figure 3.3 Frequency vs. Current (2000Vacrms,75F).

3.2 Test #2 Frequency Dependence of the Electrode System Impedance with Diesel Lube Oil

The second experiment conducted was to determine the frequency dependence of the electrode impedance. The frequency dependence was determined by measuring the resultant current draw of the electrodes at 2000Vacrms while varying the AC voltage frequency. The test was performed with the operating condition of 2000Vacrms and temperature 75F. At these conditions for frequency varying for 200Hz to 2000Hz, current varied from 3.29mA to 22.74mA. (See Table 3.3 below).

Table 3.3 Frequency vs. Current. at 2000V & 75F

Frequency (Hz)	**Current (mA)**	
200	3.29	
500	6.26	
1000	11.8	
2000	22.74	

When the data was plotted a generally straight line was obtained, with variation below 500Hz. (Refer to Figure 3.3, Frequency vs. Current at 200V &75F)

3.3 Test #3 Temperature Dependence of the Electrode System Impedance with Diesel Lube Oil

The third experiment conducted was to determine the temperature dependance of the Electrode System with Diesel Lube Oil. The temperature dependence was determined by measuring the resultant current draw of the electrodes at various temperatures. This was done in order to ensure adequate Power was available from the Power Supply system at any reasonable operation temperature. The test was performed at the operating condition of 2000Vacrms and 1000Hz frequency. The results of the tests are shown in Table 3.4 below; as temperature was varied from 75F to 165F, the current increased from 11.73mA to 24.39mA.

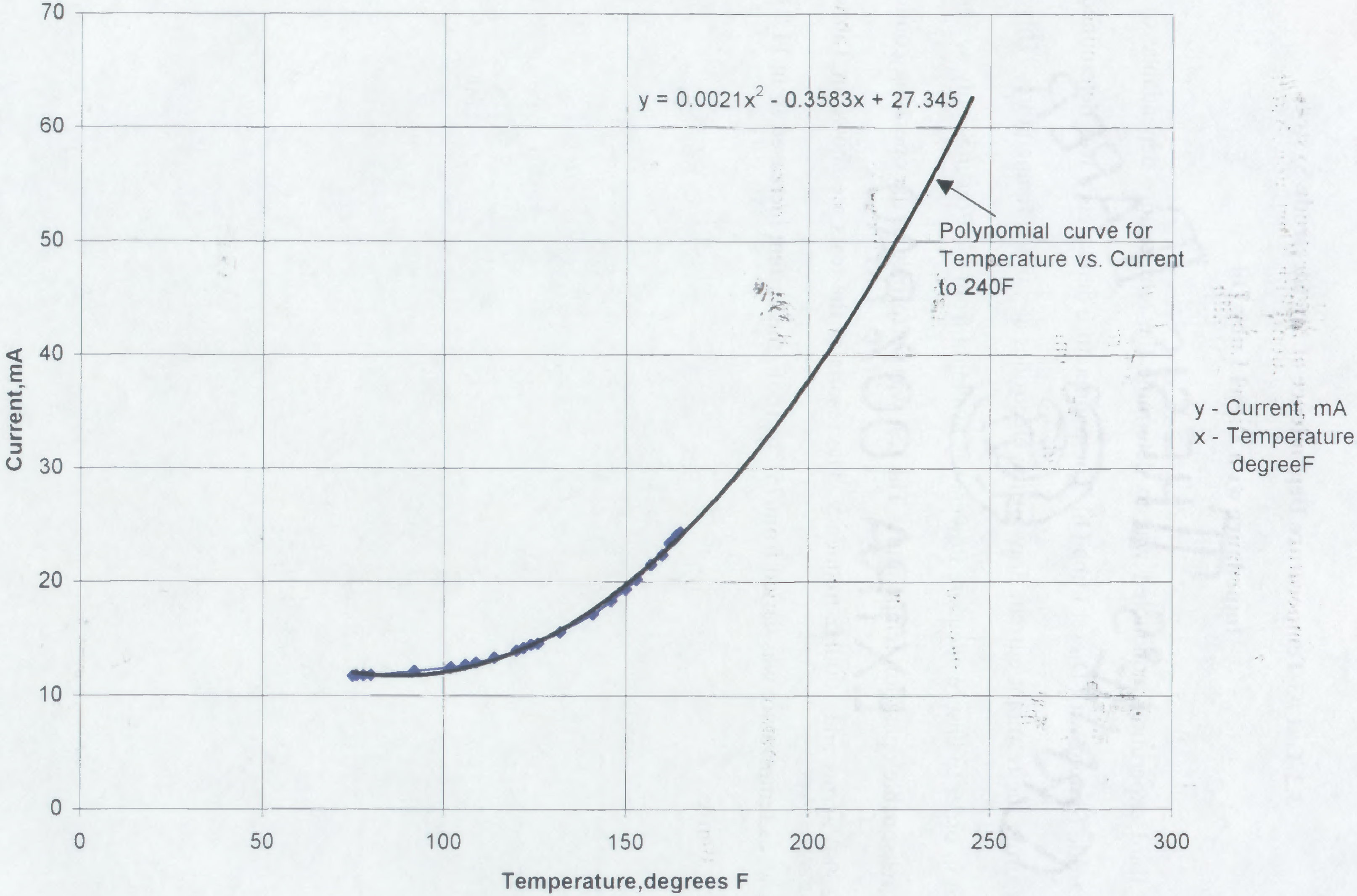


Figure 3.4 Temperature vs. Current (2000V, 1000Hz).

Table 3.4 Temperature vs. Current at 1000Hz, 2000V

Temperature (F)	**Current (mA)**	
75	11.73	
76	11.74	
78	11.75	
80	11.78	
92	12.16	
102	12.46	
106	12.69	
109	12.92	
114	13.33	
120	13.93	
122	14.21	
124	14.48	
126	14.57	
132	15.58	
141	17.15	
146	18.36	
150	19.34	
153	20.22	
157	21.49	
160	22.34	
162	23.39	
163	23.67	
164	24.11	
165	24.39	

Note: Refer to Figure 3.4 Temperature vs. Current at 2000V & 1000Hz

Since the maximum temperature achieved, 165F was lower than the operation temperature requirement of 240F (due to the current limit of the Power Supply) a trend analysis of the data was performed in order to extrapolate and determine the current draw at 240F.

Examining the resultant data shows that the current varies with temperature in a parabolic manner. Thus, a quadratic equation was used to fit the data. The quadratic equation obtained for the trend line is:

$$y = 0.0021x^2 - 0.03583x + 27.345 \tag{3.4}$$

y- current, mA; x – temperature, degree F

From the trend line analysis, the predicted current draw at 240F is 62.313mAmp as depicted in Figure 3.4

From the experiments, it was concluded that for Diesel lube oil the voltage vs. current and frequency vs. current follows a linear relationship whereas current varies in a quadratic manner with respect to the temperature.

3.4 Contamination of Oil Effect on Current, Temperature Relation

The forth and fifth experiments were conducted to determine the relation of the conductivity of Diesel Lube Oil with oil contamination (i.e. cleanliness level). At this stage of the experiment it was thought that the earlier relations might not hold true if the contamination level of particles increases in the Lube oil. The number of particles in the oil may affect the behavior of Voltage-Current, Frequency-Current and Current-Temperature relationship.

The contamination effect was determined by measuring the resultant current draw of the electrodes for two different cleanliness levels. This was done in order to ensure adequate Power was available from the Power Supply system for different contamination level oils. The tests were performed at the operating condition of 1000Hz frequency and at varying temperatures.

The clean and contaminated samples were first measured for contamination levels using the HIAC Royco Particle Counter (Refer to Experimental Setup Figure 2.19) It was determined that ratio of number of contaminants in dirty vs. clean oil were as given in Table 3.5.

Table 3.5 Contamination Level of Lube Oil in terms of number of particles

Size (μm)	**A/B**	
2	14	
5	35	
10	24	
20	35	
50	27	

A- Number of particles in the contaminated oil.
B- Number of particles in the clean oil

These numbers were significant to conduct the experiment so that the effect of the contamination level on the results could be conspicuous.

3.4 (a) Test #4 Current vs. Temperature for Contaminated Oil at 1000V &1000Hz

The experiment was conducted on contaminated oil, which had the number of particle ratio with respect to the number of particles in clean oil as given in Table 3.5. This was later compared to the cleaner oil. The oil was first heated to 184F and then brought down slowly in a controlled environment from 194F to 98F. The temperature set on the controller was 184F but in actual practice the temperature rose to 194F. The current varied from 24.4mA at 194F and decreased to 6.4mA at 98F. Due to limitations on the power supply in terms of the maximum current drawn the temperature was not raised beyond 194F but following the trend line later the current for 240F was predicted. When plotted, this data followed a parabolic curve satisfying the equation:

$$y = 0.0021x^2 - 0.4234x + 28.138 \tag{3.5}$$

y - current, mA; x – temperature, degree F

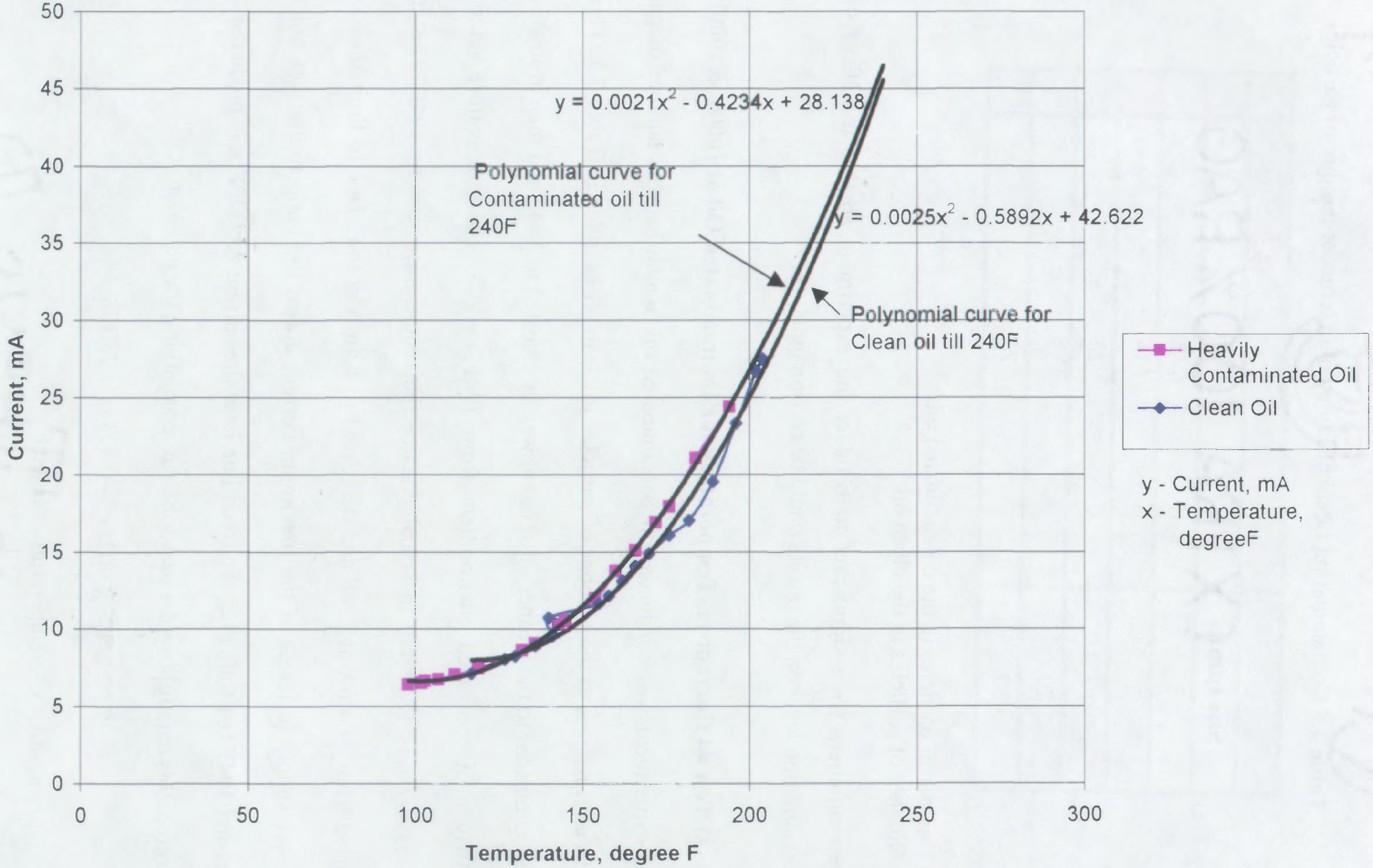


Figure 3.5 Temperature-Current Relation, for Clean and Contaminated Diesel Lube Oil@1000V,1000hz.

Table 3.6 Temperature vs. Current, Contaminated Oil at 1000V & 1000Hz

Temperature (F)	**Current (mA)**	
194	24.4	
184	21.1	
176	17.9	
172	16.9	
166	15.1	
160	13.76	
154	12	
145	10.56	
143	10.28	
136	9.07	
132	8.63	
119	7.45	
112	7.05	
107	6.76	
103	6.64	
102	6.52	
98	6.4	

Table 3.7 Prediction of Current at 240F from the polynomial Trendline for Contaminated Oil

Temperature (F)	**Current (mA)**	
240F	47.5	

The predicted current draw from the power source at 240F would be 47.5mA as shown in the Figure 3.5 and Table 3.7

3.4 (b) Test # 5 - Current vs. Temperature for Clean Oil

This experiment was conducted on oil, which was cleaner as compared to the oil in the previous experiment (Refer Table 3.5). In this experiment temperature was brought down from 204F to 117F for which the current came down from 27.5mA to 7.12mA. Here in this case too, as in Test # 4, the power supply was limited to a maximum temperature of 204F. Later from the trend line the current at 240F was predicted to be 45.2mA. Refer Table 3.8. When plotted, this data followed a parabolic curve satisfying the equation:

$$y = 0.0025x^2 - 0.5892x + 425.622 \qquad (3.6)$$

y - current, mA; x – temperature, degree F

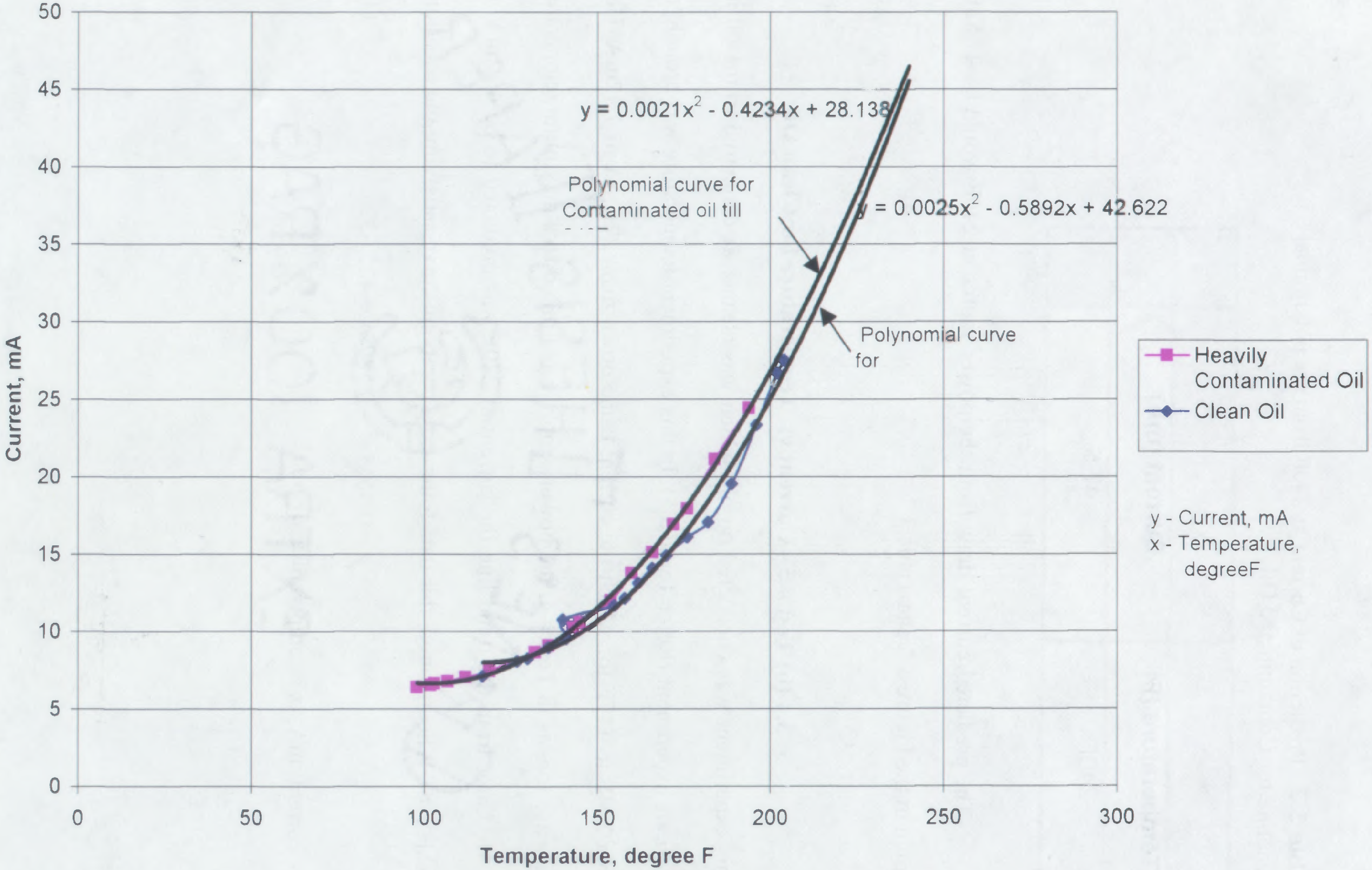


Figure 3.6 Temperature-Current Relation, for Clean and Contaminated Diesel Lube Oil@1000V,1000hz.

Table 3.8 Temperature vs. Current, Clean Oil at 1000V & 1000Hz

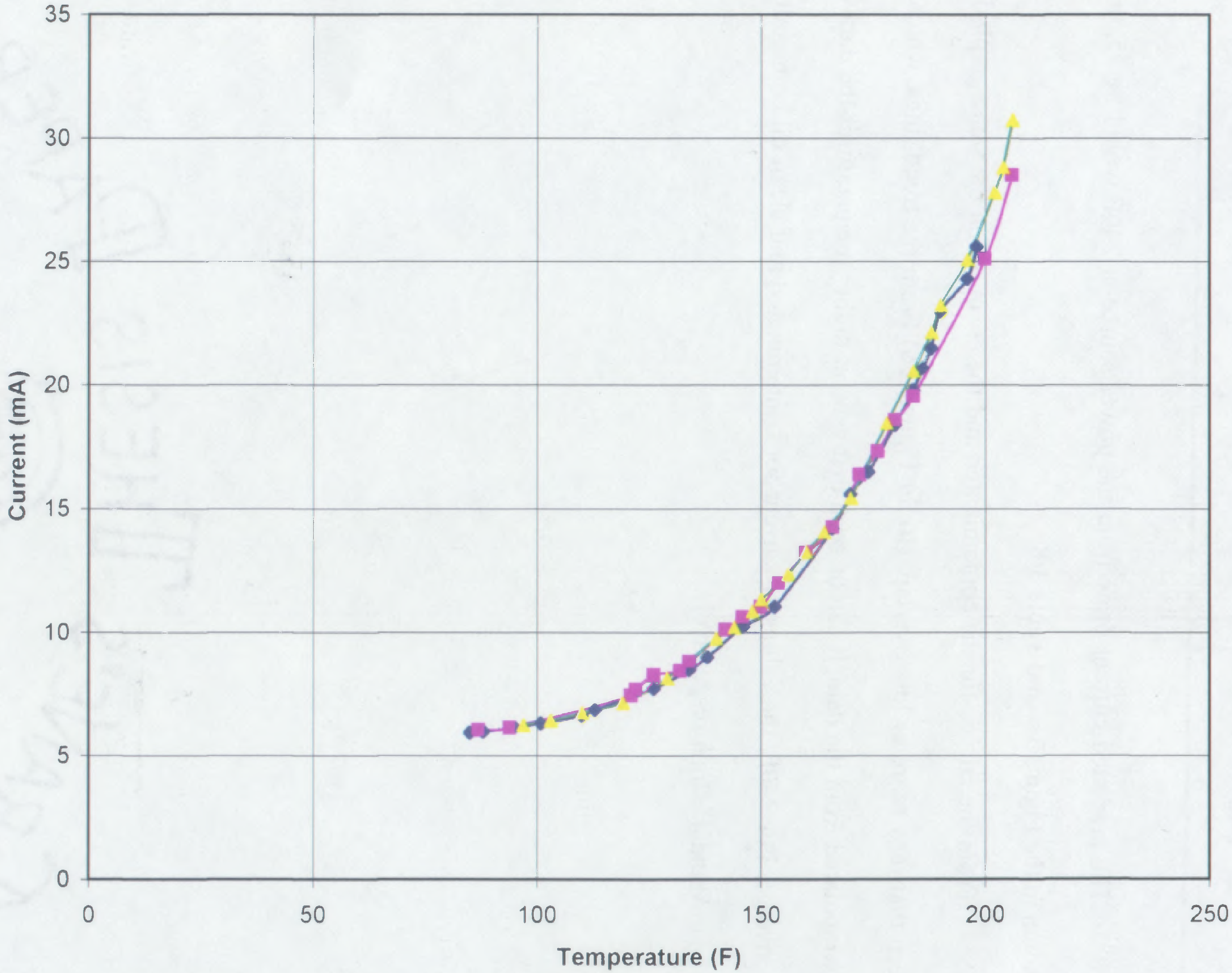
Temperature (F)	**Current (mA)**	
204	27.5	
202	26.69	
196	23.32	
189	19.52	
182	17.02	
176	16.09	
170	14.9	
166	14.06	
162	13.13	
158	12.15	
155	11.66	
140	10.74	
141	9.67	
141	9.52	
136	8.94	
130	8.24	
127	8.04	
117	7.12	

Table 3.9 Prediction of Current at 240F from the polynomial Trendline for Clean Oil

Temperature (degree, F)	**Current (mA)**	
240	45.2	

The predicted current draw from the power source at 240F would be 45.5mA as shown in the Figure 3.6 and Table 3.8

From the curves for the contaminated and the clean oil on the same graph, it was seen that they more or less overlap. (Refer Figure 3.6) From the trend lines, which were extrapolated from the data, it can be seen that even at higher temperatures the data would converge. For 240F, the values of current for contaminated and clean oil come out to be 47.5mA and 45.2mA respectively.



'x' on the dial represents **x** rpm and each rpm corresponds to **2.8ml/min**

Figure 3.7 Temperature vs. Current at Various Flow Rates (ml/min)@1000V.

3.5 Test #6 Flow Rate Dependence of the Electrode System Impedance with Diesel Lube Oil

This experiment was conducted at different flow rates, as it was thought that flow rate could be a crucial parameter, which could further put some limitations on the selection of the power source. To know the effect of flow rate a set of experiments for the same cell under similar conditions was conducted at various flow rates. The experiment was conducted at a voltage of 1000V with outlet temperature (temperature of oil coming out from the cell) falling from 198F to 85F. In this experiment the flow rate was maintained at 22.4ml/min. The current in this case fell from 25.6mA to 5.94mA at 198F and 85F respectively.

The second experiment conducted was at a flow rate of 16.8ml/min. In this case voltage was maintained at 1000V with outlet temperature of oil falling from 206F to 97F. The current in this experiment varied from 30.74mA to 6.25mA at 206F and 97F respectively.

In the third case, under similar conditions of voltage (ie 1000V) the flow rate was further reduced to 11.2ml/min and the temperature dropped from 206F to 97F. The current came down from 30.74mA to 6.25mA at 206F and 97F respectively.

The tests were conducted at three different flow rates of 22.4 ml/min, 16.8ml/min and 11.2ml/min and the temperature vs current curves were plotted on a graph at these flow rates (Refer Figure 3.7). Temperature vs. current were plotted so as to determine the change in current for varying temperatures for all the three cases of flow rate. The three curves converge on each other. From this it can reach a conclusion that flow rate doesn't affect the current vs. temperature relationship.

CHAPTER 4

CONCLUSIONS

This thesis was basically aimed at quantifying how much current was needed for a variety of operation parameters such as voltage, temperature, frequency, contamination level and flow rates. The results obtained at different temperatures of the order of 165 F to 200 F were later extrapolated to get the desired values at 240 F, temperature that is the normal operation temperature of Diesel Lube Oil.

Other important results in brief are stated below:

1. Linear Relation exists between current and voltage at frequency of 1000Hz and temperature of 75 F.
2. There is a linear relation between frequency and current at voltage of 2000V and temperature of 75 F.
3. Current varies with temperature according to the equation:

   $$y = 0.0021x^2 - 0.3583x + 27.345$$

   y - current, mA; x – temperature, degree F

   ie a quadratic relation holds true in this case at 1000Hz and 2000V.
4. Current drawn from the power source for contaminated and clean oil is almost the same for voltage and frequency of 1000V and 1000Hz respectively.
5. Flow Rate does not affect the temperature current relationship. The flow rate was varied from 40% to 80% of the maximum flow rate possible in three equal steps.

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