

AFRL-VA-WP-TR-1999-3056

**EFFECT OF PROLONGED
ELECTROHYDRODYNAMIC (EHD)
EXPOSURE ON AVIATION WORKING
FLUIDS**



JOHN S. PASCHKEWITZ

**MECHANICAL AND THERMAL SYSTEMS BRANCH
TATLAB
BLDG. 45 ANNEX
2130 8TH STREET, STE 1
WRIGHT-PATTERSON AFB, OH 45433-7542**

MAY 1999

FINAL REPORT FOR 01/12/1998 – 04/30/1999

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

19990803 097

**AIR VEHICLES DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7542**

QC QUALITY INSPECTED 2

NOTICE

USING GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA INCLUDED IN THIS DOCUMENT FOR ANY PURPOSE OTHER THAN GOVERNMENT PROCUREMENT DOES NOT IN ANY WAY OBLIGATE THE US GOVERNMENT. THE FACT THAT THE GOVERNMENT FORMULATED OR SUPPLIED THE DRAWINGS, SPECIFICATIONS, OR OTHER DATA DOES NOT LICENSE THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR CONVEY ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY RELATE TO THEM.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.



1LT John S. Paschkewitz
Thermal Systems Project Engineer
AFRL/VACM



Paul Ulrich
Chief, Mechanical and Thermal Systems
AFRL/VACM



Dennis Sedlock
Chief, Flight Systems Division
AFRL/VAC

Do not return copies of this report unless contractual obligations or notice on a specific document require its return.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE MAY 1999		3. REPORT TYPE AND DATES COVERED FINAL REPORT FOR 01/12/1998 - 04/30/1999
4. TITLE AND SUBTITLE EFFECT OF PROLONGED ELECTROHYDRODYNAMIC (EHD) EXPOSURE ON AVIATION WORKING FLUIDS			5. FUNDING NUMBERS IN-HOUSE PE 62204 PR 2402 TA 04 WU HX	
6. AUTHOR(S) JOHN S. PASCHKEWITZ				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) MECHANICAL AND THERMAL SYSTEMS BRANCH TATLAB BLDG 45 ANNEX 2130 8TH STREET, STE1 WRIGHT-PATTERSON AFB, OH 45433-7542			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AIR VEHICLES DIRECTORATE AIR FORCE RESEARCH LABORATORY AIR FORCE MATERIEL COMMAND WRIGHT-PATTERSON AFB, OH 45433-7542 POC: JOHN S. PASCHKEWITZ, 1LT, AFRL/VACM, 937-255-4640			10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-VA-WP-TR-1999-3056	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Two aviation working fluids, PAO and FC-72, were exposed to pulsed high voltage for 200 hours in a simulation of electrohydrodynamic heat transfer enhancement. The fluids were analyzed for changes in chemical, physical and electrical properties. The electrode surfaces were also analyzed for any observed buildup. No bulk fluid chemical or physical property changes were observed. There was a change in the electrical properties of PAO, as well as noticeable buildup on the electrode surfaces. This buildup was attributed to electrically induced oxidation reactions. The change in electrical properties could have application of an EHD-enhanced thermal management system are discussed.				
14. SUBJECT TERMS Electrohydrodynamics, EHD, active heat transfer enhancement, voltage exposure, charge injection, avionics cooling			15. NUMBER OF PAGES 22	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR	

CONTENTS

1. SUMMARY OF WORK	1
2. BACKGROUND	1
2.1 GENERAL BACKGROUND ON EHD ENHANCEMENT	1
<i>Table 1: Representative EHD enhancements in air.....</i>	<i>2</i>
<i>Table 2: Representative EHD enhancements in single-phase liquids.....</i>	<i>2</i>
2.2 PRIOR RESEARCH ON EHD EXPOSURE IMPACT ON FLUID PROPERTIES	3
3. EXPERIMENTAL.....	3
<i>Table 3: Summary of Experimental Conditions.....</i>	<i>6</i>
<i>Table 4: Summary of Fluid Analysis Tests Performed</i>	<i>6</i>
4. RESULTS AND DISCUSSION	7
4.1 BULK PROPERTY ANALYSIS	7
<i>Table 5: FC-72 Exposure Results.....</i>	<i>10</i>
<i>Table 6: PAO Exposure Results.....</i>	<i>12</i>
<i>Table 5: PAO Control Test Results.....</i>	<i>13</i>
4.2 SURFACE ANALYSIS	13
5. CONCLUSIONS.....	16
6. RECOMMENDATIONS	16
6.1 FUTURE WORK	16
6.2 RECOMMENDATIONS FOR A FIELDDED EHD SYSTEM.....	17
7. ACKNOWLEDGEMENTS	17
8. REFERENCES	18

TABLE OF FIGURES

Figure 1 : Test Loop Schematic.....	4
Figure 2: Test Specimen A	5
Figure 3: Test Specimen B	5
Figure 4: FC-72 Gas Chromatography Results.....	8
Figure 5: FC-72 IR Spectra	9
Figure 6: PAO Gas Chromatography Results.....	11
Figure 7: PAO IR Spectra.....	12
Figure 8: PAO GC Results - Check for Antioxidant Depletion.....	15

1. Summary of Work

Two aviation working fluids, PAO and FC-72, were exposed to pulsed high voltage for 200 hours in a simulation of electrohydrodynamic heat transfer enhancement. The fluids were analyzed for changes in chemical, physical and electrical properties. The electrode surfaces were also analyzed for any observed buildup. No bulk fluid chemical or physical property changes were observed. There was a change in the electrical properties of PAO, as well as noticeable buildup on the electrode surfaces. This buildup was attributed to electrically induced oxidation reactions. The change in electrical properties could have been due to variations in moisture content, a variable that was not tightly controlled. Implications for the design and application of an EHD-enhanced thermal management system are discussed.

This work is part of a larger study investigating the application of electrohydrodynamic enhancement to aircraft systems. The effort includes parametric testing to determine the impact of various operating variables on the fluid physics and heat transfer behavior. The parametric data combined with transient testing data will enable the design of a control system for a "smart" EHD-enhanced thermal management system in which heat transfer can be actively modified.

2. Background

2.1 General Background on EHD Enhancement

Electrohydrodynamic (EHD) enhancement is a promising technique for making large improvements in heat transfer, particularly in single-phase liquids or gases, which are typically act as dominant heat transfer resistances. Application of an intense (kV/cm) electrical field to a low conductivity (typically nS/m) liquid will generate secondary motion in the fluid (Fernandez and Poulter, 1987). The resulting secondary flow yields an increase in heat transfer. This increase in heat transfer can then be exploited to reduce heat exchanger surface area and volume.

The electrical body force is defined as (Chu, 1959):

$$F_e = \rho_e E - \frac{1}{2} E^2 \nabla \epsilon + \nabla \left(\frac{1}{2} \rho E^2 \left(\frac{\partial \epsilon}{\partial \rho} \right)_T \right) \quad (1)$$

In this equation, the first term represents the Coulomb force resulting from free charge in the fluid. This free charge results from electrochemical reactions at the fluid-electrode interface, referred to as charge injection, thermally induced electrical conductivity gradients, or the dissociation of trace impurities in the fluid bulk. The second term is called the dielectrophoretic force and accounts for spatial variations in the electric permittivity due to polarization or phase change. The last term is the electrostriction term and accounts for variations in the electric field and permittivity with density. Electrostriction is the principle by which piezoelectric materials operate. In air or a single-phase liquid, the dielectrophoretic and electrostrictive contributions are negligible when compared to the Coulomb force.

There have been numerous studies documenting the heat transfer augmentation performance of EHD (Jones, 1978). Some of these studies have been summarized in Tables 1 and 2 below. In all of the cases, enhancement has been significant and generally pressure drops have been relatively

low in comparison to other augmentation techniques. EHD is also promising since it is an actively controllable enhancement, allowing heat transfer to be improved on an “on-demand” basis. This type of application is particularly useful for systems where large pulses in heat load are observed and typically result in oversized thermal management hardware.

Table 1: Representative EHD enhancements in air

Source	Configuration	Re	Enhancement	Pressure Drop
Ohadi et al., 1991	Shell-tube	Tube = 2000, Shell = 500	322% increase in U	$\Delta P/\Delta P_o = 1.75$
Blanford et al., 1995	Tube-plate fin, air-side enhanced	1000 to 3000	$U/U_o = 1.9$ to 3.3	Not measured
Velkoff, 1979	Parallel wires, free stream over flat plate	$V = 0$ to 47.5 fps	$Nu/Nu_o = 3.75$ at $V = 4.6$ fps	Not measured
Bradley and Hoburg, 1985	Rectangular channel with nickel mesh	540, 750, 875	40% improvement in h	Not measured
Robinson, 1970	Heated, charged wire with coaxial pipe	92 ft/s	10% improvement in h	Not measured
Ohadi et al., 1991	Concentric wire-cylinder, single and double wire configurations	0 to 15000	215% improvement in h for single wire at $Re = 2000$ 260% increase in h for double wire at $Re = 3000$	Not measured
Tada et al., 1997	Parallel plates with centered wire	1200, 2400, 3950	300% increase in h	70% increase in pumping power
Moss and Grey, 1966	Concentric wire-cylinder	0 to 10000	100% increase in h at $Re = 1000$	Not measured

Table 2: Representative EHD enhancements in single-phase liquids

Source	Configuration	Fluid Used	Re	Enhancement	ΔP penalty
Fernandez and Poulter, 1987	Concentric wire-cylinder	transformer oil	150	$Nu/Nu_o = 20$	$\Delta P/\Delta P_o = 3$
Fujino et al., 1989	Parallel Plates	R113 (liquid phase)	191	$Nu/Nu_o = 4$	$\Delta P/\Delta P_o = 1.5$
Perez et al., 1987	Concentric wire-cylinder	transformer oil	50	$Nu/Nu_o = 10$	Not meas.
Poulter and Miller, 1984	Concentric wire-cylinder	Aviation fuel (Avtur)	500-2500	$Nu/Nu_o = 10$	Not meas.

However, the impact of EHD exposure on the fluid properties or chemical composition have not been well-investigated. As discussed above, free charge from electrochemical reactions at the electrode surfaces or dissociation of impurities in the fluid bulk will have a direct impact on the electrical body force and therefore the heat transfer enhancement. It is possible that the chemistry behind these sources of free charge could change over time due to prolonged high voltage exposure. There has been little research on the effect of prolonged high voltage exposure on heat transfer working fluids, and none on fluids of aviation interest.

Unfortunately, surface chemistry and electrochemistry are sciences in their analytical infancy. It is not possible with state-of-the-art computational chemistry to accurately predict metal-fluid electrochemical interactions. Even the experimental investigation of reaction kinetics or

product/reactant identification is a difficult task (Bockris, 1993). For EHD flows in particular, the trace level impurities (in the ppm to ppb range) in the fluid and on the metal surface (which profoundly impact system behavior), are difficult and highly expensive to identify and characterize. Therefore, this work and others on EHD exposure effects are largely empirical.

2.2 Prior Research on EHD Exposure Impact on Fluid Properties

There are a small number of published works investigating the exposure effects of EHD on working fluids. Seyed-Yagoobi *et al.* (1984) reported the removal of impurities and a drop in the fluid conductivity as a result of exposure to both AC and DC electric fields in transformer oil. Yamashita and Yabe (1997) conducted the most thorough test of fluid exposure, using a EHD-enhanced refrigerant R-123 (CHCl_2CF_3) evaporator with a steady 20 kV voltage for 1000 hours. They analyzed both the working fluid and the electrode and heat exchange surfaces. A thin gray-black film deposited on the electrode and heat transfer surfaces was determined to be primarily carbon with trace amounts of aluminum, silicon and oxygen using Auger spectroscopy and XPS. They concluded that the carbon was the product of localized R-123 breakdown and the inorganic materials originated in the desiccant used in their test. Like Seyed-Yagoobi, they also reported improvements in the fluid purity and electrical properties, seeing an order of magnitude decrease in the fluid electrical conductivity.

Seyed-Yagoobi (1999) recently performed a continuous six-month exposure test with an EHD-enhanced condenser (using R-123) and monitored both enhancement performance and chemical composition using mass spectrometry. The heat transfer performance varied with time. However, no chemical changes were observed in samples of the working fluid.

In a high-voltage metal electrode/dielectric fluid system, some ionization or electrochemistry might be expected. Ion injection in dielectric liquids using a variety of electrode materials and configurations has been investigated and reported in the literature for nearly thirty years. (Denat *et al.* (1979) and Alj (1985)). The low concentrations of ions present in the fluid would be unlikely to cause bulk chemical changes.

Although electrochemical changes in the bulk of the fluid are unlikely, it is quite possible that the local electric fields around a narrow wire can reach strengths that may induce local oxidation or reduction of the working fluid, forming an oxide layer. This buildup could be expected to impact the charge injection behavior or the transient current behavior, which would be of interest in a pulsed EHD system (Zahn, 1998). Work conducted by AFRL/VACM has shown that transient current and heat transfer performance are directly correlated.

The objective of this work was to investigate the impact of pulsed EHD exposure on two fluids of interest for aviation systems. No prior work has investigated either the effect of pulsed exposure or aviation fluids. The high voltage was pulsed in order to simulate an "on-demand" EHD system which would allow selective application of enhancement. This type of system could be useful for a mission profile with large "spikes" in heat load.

3. Experimental

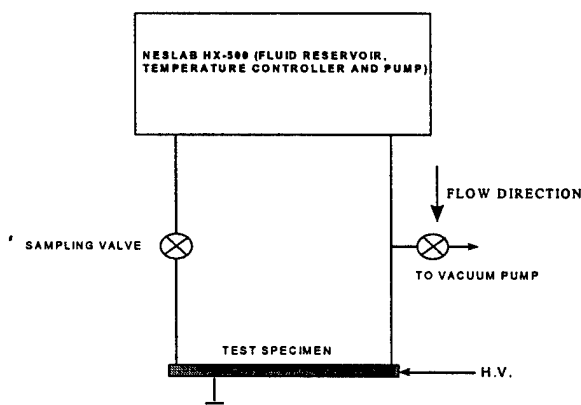
Two working fluids were selected for exposure testing, hydrogenated polyalphaolefin decene dimer (PAO) and FC-72. PAO is a widely used avionics coolant that is both chemically inert and electrically insulative. PAOs in general are a blend of various olefins that vary in molecular weight with viscosity grade. For this test, ROYCO 602 2cSt PAO conforming to MIL-PRF

87252 was used which contains many isomers of twenty carbon hydrocarbons. This PAO also contains a phenolic antioxidant additive (~ 0.5% by weight) that gives the fluid a pale yellow color. FC-72 is the 3M trade name for perfluorohexane. FC-72 is not used in operational aircraft, but is a superior two-phase heat transfer fluid and liquid dielectric, and was tested as a potential future heat transfer fluid. FC-72 has exceptional electrical properties and low solubility for polar contaminants that make it attractive for EHD use.

This test simulated representative flow conditions that would be expected on a typical aircraft environmental control system. The system was run at isothermal conditions in order to simplify the experiment. Thermal breakdown of either fluid does not occur at typical operating temperatures on the order of 40°C. The voltage was pulsed for 30 seconds on/off since the application of "on-demand" cooling would be on the order of 30 seconds to several minutes, depending on the subsystem needing cooling. A constant DC voltage was used to simulate repeated enhancement for a given subsystem. A voltage of 10kV was used throughout the test. In actual EHD heat exchanger operation, applied voltages might be higher. In the test loop, both working fluids were circulated at lower flowrates than typically seen on actual units in order to increase the residence time in the specimen and enhance the likelihood of electrical interaction.

The test loop was constructed as shown in Figure 1. The system consisted of a NESLAB HX-500 fluid refrigeration unit, an EHD test specimen connected to a Glassman 40 kV, 50 mA high voltage power supply (HVPS), an EG&G turbine flowmeter, and a Dopak in-line fluid sampling valve. All plumbing consisted of 316 stainless steel. The HVPS was controlled using a Hewlett-Packard 0-10 V low voltage power supply connected to a National Instruments GPIB controller card in a Pentium PC. A custom Visual BASIC program was used to control the operation of the power supply. Voltage on and off times and voltage magnitude could be specified using the software. Voltages and currents were obtained from the HVPS display. Currents were typically unmeasurable (<0.01 mA). The turbine flowmeter was connected to an EG&G FC-70 flow computer which was programmed to compensate for the differences in viscosity between FC-72 and PAO. A desiccant filter was not used since typical aircraft cooling loops do not have one in-line.

Figure 1 : Test Loop Schematic



Two test specimens were used. For the first 2000 cycles of the FC-72 test, a channel specimen (test specimen A) shown in Figure 2 was used. This specimen was used in previous work and repaired for use in this test. The replacement of the original borosilicate glass windows with polycarbonate ones and the use of silicone sealant in place of the original Teflon seals caused fluid compatibility problems. The specimen was replaced with a 316 stainless steel wire-cylinder design (test specimen B) shown in Figure 3. This specimen was used for the remainder of the testing.

Figure 2: Test Specimen A

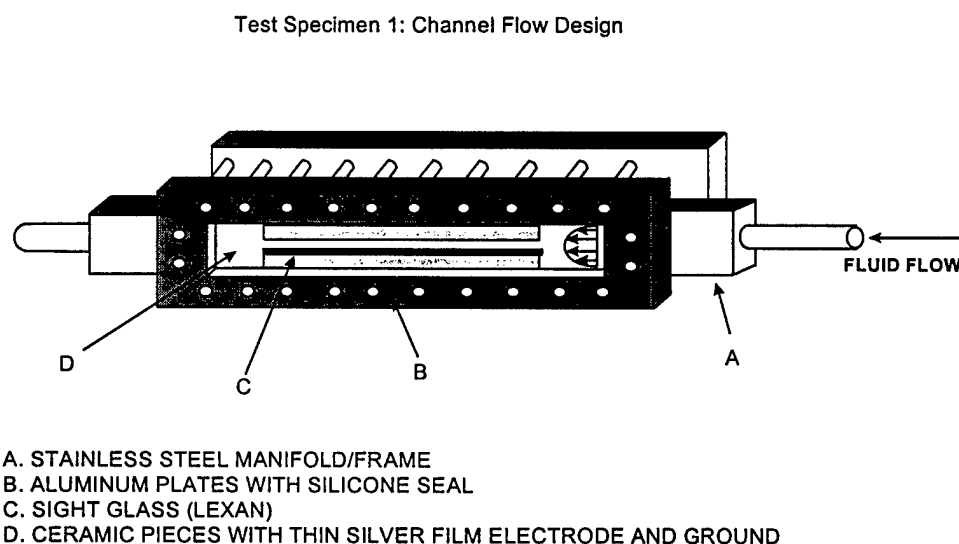
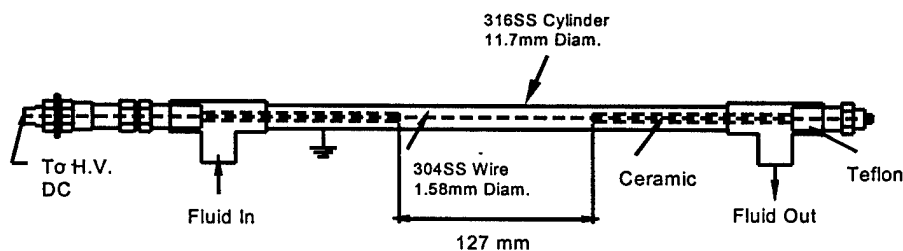


Figure 3: Test Specimen B



A summary of the experimental conditions for each of the working fluids is given in Table 3.

Table 3: Summary of Experimental Conditions

Fluid	Voltage and Frequency	Flowrate (Reynolds No.)	Total No. exposure cycles/time	Temperature
FC-72	10 kV, 30 sec on/off square wave	0.30 ± 0.01 gpm Re = 223 (specimen A) Re = 151 (specimen B)	10,834 (with 1994 using specimen A) 173 hours	$20^{\circ}\text{C} \pm 1^{\circ}\text{C}$
PAO	0	0.40 ± 0.01 gpm Re = 10	200 hours	$30^{\circ}\text{C} \pm 1^{\circ}\text{C}$
PAO	10 kV, 1 Hz square wave	0.40 ± 0.01 gpm Re = 10	11,939 198 hours	$30^{\circ}\text{C} \pm 1^{\circ}\text{C}$

Fluid samples were taken at the end of each five day working period for a total period of 20 days. For FC-72, only four samples were taken. Samples were dispensed into chemically cleaned sample bottles and sent to two laboratories for further analysis. Phoenix Chemical Laboratories (Chicago, Illinois) performed a series of ASTM tests to examine changes in bulk physical and electrical properties as well as infrared (IR) absorption spectroscopy and to examine chemical changes. The infrared analysis used a variable thickness thin film between potassium bromide plates. Phoenix also used atomic absorption to determine the metal content. The tests performed by Phoenix were conducted on the initial and final samples from the test loop. All samples, including ones of virgin material not exposed to the test loop, were analyzed using gas chromatography, performed by the AFRL Materials Directorate (AFRL/MLBT). A HP6890 gas chromatograph with a FID was used to qualitatively analyze chemical changes in the working fluids. Table 4 summarizes the tests used, and estimated uncertainties in the results. Detailed descriptions of the test methodologies are given in the Annual Book of ASTM standards (1999).

Table 4: Summary of Fluid Analysis Tests Performed

Test	Description	Details	Uncertainty
ASTM D2624	Electrical Conductivity		± 1 pS/m for conductivity < 20 pS/m (FC-72) $\sim \pm 20$ pS/m for 200-500pS/m
ASTM D877	Dielectric Strength	Tested at room temp.	$\sigma/\text{mean} \leq 0.1$ for consistency "pass"
ASTM D2717	Thermal Conductivity	Tested at 30°C	$\pm 5\%$
ASTM D445	Kinematic Viscosity	Tested at 40°C (FC-72) at 30°C (PAO)	$\pm 5\%$
ASTM D2766	Specific Heat	Tested over range of 20°C to 50°C (FC-72) Tested at 30°C (PAO)	$\pm 5\%$ (5-point) $\pm 10\%$ (single point)
Metals Content	Atomic Absorption	Ag (FC-72) Cr, Fe (PAO)	$\pm 10\%$
IR spectroscopy		Thin film w. KBr plates	N/A
Gas chromatography		FID, sub-ambient cryogenic method	$\pm 0.1\%$

The tests were chosen to examine the effects, if any, on the chemical, electrical, and thermal properties of the fluid. Differences in GC chromatograms and IR spectra would indicate

chemical changes or breakdown, which could then be linked to differences in the bulk properties determined using the standardized ASTM test methods. The three thermal property tests were chosen to examine to possible effects on heat transfer properties due to electrically induced chemical changes. Metals content testing was used to determine if any charged electrode material-fluid interactions had occurred. The original specimen used a silver electrode, while the replacement used a 304 stainless steel electrode, an alloy consisting primarily of chromium and iron.

After completion of the 20 days of testing with FC-72, the test loop was drained, flushed with isopropyl alcohol and PAO, and then refilled. The PAO was then exposed to the high voltage for 20 days with samples taken as described before.

A "control" test was completed to determine if any of the changes in PAO properties were due to exposure to the test loop and not due to electrical exposure. The loop was drained, but not flushed with any solvent prior to this test. The test was run for a total of 200 hours with the samples taken every 50 hours. Upon completion of this control test, the loop and test specimen were disassembled and examined. The wire within the specimen (see specimen B, Figure 3) was sent to AFRL/MLBT for analysis of surface buildup using supercritical fluid (SFC) and gas chromatography.

4. Results and Discussion

4.1 Bulk Property Analysis

Figure 4 is a series of gas chromatograms for FC-72. The series shows that no changes occurred in the chemical composition as a result of the exposure. The fluid purity decreased from 96% to 94% after being taken from the manufacturer's drum and loaded into the test loop. Each of the four samples show no significant differences in composition, thus the fluid remained unchanged chemically. The IR spectra for the FC-72 samples are shown in Figure 5. The differences in the spectra are an artifact of the test method used. The percent transmission is a function of the variable film thickness, so only characteristic peaks can be compared. The only true difference is a small peak at 3700 cm^{-1} , which is due to a trace amount of water introduced into the loop. The peak at approximately 2400 cm^{-1} in the zero exposure sample spectrum is an overtone of the high absorbance at approximately 1200 cm^{-1} . The same peak can be seen in the post-exposure data, but due to the differences in film thickness the overtone is not as pronounced.

FC-72 Gas Chromatography Results

Current Chromatogram(s)

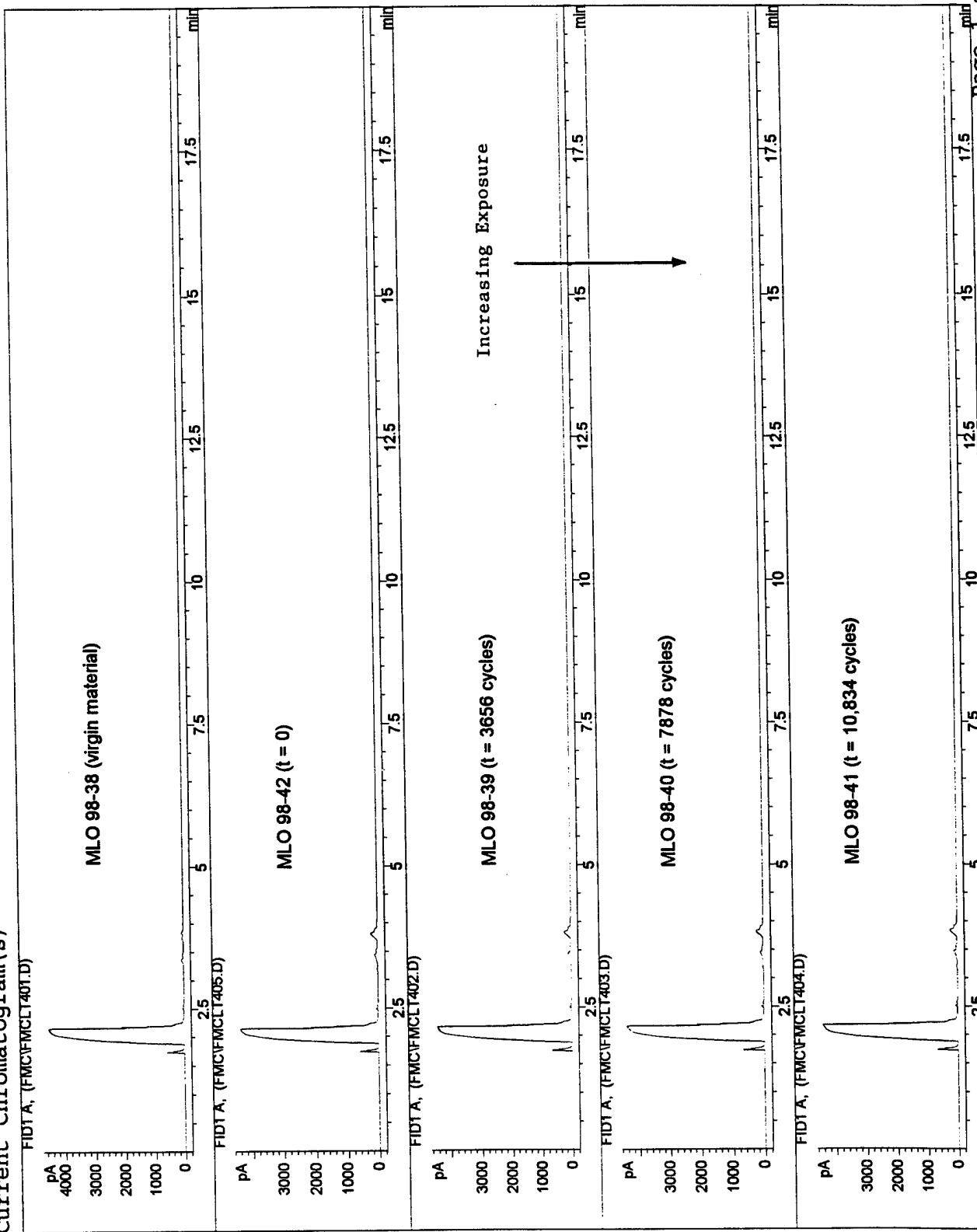
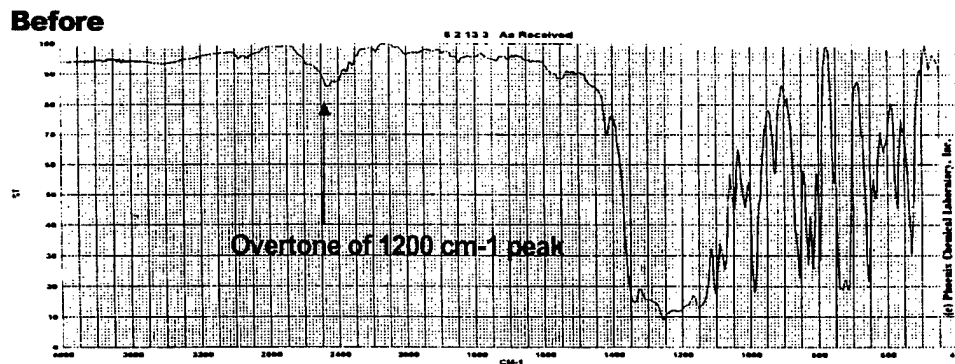
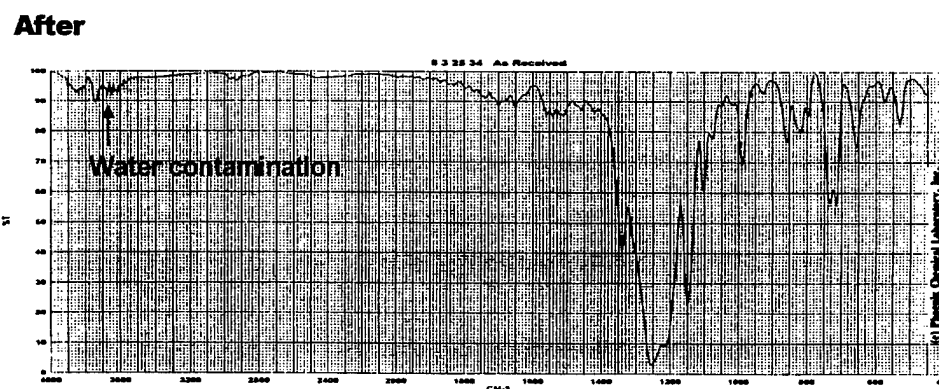


Figure 5: FC-72 IR Spectra



FC-72 IR Spectroscopy results



The lack of chemical change is in agreement with the absence of bulk property changes, as summarized in Table 5.

Table 5: FC-72 Exposure Results

Test	Mfr's Data (3M) (typical)	Before 0 cycles	After (10,834 cycles)	Notes
Electrical conductivity	1.0 pS/m	<1 pS/m	< 1 pS/m	Below minimum threshold of test
Dielectric Strength (unfiltered), kV (1" gap)	N/A	40.2 *	46.9±2.8	*= did not meet statistical consistency criterion
Dielectric Strength (filtered), kV (1" gap)	38	46.0± 1.75	45.2±2.6	
Silver, ppm	N/A	< 0.001	< 0.001	
Viscosity, @ 40°C, cSt	0.35	0.36	0.36	
Thermal Conductivity, cal/sec (cm ²) (°C/cm) @ 30°C (x10E5)	13.6	19.3	19.1	
Specific Heat (cal/g °C)				
@ 20°C	0.250	0.262	0.244	±5% uncertainty
@ 30°C	0.252	0.267	0.250	
@ 40°C	0.255	0.272	0.256	
@ 50°C	0.260	0.277	0.262	

All of the base case, "no EHD" exposure values closely agree with manufacturer's data. The results of the dielectric strength testing on the unfiltered samples suggest that the fluid may have been purified slightly by the electric field. The non-exposed unfiltered fluid was too contaminated to obtain a statistically meaningful measurement, but the unfiltered exposed fluid dielectric strength was clean enough to be measurable and identical to that of the filtered exposed fluid.

As with FC-72, the PAO GC results (Figure 6) show no significant chemical changes. Figure 7 shows the PAO IR spectra and as with the FC-72, the spectra are identical except for the absorbance variation. Again, this is an artifact of the test method used as described earlier.

PAO Gas Chromatography Results

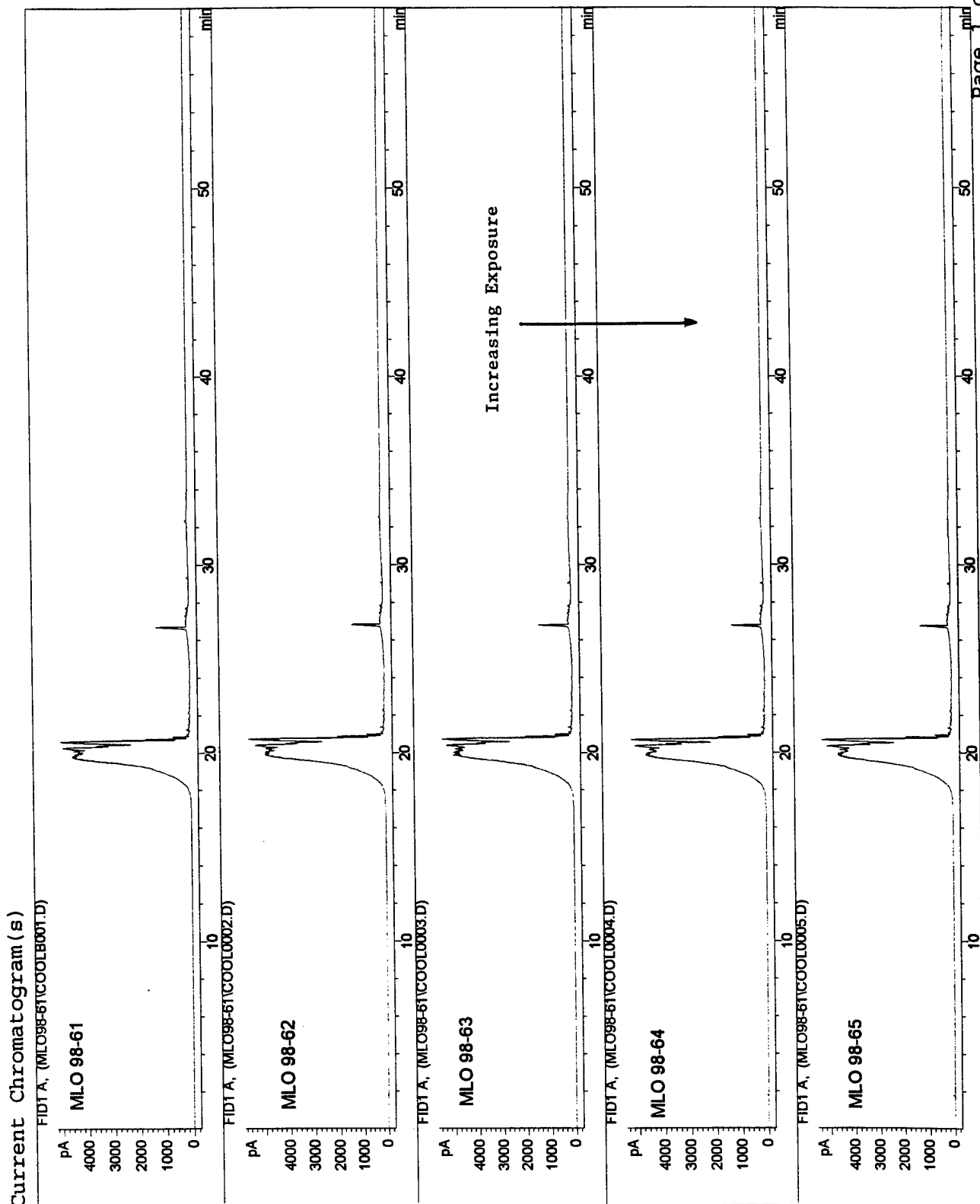
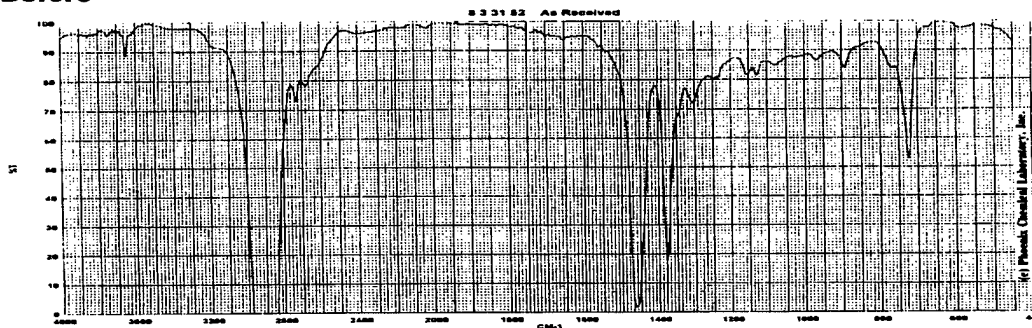


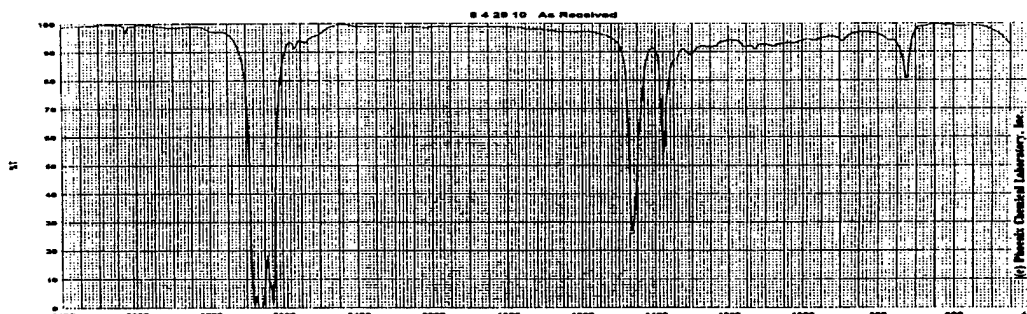
Figure 7: PAO IR Spectra

Before



PAO IR Spectroscopy results

After



There are substantial changes in the electrical properties as shown in Table 6. There is a 50% reduction of the dielectric strength and a 67% increase in the fluid electrical conductivity. Since the chromium content is below the detection level, there is essentially no correlation between the change in electrical properties and the metal content. The decrease in dielectric strength and conductivity after exposure and filtering suggests that the source of contamination is not a conductive particulate.

Table 6: PAO Exposure Results

Test	Mfr's Data	Before 0 cycles	After (11,939 cycles)	Notes
Electrical conductivity	100 pS/m	270 pS/m	450 pS/m	
Dielectric Strength (unfiltered), kV (1" gap)	N/A	22.6 ± 6.23*	29.1 ± 4.08*	* = did not meet statistical consistency criterion
Dielectric Strength (filtered) kV (1" gap)	35	46.6 ± 1.69	26.8 ± 3.68	
Chromium, ppm	N/A	<0.003	<0.01	
Iron, ppm	N/A	0.30	0.29	
Viscosity, 40°C, cSt	7.5	7.49	7.35	
Thermal Conductivity cal/sec(cm²)(°C/cm) 30°C, (x10E5)	33.9	32.0	32.6	
Specific Heat (cal/g °C) @ 30°C	0.53	0.487	0.486	±10% uncertainty

The PAO control test results are given in Table 7. The fluid conductivity values are significantly different than those obtained from the exposed samples. This variation in conductivity could be due to batch to batch variation in the product (two different drums of the same product from the same manufacturer were used), specimen changes during shipping to the laboratory, or inherent reproducibility in low conductivity measurement. There is no change in the chromium content and an increase in iron content. For the control, copper content was also measured and this value decreased after 200 hours of exposure. Although there are changes in the fluid properties, these changes are substantially different than those observed due to the electrical exposure.

Table 5: PAO Control Test Results

Test	Mfr's Data	Before 0 hrs	After (200 hrs)	Notes
Electrical conductivity	100 pS/m	90 pS/m	60 pS/m	
Dielectric Strength (unfiltered), kV (1" gap)	N/A	29.8*	47.2	* = did not meet statistical consistency criterion
Dielectric Strength (filtered) kV (1" gap)	35	50.6	52.8	
Chromium, ppm	N/A	<0.002	<0.002	
Iron, ppm	N/A	0.12	0.18	
Copper, ppm	N/A	0.91	0.51	
Viscosity, 40°C, cSt	7.5	7.49	7.35	
Thermal Conductivity cal/sec(cm ²)(°C/cm) 30°C, (x10E5)	33.9	32.0	32.6	
Specific Heat (cal/g °C) @ 30°C	0.53	0.487	0.486	±10% uncertainty

A likely cause of the variation in electrical properties is the fluid water content. Since a desiccant was not used in the test loop, fluid water content could have been considerable. PAO has a water solubility of approximately 150 ppm, which could be responsible for the large variations in the electrical conductivity and the dielectric strength. Since there is no clear correlation between the content of any of the metals checked for and the electrical properties and water content was not measured, there can be no conclusive discussion of this variable in this work.

4.2 Surface Analysis

Disassembly of the specimen after PAO EHD exposure testing revealed a thick dark brown sludge had been deposited on both the wire and cylinder surfaces. This sludge was never completely soluble in any of the solvents used to prepare it for chemical analysis using gas chromatography or supercritical fluid (SFC) chromatography, including hexane, acetone, THF or methylene chloride. The material that was solvated was chemically homogeneous and consistent with GC data for PAO. The GC and SFC peaks were primarily those of the solvent due to the low sludge solubility.

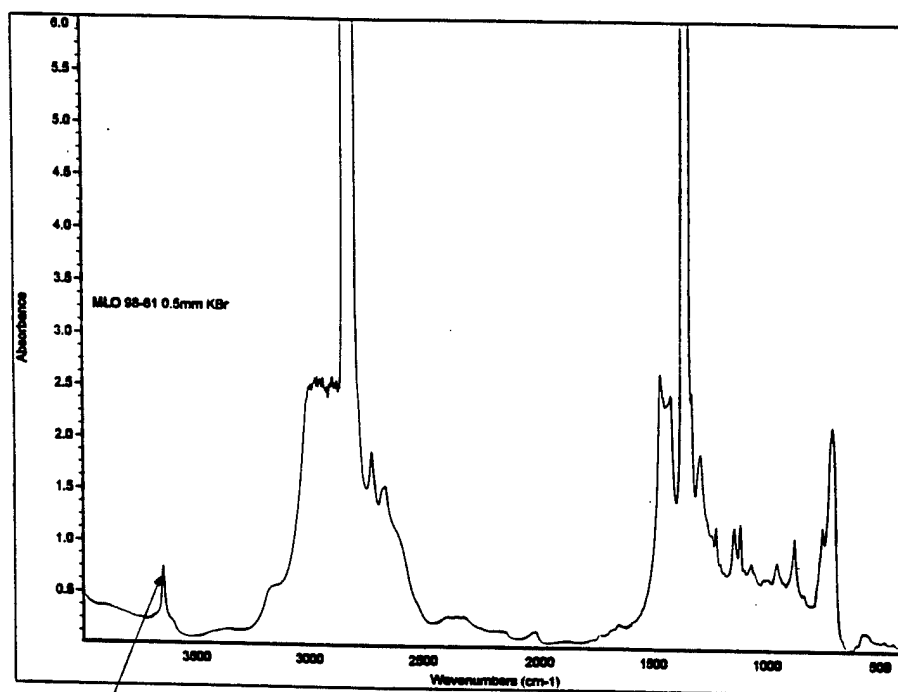
This result, combined with the low particulate content in PAO required to meet military specifications, suggests that the sludge is an electrically induced oxidation product. The physical appearance of the sludge closely resembled that of thermally oxidation products. Given the low solubility of the buildup and GC data, the sludge appears to be "coke" from nearly complete oxidation of the PAO. This coke buildup on the surface of the electrode might have a

detrimental effect on the EHD enhancement performance. No known study has investigated the role of localized oxidation buildup at the electrodes on EHD flows.

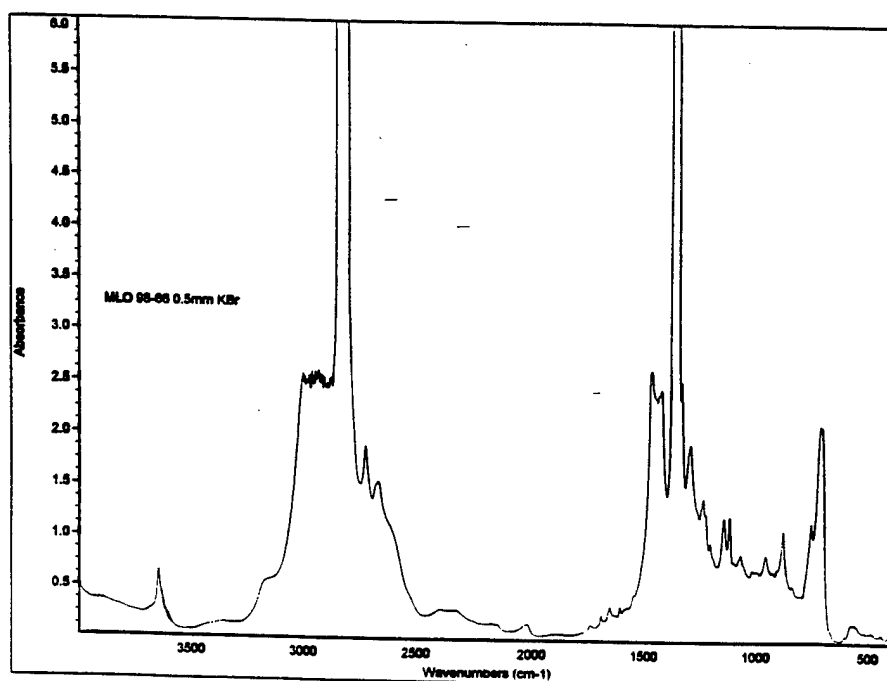
Thermal oxidation analysis on transformer oils, which are frequently exposed to electrohydrodynamic effects, has been completed by at least one author (Lamarre et al., 1987). It would be expected that electrical oxidation would exhibit similar results to the thermal oxidation case. Lamarre et al., found that the dielectric constant and conductivity of mineral oils were a variable of the dissolved-copper, peroxide, and soluble acidity contents. Based on their analysis of the sludge and the fluid electrical properties as oxidation progressed, the authors concluded that changes in electrical properties occurred after the antioxidant was completely neutralized and sludge formation became significant. The acidity of the oil increased significantly as the sludge formed.

This result suggests that the use of an acidity test, for example ASTM D974, should be used to infer the buildup of sludge over time due to EHD exposure. Using the samples taken from the EHD-exposed PAO, AFRL/MLBT tested for acid number and used fixed path-length IR spectroscopy to determine if the antioxidant had been depleted. The acid number was zero for both the unexposed and 200 hour exposure samples. The IR spectra are shown in Figure 8. The antioxidant peak is at approximately 3800 cm⁻¹ and no change in the area of the peak is observed, suggesting that there is no significant antioxidant depletion in the bulk. Combined with the acid number data, these results suggest that the oxidation is localized near the electrode surface. This highly localized behavior will make monitoring of the sludge buildup at the electrode a difficult task.

Figure 8: PAO GC Results - Check for Antioxidant Depletion



Antioxidant Peak (3800 cm-1)



5. Conclusions

This work demonstrated that EHD enhancement has some effect on two aviation working fluids. Although bulk fluid properties remained unchanged due to exposure to the intense electrical field, there were localized changes at the electrode surface. Although heat transfer performance was not examined, it would be expected that these changes would affect the overall system performance. It is also likely that these effects would be observed in other working fluids than the ones tested here.

An implication of the test results is that water content must be very tightly controlled within an EHD-enhanced system. A desiccant filter will be required to prevent large increases in electrical conductivity due to water content. Increased conductivity will act to decrease the EHD effect and increase power consumption (overall current will be increased). Very high water or other impurity content could result in a short-circuit which would prevent the use of EHD altogether.

It is possible that there are measurable metal content changes that affect the EHD performance. It would be ideal to use an atomic absorption unit that can examine the content of multiple metals at a time. Significant changes in metal content would provide insight into specific metal-liquid interactions that would impact heat transfer performance.

6. Recommendations

6.1 Future Work

This work showed that fluid changes are localized and helped to refine the chemical analysis tool kit that will make future testing more insightful. Experimental variables need to be more tightly controlled to accurately assess what changes are due to EHD. Unfortunately, the primary question of what the impact of EHD is on aviation working fluids has not been completely answered. The impact of the observed changes in bulk fluid electrical properties on the heat transfer performance also remains unresolved. A future test should incorporate the following:

- Identical batches of working fluid should be used for both the control and the exposed tests. Ideally the two tests would be run in parallel using identical equipment.
- All parts of the test loop that contact the fluid should be well-characterized meticulously cleaned and baked.
- Use a constant heat flux and voltage and monitor enhancement continuously.
- Measure current using a picoammeter before each fluid sampling or continuously.
- The fluid should be desiccated using a method for transformer oils (freezing and vacuum, desiccant)
- A desiccant of known composition should be incorporated into the test loop.
- Fluid samples should be examined for moisture content immediately after sampling.
- Fluid samples should be analyzed using GC (for organic chemistry changes) and atomic absorption (for a variety of metals).
- The electrode and tube surfaces should be thoroughly characterized prior to testing using a variety of surface chemistry tools (XPS, Auger) and after exposure using the same tools.
- Other advanced monitoring tools should be considered:
 - Use of an *in situ* spectroscopic method such as Mossbauer spectroscopy would allow real time analysis of the changes locally at the electrode-fluid interface, but integrating such a

system into a high voltage test article would present significant technical and cost challenges.

- Use of an electro-optic Kerr cell could provide real time visualization of changes in electric field and charge distribution of the working fluid, from which changes at the electrode surface might be inferred.

A test incorporating these suggestions should be able to better characterize any chemical changes that occur due to EHD exposure. The test would take a minimum of 5 weeks to run, but a longer exposure period, on the order of three to six months would be more realistic. This test is beyond the scope of this effort, and the suggested work will need to be completed by academia or industry.

6.2 Recommendations for a fielded EHD system

This work has demonstrated that the EHD technique may cause local fluid oxidation at the charged electrode surface. For a "real-world" system, this problem can be tackled in several ways.

- Decrease the amount of oxygen in the working fluid
 - Increase the antioxidant in the working fluid. PAO already contains an antioxidant (intended to improve storage life), and it would be easy to implement an additive for a refill (much like the JP8+100 additive for fuel) that would not require a new specification or cause substantial logistics problems. The downside of this solution is that it might affect the EHD performance (increased antioxidant content might change the electrical properties) and would need to be experimentally characterized.
 - Use an inert gas or nitrogen blanket in the fluid reservoir.
- Water content is a critical variable for EHD systems. The water content could most easily be controlled using an in-line desiccant/filter unit like those seen on air-conditioning systems. This unit would need to be periodically changed. The resulting pressure drop penalty would need to be accounted for in a system-level analysis to determine if the EHD option is feasible.

Overall, it appears that cleanliness and fluid handling methods similar to those used for high voltage transformer oils will need to be implemented in the field/depot if this heat transfer enhancement method is employed in a serviceable system. Due to the sensitivity of EHD heat transfer enhancement performance to both oxygen and water content, an EHD-enhanced heat transfer system will be better implemented as a sealed unit that is not serviced but just replaced at the logistics centers.

7. Acknowledgements

The author would like to thank Lois Gschwender, Ed Snyder, and George Fultz (AFRL/MLBT) for going providing exceptional analytical chemistry support and interpretation of analytical results, as well as general technical support throughout the course of the project, and Chuck Blair (Wyle Labs) for his excellent technician support. The author would also like to thank Lois Gschwender, Ed Snyder, Bill Czyzewski and Dave Brown (both AFRL/VACM) for their assistance in the technical editing of the final manuscript.

8. References

- Alj, A., Denat, A., Gosse, B., and Gosse, J., 1985, "Creation of Charge Carriers in Nonpolar Liquids." *IEEE Transactions on Electrical Insulation*, Vol EI-20, No. 2, 221-231.
- American Society for Testing and Materials. *Annual Book of ASTM Standards*. Philadelphia, PA, ASTM, 1999.
- Blandford, M., Ohadi, M.M., and Dessiatoun, S.V., 1995, "Compound Air-Side Enhancement Heat Transfer Enhancement in a Cross-Flow Refrigerant-to-Air Heat Exchanger," *ASHRAE Transactions*, 101, 2.
- Bockris, J. O'M. and Khan, S., 1995, *Surface Electrochemistry: A Molecular Level Approach*, Plenum Press, New York.
- Bradley, R. and Hoburg, J., 1985, "Electrohydrodynamic Augmentation of Forced Convection Heat Transfer," *IEEE Trans. on Industry Applications*, Vol. IA-21, 6, 1373-1376.
- Chu, B.-T., 1959, "Thermodynamics of Electrically Conducting Fluids," *Phys. Fluids*, Vol.2, No.5, 473-484.
- Denat, A. B. Gosse, and J.P. Gosse, 1979, "Ion Injections in Hydrocarbons." *J. Electrostatics*, 7, 205-225.
- Fernandez, J.L., and Poulter, R., 1987, "Radial Mass Flow in Electrohydrodynamically-Enhanced Forced Heat Transfer in Tubes," *Int. J. Heat Mass Transfer*, 30, 10, 2125-2136.
- Fujino, T., Yokoyama, Y., and Mori, Y.H., 1989, "Augmentation of Laminar Forced-Convective Heat Transfer by the Application of a Transverse Electric Field," *ASME J. Heat Transfer*, Vol. 111, pp.345-351.
- Jones, T.B., 1978, "Electrohydrodynamically Enhanced Heat Transfer in Liquids- A Review," *Advances In Heat Transfer*, 14, 107-148.
- Lamarre, C., Crine, J.P., and Duval, M., 1987, "Influence of Oxidation on the Electrical Properties of Inhibited Napthenic and Paraffinic Transformer Oils," *IEEE Transactions on Electrical Insulation*, Vol. EI-22, No. 1, 57-62.
- Moss, R. and Grey, J., 1966, "Heat Transfer Augmentation by Steady and Alternating Electric Fields," *Proc. 1966 Heat Transfer and Fluid Mech. Inst.*, Stanford Univ. Press, Palo Alto, CA, pp. 210-235.
- Neve, R.S. and Y.Y. Yan, 1996, "Enhancement of Heat Exchanger Performance Using Combined Electrohydrodynamic and Passive Methods." *Int. Journal of Heat and Fluid Flow*, Vol.17, 403-409.
- Ohadi, M.M., Sharaf, N., and Nelson, D.A., 1991, "Electrohydrodynamic Enhancement of Heat Transfer in a Shell and Tube Heat Exchanger," *Experimental Heat Transfer*, 4, 19-39.

- Ohadi, M.M., Nelson, D.A. and Zia, S., 1991, "Heat Transfer Enhancement of Laminar and Turbulent Pipe Flow via Corona Discharge," *Int. J. Heat Mass Transfer*, 34, 4/5, 1175-1187.
- Perez, A.T., Atten, P., Malraison, B., Elouadie, L. and McCluskey, F.M.J., 1988, "Heat Transfer Augmentation Induced by Electrically Generated Convection in Liquids," *Experimental Heat Transfer, Fluid Mechanics, and Thermodynamics 1988*, R.K. Shah et al., ed., Elsevier Science Publishing, Inc., Amsterdam, pp. 941-947.
- Poulter, R. and Miller, I.A., 1984, "Heat Transfer Enhancement in Shell/Tube Heat Exchangers Employing Electrostatic Fields," *First UK Conference on Heat Transfer*, IChemE, London, pp. 707-715.
- Richardson, A.T., Castellanos, A., and Atten, P., 1987, "Single Phase Heat Transfer Augmentation in Dielectric Liquids using DC Electric Fields," *Inst. Phys. Conf. Ser. No. 85, Electrostatics '87*, Oxford, IOP Publishing, London, pp. 103-108.
- Robinson, M., 1970, "Convective Heat Transfer at the Surface of a Corona Electrode," *Int. J. Heat Mass Transfer*, 13, 263-274.
- Seyed-Yagoobi, J., P. Krein, J. Crowley, J. Chato, 1984, "Effects of Long-Term Low-Level Charge Injection on Insulating Oil," *Proceedings of the 1984 Conference on Electrical Insulation and Dielectric Phenomena*, Wilmington, DE, Oct. 1984, IEEE, Piscataway, NJ.
- Seyed-Yagoobi, J., 1999, personal communication.
- Tada, Y., Takimoto, A., and Hayashi, Y., 1997, "Heat Transfer Enhancement in a Convective Field by Applying Ionic Wind," *Enhanced Heat Transfer*, Vol. 4, pp. 71-86.
- Velkoff, H.R. and Godfrey, R., 1979, "Low-Velocity Heat Transfer to Flat Plate in the Presence of Corona Discharge in Air," *ASME J. Heat Transfer*, 101, 157-163.
- Yabe, A., Mori, Y. and Hijikata, K., 1987, "Heat Transfer Enhancement Techniques Utilizing Electric Fields," *Heat Transfer in High Technology and Power Engineering*, Yang, W-L, and Mori, Y., ed., Hemisphere Publishing Co., New York, pp. 394-405.
- Yamashita, K. and A. Yabe, 1997, "Electrohydrodynamic Enhancement of Falling Film Evaporation and its Long-Term Effect on Heat Exchangers," *ASME J. Heat Transfer*, 119, 339-347.