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THERMAL AND ELECTRICAL PROPERTIES OF LUBRICANTS FOR HEV/EV APPLICATIONS

Final Report

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COORDINATING RESEARCH COUNCIL, INC.
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Preface

CRC would like to acknowledge the member companies who helped supply base oils for this study including Chevron, Chevron Phillips Chemical Co., Croda, Dow Chemical, Infineum, Oleon, Phillips 66 Co. Additionally, Oleon contributed financially to this work by funding testing directly.

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List of Acronyms and Abbreviations

EV: electric vehicle
HEV: hybrid electric vehicle
CRC: Coordinating Research Council
SwRI: Southwest Research Institute

Executive Summary

At Coordinating Research Council's request, Southwest Research Institute and an outsourced lab conducted 5 thermal characteristic and electrical property tests at specified temperatures for a set of 29 samples to create a base oil database. The properties included density, kinematic viscosity, specific heat capacity, specific resistivity, and thermal conductivity. The temperature ranges tested ranged from -25°C to 130°C, and varied for the specific test method. Base oil samples were supplied ranging from Group I to Group V base oils. As the test temperature increased, density, kinematic viscosity, thermal conductivity, and specific resistivity values decreased, while specific heat capacity increased. Within each base oil group, as viscosity increased, the density and thermal conductivity values increased. Moving from Group I to Group IV, the density and specific heat capacity decreased while the thermal conductivity values increased.

Background

In an effort to better understand the thermal and electrical properties of lubricants used for hybrid electric vehicles and electric vehicle applications, CRC sought to create a database of these properties for Group I to Group V base oils with an emphasis on Group III through Group V base oils. The thermal characteristics such as thermal conductivity, density, viscosity, and specific heat are important to understand as they will need to be optimized for future hybrid and electric vehicle lubricants. Electrical properties such as electrical resistivity and conductivity are necessary to measure to ensure the non-conductance of lubricants used in the hybrid and electric vehicles. For those reasons, a matrix of thermal characteristic tests and electrical property tests at specified temperatures were conducted on 29 samples to generate a better understanding of these base stocks. In the need to understand the properties it was important to consider the laboratory quality practices, familiarity with testing, and precision.

Approach

The experimental plan was to measure kinematic viscosity, density, thermal conductivity, specific heat, and specific resistivity of 29 base oils suggested and supplied by CRC members and associated companies. The temperatures requested for these properties varied from -25°C to 130°C and are listed in Table 1 of the Oil Property Tests. This testing program lasted from February 1, 2021, when samples first arrived at SwRI, to June 30, 2021, when all testing was completed. The tests were completed on SwRI Work Orders G19648, G20057, and G20592.

Table 1: Oil Property Tests		
Item #	**Property**	**Test Method and Temperatures**
1	Kinematic Viscosity	ASTM D445 at 40, 100°C
2	Density	ASTM D4052 at 40, 60, 80, 95°C
3	Thermal Conductivity	ASTM D7896 at 0, 40, 70, 100, 130°C
4	Specific Heat	ASTM E1269 at -25, 0, 40, 70, 100, 130°C
5	Specific Resistivity	ASTM D1169 at 25, 40, 70, 100, 110°C

CRC member companies selected and sent all of the base oils for this study to SwRI. They are listed in Table 2: Sample Description. The samples varied from Group I to Group V with a range of viscosities to represent some of the base oils available on the market. The requested amount was 600 mL per sample to allow sufficient testing volume. Four (4) of the five tests were performed at Southwest Research Institute while ASTM D1169 specific resistivity was conducted at another lab, United Power Services, Inc in Nashville, Tennessee.

As samples arrived at different time points from different sources, a majority of testing (23 samples) was scheduled at a similar time, with 6 samples arriving afterwards. Tests were run as samples arrived and continued as additional samples arrived. The bulk of the samples, 27 of 29, were shipped together to the outsourced lab in one batch, however the last 2 samples were shipped separately. Hence, the completion of the tests varied for the samples and tests.

Table 2: Sample Description		
Sample name	**Trade name**	**Details**
Group I, 4 cSt	Holly	SN148
Group II+, 4 cSt	EHC45	
Group III A, 4 cSt	UltraS	
Group III B, 2 cSt	Yubase	
Group III B, 3 cSt	Yubase	
Group III B, 4 cSt	Yubase	
Group III B, 6 cSt	Yubase	
Group III B, 8 cSt	Yubase	
Group III+ B, 4 cSt	VHVI	
Group III+ A, 4 cSt	XHVI	GTL-based
Group III+ A, 8 cSt	XHVI	GTL-based
Group IV, 3 cSt	Synfluid (PAO)	
Group IV, 5 cSt	Synfluid (PAO)	
Group IV, 6 cSt	Synfluid (PAO)	
Group IV, 8 cSt	Synfluid (PAO)	
Group IV, 65 cSt	Metallocene (m-PAO)	
Group V, Di-ester, 3.2 cSt		Short chain branched
Group V, Monoester, 2.9 cSt		Mixed chain, mixed linear branched
Group V, Monoester, 4.2 cSt		Long chain linear
Group V, Monoester, 5.5 cSt		Long chain branched
Group V, Polyolester, 4.1 cSt		Short chain linear
Group V, Polyolester, 4.4 cSt		Medium chain linear
Group V, Adipate Ester, 4 cSt	Hitec	
Group V, PAG, 4 cSt	UCON OSP-18	
Group V, PAG Blend, 4 cSt	UCON LB-135	
Group V, bio-based Polyolester		
Group V, bio-based Di-ester		Multi branched
Group V, bio-based Monoalcohol Ester A		Branched
Group V, bio-based Monoalcohol Ester B		Multi branched

The selected standardized test methods are noted below in Table 3: Test Method Summary including the year designation, general test procedure, method significance, instrument used, and comments on test repeatability and reproducibility.

Testing was conducted as described per the ASTM methods with no additional repeat testing. Duplicate testing was offered but not selected for this project. Running a fresh new aliquot of the sample for each test or repeat test is recommended and never reusing any sample. A repeat test would be when a new sample aliquot is taken and gone through the whole test procedure.

To minimize test result variability, SwRI used certified technicians, calibrated and referenced equipment (where applicable), and adherence to quality certifications. SwRI accreditations include ISO 9001, ISO 14001, ISO 17025, and participation in ASTM and other industry crosscheck and proficiency testing programs. United Power Services, Inc. does participate in ASTM Proficiency Test Program for Insulating Fluids.

Table 3: Test Method Summary				
Test Method	General Procedure	Method Significance	Instrument	Precision
ASTM D445-21 Kinematic viscosity	A fixed sample amount, after equilibrating at test temperature, is allowed to flow under gravity into the capillary of a viscometer and this time is measured and used with the calibration constant of the viscometer to calculate the kinematic viscosity. Two determinations are made and the average of the two is reported.	Important property of sample in determining storage, handling, and operation conditions. This method limits application to Newtonian fluids where shear stress and shear rate are proportional	Manual kinematic viscosity baths, calibrated viscometers	Per test method, repeatability for base oils at 40°C is 1.01 % and at 100°C is 0.85% of the average of two results. Reproducibility for base oils at 40°C is 1.36% and at 100°C is 1.90% of the average of two results.
ASTM D4052-18a Density	Sample is prepared to temperature and injected into digital density analyzer where the change in the oscillating U-tube frequency determines the density of the sample	It is a fundamental physical property of sample used to characterize petroleum products	Anton Paar DMA 4500 M	Per test method, at 15°C, repeatability of base stocks is 0.00016 (single determination), while reproducibility is 0.00052 (single determination)
ASTM D7896-19 Thermal Conductivity	A thin wire is immersed in the test liquid where current is sent through the wire, heating the wire and liquid. As the wire cools, the wire resistance is measured and this temperature-time profile determines the thermal properties.	Fundamental property of a material measuring its ability to resist electrical current	ThermTest Flucon Fluid Control GMBA Lambda	Limited precision data as test method precision was based on one lab
ASTM E1269-11(2018) Specific Heat Capacity	A very small sample aliquot is placed into a pan and heated from initial temperature to final temperature at 20°C/min and the heat flow measured. Usually compared to a reference material (sapphire).	Measurement of the heat needed to raise 1 kg of material by 1 Kelvin. Helpful in understanding heat absorbing property of material.	TA Instruments Q2000-2455 DSC	Per test method for temperature range of 40°C to 80°C, the repeatability was 6.2% of average of two results, and the reproducibility was 8.4% of average of two results.

Test Method	General Procedure	Method Significance	Instrument	Precision
ASTM D1169-19a Specific Resistivity	Direct polarity of potential is applied to test specimen for 1 min and the current and voltage are recorded. After a short circuit for 5 min, the reverse polarity of potential is applied and again current and voltage are recorded to determine resistivity.	The resistivity is a measure of its electrical insulating properties under test conditions. High resistivity reflects low content of free ions and ion-forming particles, and normally indicates a low concentration of conductive contaminants.	Baur DTL	Per test procedure on referee method: results of two properly conducted tests (each the average of two fillings) by the same operator on the same sample using the same equipment should not differ from each other by more than 5.7 % of their average. Unable to produce additional precision and bias due to limited interest in round robin participation and lack of a reference material. Max detection limit of 10E15.

Additional test comments are noted below per test method.

ASTM D445: Kinematic viscosity was performed by six technicians with about ten different viscometers from March to May.

ASTM D4052: Density was tested by two technicians with one instrument between March and May.

ASTM D7896: Thermal conductivity was run on two instruments by one technician between March and June.

ASTM E1269: Specific heat capacity was run on one instrument with two technicians performing testing. The majority of samples (22) were run on the same date, and the remaining seven tests run after a time gap of about 4-8 weeks. This instrument did undergo repair during the gap where the chiller was replaced. Reference standard and calibration were completed before any testing was restarted on the instrument.

ASTM D1169 (by United Power Services, Inc):
ASTM D1169 has two options for the analysis – referee and routine.
Referee – Clean cell completely between each different sample. Fill the cup and take a reading. Reverse polarity and take another reading and average the results. This is automated on the equipment. Fill the cup again without rinsing and repeat the procedure of taking two readings. Report the average of the two sets of results.

Routine – No cleaning of the test cell between samples is required if the test specimens are of the same type of fluid. However, it is required to rinse with the test specimen prior to analysis, which was done. For routine tests, only one reading is taken and the average is reported.

Due to the limited volume of sample, samples ran the analysis two times on the same cup filling- a hybrid of the two methods (referee and routine). In between fluids, the cell was not broken down and cleaned. To clean between each sample would have quadrupled the amount of time taken for the analysis. Ideally, samples should have had separate fillings (two aliquots) of the cup. To do so, one sample would have had to complete all temperatures, allowed to cool down so it can be cleaned, and then start the next sample. It would have added significantly to the cost of the analysis.

Two qualified personnel were available to run this test and tests were completed in April and June. Southwest Research Institute then compiled the data and produced this final reporting documenting the sample data and charts.

Retesting

Additionally, 10 samples were rerun to check variability and inconsistent results. These samples were retested for specific resistivity ASTM D1169, thermal conductivity ASTM D7896, and specific heat ASTM E1269 as shown in Table 4. New aliquots of the samples were then supplied to be used for retesting. As some data showed consistency, these results were included with the original data. Some questionable original data were replaced with rerun data.

Table 4: Retest Samples and Test Methods

Sample	Tests Required
Group III A, 4 cSt	Specific Resistivity ASTM D1169
Group III B, 2 cSt	Thermal Conductivity ASTM D7896
Group III B, 3 cSt	Thermal Conductivity ASTM D7896
Group III B, 4 cSt	Specific Resistivity ASTM D1169
Group III B, 8 cSt	Specific Resistivity ASTM D1169
Group III+ A, 4 cSt	Specific Resistivity ASTM D1169
Group III+ B, 4 cSt	Specific Resistivity ASTM D1169
Group IV, 3 cSt	Thermal Conductivity ASTM D7896, Specific Resistivity ASTM D1169
Group IV, 8 cSt	Thermal Conductivity ASTM D7896, Specific Resistivity ASTM D1169
Group V, Monoester 4.2 cSt	Specific Heat ASTM E1269

Results

Below are the test results for the 29 base oil samples across 5 different test methods. Additionally, this data is available in csv format as a separate file. A few charts are included to look at general data relationships.

See below Table 5: Kinematic Viscosity Results.

Table 5: Kinematic Viscosity Results		
ASTM D445, cSt		
Sample	**40°C**	**100°C**
Group I, 4 cSt	25.847	4.668
Group II+, 4 cSt	23.215	4.666
Group III A, 4 cSt	19.642	4.267
Group III B, 2 cSt	9.435	2.547
Group III B, 3 cSt	12.193	3.078
Group III B, 4 cSt	19.192	4.186
Group III B, 6 cSt	35.656	6.458
Group III B, 8 cSt	45.778	7.623
Group III+ A, 4 cSt	17.948	4.092
Group III+ A, 8 cSt	43.637	7.671
Group III+ B, 4 cSt	19.003	4.268
Group IV, 3 cSt	8.109	2.393
Group IV, 5 cSt	24.588	5.169
Group IV, 6 cSt	30.562	5.844
Group IV, 8 cSt	46.875	7.840
Group IV, 65 cSt	611.831	63.859
Group V, Di-ester, 3.2 cSt	11.489	3.200
Group V, Monoester, 2.9 cSt	9.616	2.781
Group V, Monoester, 4.2 cSt	17.014	4.253
Group V, Monoester, 5.5 cSt	25.457	5.526
Group V, Polyolester, 4.1 cSt	18.882	4.177
Group V, Polyolester, 4.4 cSt	19.606	4.434
Group V, Adipate Ester, 4 cSt	13.885	3.586
Group V PAG Blend, 4 cSt	19.785	4.496
Group V PAG, 4 cSt	16.700	3.804
Group V, Bio-based Polyester	6.61	2.12
Group V, Bio-based Di-ester	25.715	5.182
Group V, Bio-based Monoalcohol Ester A	4.351	1.56
Group V, Bio-based Monoalcohol Ester B	21.141	4.473

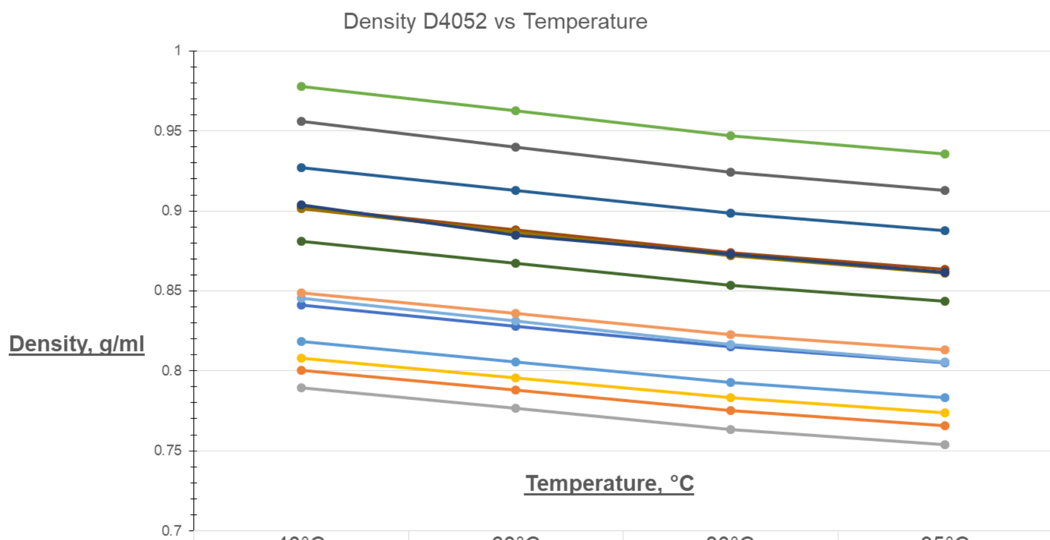
For kinematic viscosity, as the test temperature increased, the viscosity result decreased. The range of results for this dataset was from 2.393 cSt to 611.831 cSt.

See below Table 6: Density Results.

Table 6 Density Results ASTM D4052, g/mL				
Sample	**40°C**	**60°C**	**80°C**	**95°C**
Group I, 4 cSt	0.8439	0.8313	0.8186	0.8092
Group II+, 4 cSt	0.8253	0.8127	0.8001	0.7906
Group III A, 4 cSt	0.8188	0.8061	0.7935	0.7840
Group III B, 2 cSt	0.8192	0.8061	0.7931	0.7833
Group III B, 3 cSt	0.8171	0.8042	0.7913	0.7817
Group III B, 4 cSt	0.8183	0.8056	0.7930	0.7835
Group III B, 6 cSt	0.8256	0.8131	0.8008	0.7915
Group III B, 8 cSt	0.8293	0.8170	0.8046	0.7954
Group III+ A, 4 cSt	0.8006	0.7879	0.7752	0.7658
Group III+ A, 8 cSt	0.8120	0.7996	0.7873	0.7781
Group III+ B, 4 cSt	0.8118	0.7992	0.7866	0.7771
Group IV, 3 cSt	0.7896	0.7766	0.7635	0.7537
Group IV, 5 cSt	0.8082	0.7956	0.7832	0.7738
Group IV, 6 cSt	0.8114	0.7989	0.7865	0.7771
Group IV, 8 cSt	0.8163	0.8039	0.7916	0.7824
Group IV, 65 cSt	0.8287	0.8168	0.8049	0.7960
Group V, Di-ester, 3.2 cSt	0.8992	0.8849	0.8705	0.8598
Group V, Monoester, 2.9 cSt	0.8422	0.8286	0.8150	0.8048
Group V, Monoester, 4.2 cSt	0.8413	0.8281	0.8149	0.8050
Group V, Monoester, 5.5 cSt	0.8476	0.8346	0.8217	0.8120
Group V, Polyolester, 4.1 cSt	0.9779	0.9625	0.9472	0.9358
Group V, Polyolester, 4.4 cSt	0.9271	0.9127	0.8984	0.8878
Group V, Adipate Ester, 4 cSt	0.9026	0.8883	0.8740	0.8633
Group V PAG Blend, 4 cSt	0.9559	0.9401	0.9244	0.9127
Group V PAG, 4 cSt	0.9015	0.8868	0.8721	0.8611
Group V, Bio-based Polyester	0.9039	0.885	0.8732	0.8618
Group V, Bio-based Di-ester	0.8809	0.8672	0.8536	0.8434
Group V, Bio-based Monoalcohol Ester A	0.8456	0.831	0.8165	0.8055
Group V, Bio-based Monoalcohol Ester B	0.849	0.8359	0.8228	0.813

For density, as test temperature increased, the density decreased for the same sample. Generally the density values decreased for Groups I through IV samples. Group V sample densities varied widely likely as a result of the widely varying composition of Group V base oils. Within each Group, as the viscosity result increased, the density also increased. The range of results for this dataset was from 0.7537 to 0.9779 g/mL.

See below Figure 1: Density vs Temperature Chart comparing a subset of samples.



	40°C	60°C	80°C	95°C
Group III B, 4 cSt	0.8183	0.8056	0.793	0.7835
Group III+ A, 4 cSt	0.8006	0.7879	0.7752	0.7658
Group IV, 3 cSt	0.7896	0.7766	0.7635	0.7537
Group IV, 5 cSt	0.8082	0.7956	0.7832	0.7738
Group V, Monoester, 4.2 cSt	0.8413	0.8281	0.8149	0.805
Group V, Polyolester, 4.1 cSt	0.9779	0.9625	0.9472	0.9358
Group V, Polyolester, 4.4 cSt	0.9271	0.9127	0.8984	0.8878
Group V, Adipate Ester, 4 cSt	0.9026	0.8883	0.874	0.8633
Group V PAG Blend, 4 cSt	0.9559	0.9401	0.9244	0.9127
Group V PAG, 4 cSt	0.9015	0.8868	0.8721	0.8611
Group V, Bio-based Polyester	0.9039	0.885	0.8732	0.8618
Group V, Bio-based Di-ester	0.8809	0.8672	0.8536	0.8434
Group V, Bio-based Monoalcohol Ester A	0.8456	0.831	0.8165	0.8055
Group V, Bio-based Monoalcohol Ester B	0.849	0.8359	0.8228	0.813

Figure 1: Density vs Temperature Chart

See below Table 7: Thermal Conductivity Results.

Table 7: Thermal Conductivity Results					
ASTM D7896, W/m*K					
Sample	**0°C**	**40°C**	**70°C**	**100°C**	**130°C**
Group I, 4 cSt	0.1291	0.1268	0.1250	0.1232	0.1215
Group II+, 4 cSt	0.1364	0.1336	0.1314	0.1293	0.1272
Group III A, 4 cSt	0.1396	0.1364	0.1340	0.1316	0.1291
Group III B, 2 cSt run 2	0.1312	0.1264	0.1229	0.1195	0.1159
Group III B, 3 cSt	0.1314	0.1286	0.1265	0.1244	0.1223
Group III B, 3 cSt Rerun	0.1348	0.1299	0.1262	0.1226	0.1189
Group III B, 4 cSt	0.1394	0.1361	0.1337	0.1313	0.1289
Group III B, 6 cSt	0.1452	0.1419	0.1395	0.1370	0.1345
Group III B, 8 cSt	0.1466	0.1435	0.1412	0.1389	0.1366
Group III+ A, 4 cSt	0.1464	0.1408	0.1366	0.1324	0.1282
Group III+ A, 8 cSt	0.1532	0.1496	0.1468	0.1441	0.1414
Group III+ B, 4 cSt	0.1438	0.1391	0.1356	0.1321	0.1285
Group IV, 3 cSt	0.1453	0.1389	0.1340	0.1292	0.1244
Group IV, 3 cSt Rerun	0.1422	0.1382	0.1339	0.1295	0.1251
Group IV, 5 cSt	0.1534	0.1481	0.1440	0.1400	0.1360
Group IV, 6 cSt	0.1518	0.1463	0.1422	0.1381	0.1340
Group IV, 8 cSt	0.1525	0.1477	0.1440	0.1404	0.1367
Group IV, 8 cSt Rerun	0.1543	0.1488	0.1449	0.1410	0.1371
Group IV, M-PAO, 65 cSt	0.1573	0.1534	0.1504	0.1475	0.1445
Group V, Di-ester, 3.2 cSt	0.1498	0.1445	0.1405	0.1365	0.1324
Group V, Monoester, 2.9 cSt	0.1492	0.1446	0.1412	0.1377	0.1342
Group V, Monoester, 4.2 cSt	0.1579	0.1531	0.1494	0.1458	0.1422
Group V, Monoester, 5.5 cSt	0.1550	0.1510	0.1480	0.1450	0.1420
Group V, Polyolester, 4.1 cSt	0.1514	0.1459	0.1418	0.1376	0.1335
Group V, Polyolester, 4.4 cSt	0.1535	0.1479	0.1437	0.1395	0.1353
Group V, Adipate Ester, 4 cSt	0.1399	0.1355	0.1322	0.1289	0.1257
Group V PAG Blend, 4 cSt	0.1453	0.1414	0.1384	0.1354	0.1324
Group V PAG, 4 cSt	0.1524	0.1467	0.1427	0.1386	0.1345
Group V, Bio-based Polyester	0.1437	0.1395	0.1363	0.1332	0.1300
Group V, Bio-based Di-ester	0.1519	0.1482	0.1454	0.1425	0.1397
Group V, Bio-based Monoalcohol Ester A	0.1319	0.1265	0.1224	0.1184	0.1143
Group V, Bio-based Monoalcohol Ester B	0.1496	0.1462	0.1437	0.1412	0.1386

On the thermal conductivity results, as the test temperature increased, the conductivity values decreased. Within each base oil group, as viscosity increased, thermal conductivity results also increased. Moving from Group 1 samples to Group IV samples, the thermal conductivity increased generally. The higher values for Group III B 2 cSt are noted compared to other Group III B samples. The Group

IV 3 cSt fluid results also varied from the other Group IV oils and was rerun along with the Group IV, 8 cSt sample. The range of results for this data was from 0.1215 to 0.1579 W/mK. The initial results on Group IIIB 2 cSt were totally inconsistent with the results in the same group and thus was not included in the report.

See below Figures 2 -5 for the thermal conductivity charts for a subset of samples.

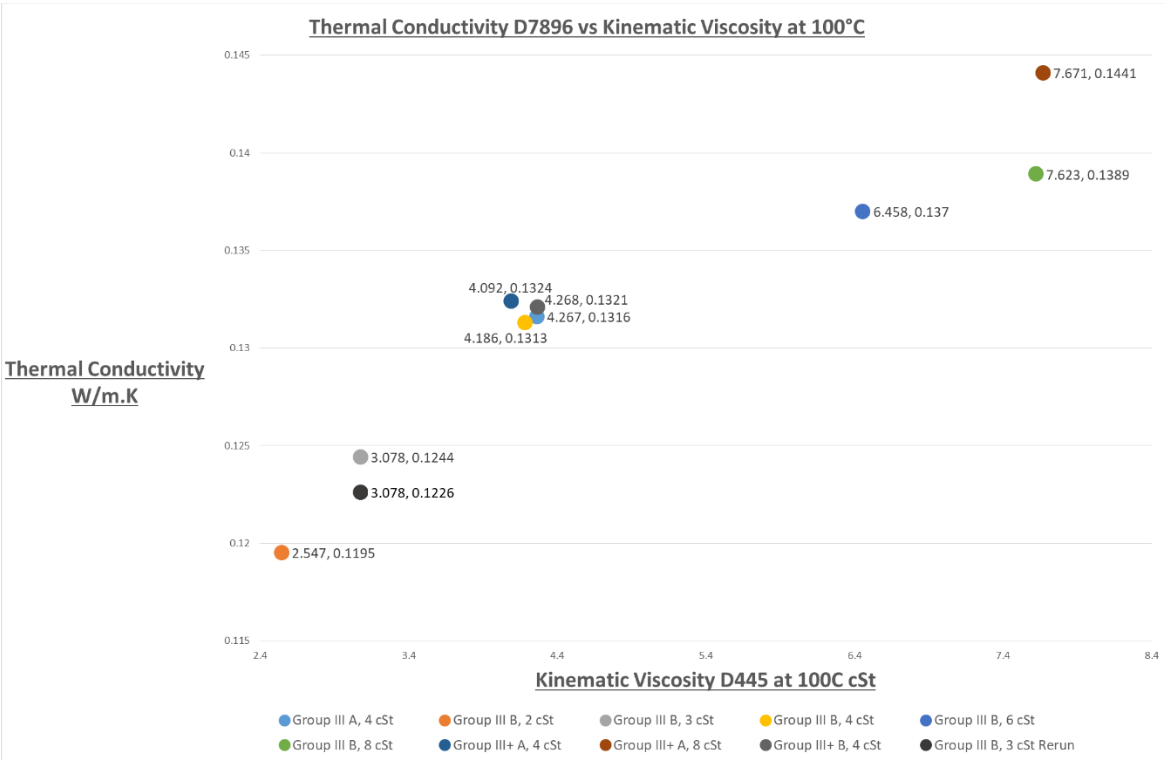


Figure 2: Thermal Conductivity vs Viscosity, Group III Chart

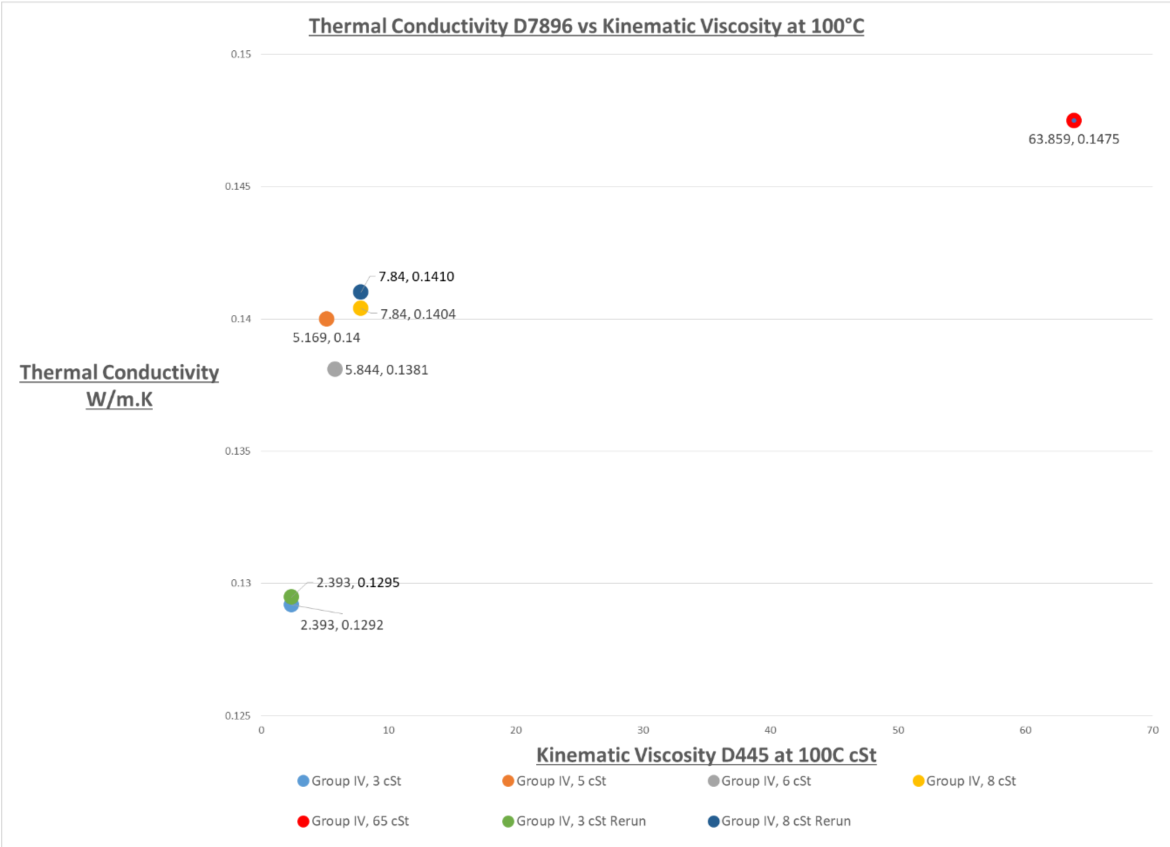


Figure 3: Thermal Conductivity vs Viscosity, Group IV Chart

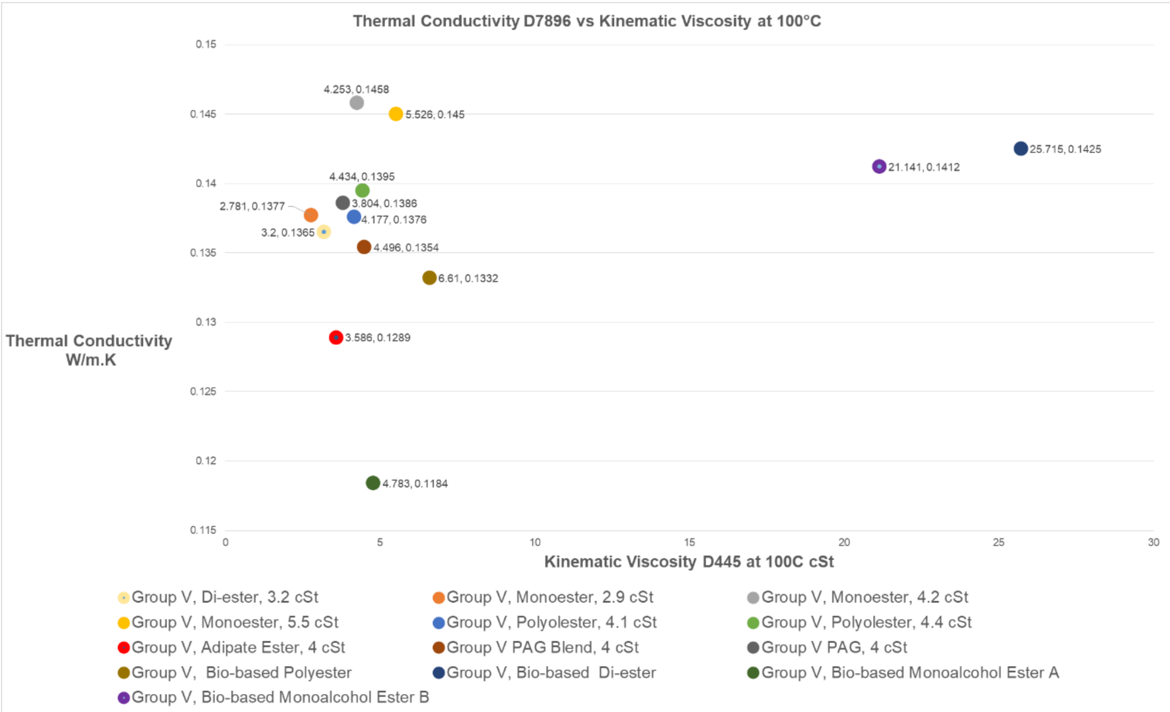
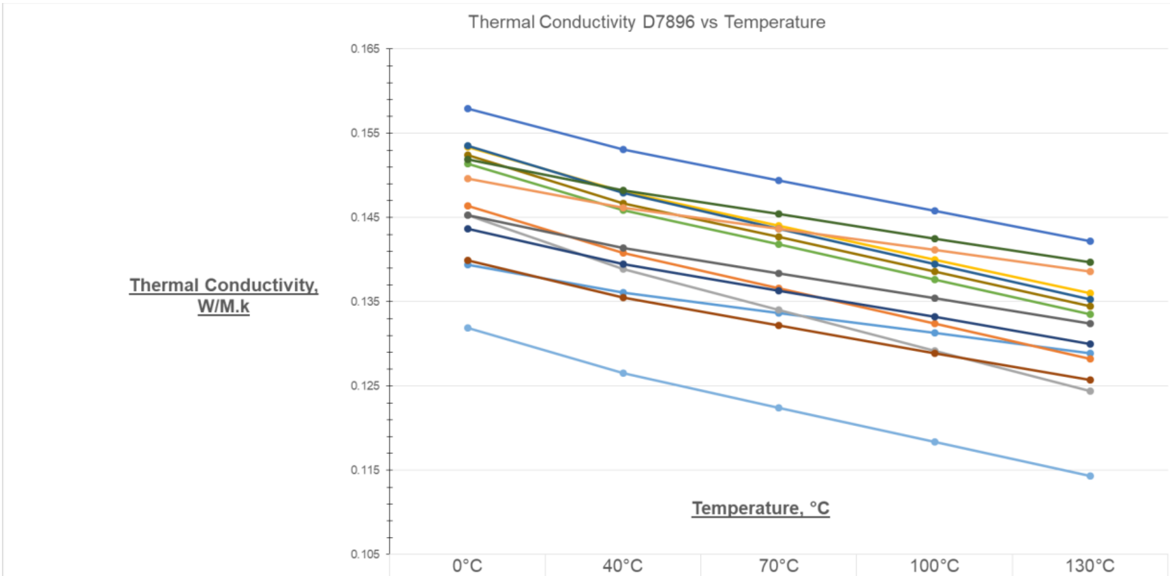


Figure 4: Thermal Conductivity vs Viscosity, Group V Chart



	0°C	40°C	70°C	100°C	130°C
Group III B, 4 cSt	0.1394	0.1361	0.1337	0.1313	0.1289
Group III+ A, 4 cSt	0.1464	0.1408	0.1366	0.1324	0.1282
Group IV, 3 cSt	0.1453	0.1389	0.134	0.1292	0.1244
Group IV, 5 cSt	0.1534	0.1481	0.144	0.14	0.136
Group V, Monoester, 4.2 cSt	0.1579	0.1531	0.1494	0.1458	0.1422
Group V, Polyolester, 4.1 cSt	0.1514	0.1459	0.1418	0.1376	0.1335
Group V, Polyolester, 4.4 cSt	0.1535	0.1479	0.1437	0.1395	0.1353
Group V, Adipate Ester, 4 cSt	0.1399	0.1355	0.1322	0.1289	0.1257
Group V PAG Blend, 4 cSt	0.1453	0.1414	0.1384	0.1354	0.1324
Group V PAG, 4 cSt	0.1524	0.1467	0.1427	0.1386	0.1345
Group V, Bio-based Polyester	0.1437	0.1395	0.1363	0.1332	0.13
Group V, Bio-based Di-ester	0.1519	0.1482	0.1454	0.1425	0.1397
Group V, Bio-based Monoalcohol Ester A	0.1319	0.1265	0.1224	0.1184	0.1143
Group V, Bio-based Monoalcohol Ester B	0.1496	0.1462	0.1437	0.1412	0.1386

Figure 5: Thermal Conductivity vs Temperature Chart

See below Table 8: Specific Heat Capacity Results.

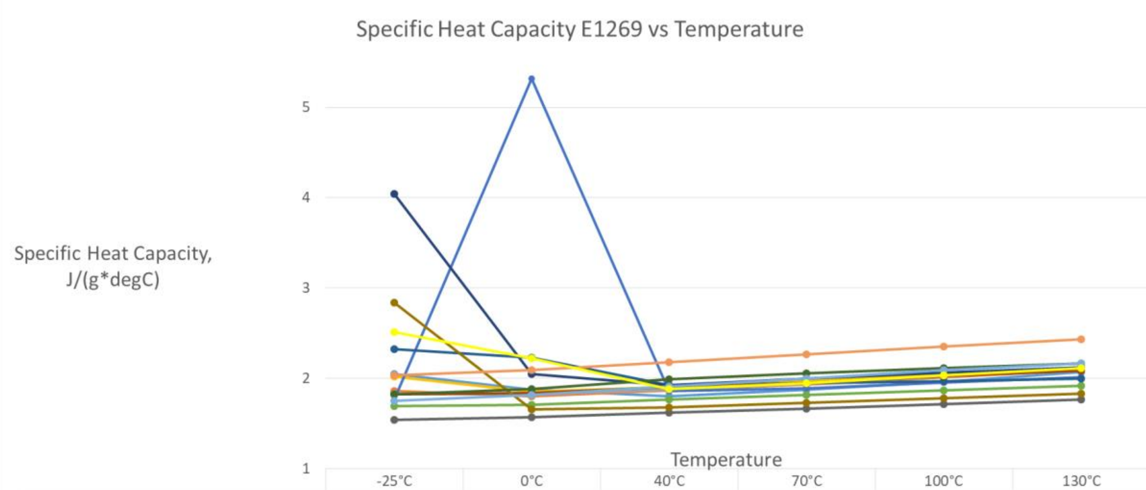
Table 8: Specific Heat Capacity Results ASTM E1269, J/(g*degC)						
Sample	**-25°C**	**0°C**	**40°C**	**70°C**	**100°C**	**130°C**
Group I, 4 cSt	1.918	1.794	1.864	1.967	2.056	2.139
Group II+, 4 cSt	1.832	1.723	1.746	1.821	1.908	1.996
Group III A, 4 cSt	1.850	1.693	1.689	1.758	1.841	1.924
Group III B, 2 cSt	1.709	1.689	1.802	1.896	1.987	2.077
Group III B, 3 cSt	1.744	1.728	1.834	1.918	2.018	2.117
Group III B, 4 cSt	2.045	1.871	1.802	1.875	1.965	2.067
Group III B, 6 cSt	1.834	1.648	1.628	1.720	1.837	1.928
Group III B, 8 cSt	1.905	1.746	1.734	1.805	1.885	1.960
Group III+ A, 4 cSt	1.863	1.805	1.870	1.933	2.010	2.092
Group III+ A, 8 cSt	2.019	1.902	1.929	1.992	2.071	2.152
Group III+ B, 4 cSt	1.898	1.840	1.894	2.002	2.063	2.129
Group IV, 3 cSt	1.833	1.822	1.874	1.942	2.023	2.111
Group IV, 5 cSt	2.023	1.852	1.906	1.969	2.039	2.108
Group IV, 6 cSt	1.731	1.765	1.844	1.910	1.991	2.071
Group IV, 8 cSt	1.781	1.799	1.881	1.968	2.047	2.125
Group IV, M-PAO, 65 cSt	1.630	1.672	1.761	1.837	1.921	1.996
Group V, Di-ester, 3.2 cSt	1.566	1.584	1.630	1.677	1.743	1.813
Group V, Monoester, 2.9 cSt	1.443	4.161*	1.953	2.017	2.093	2.174
Group V, Monoester, 4.2 cSt	1.768	5.321*	1.860	1.889	1.953	2.015
Group V, Monoester, 4.2 cSt Rerun	2.510	2.225	1.880	1.947	2.033	2.510
Group V, Monoester, 5.5 cSt	2.458	2.198	1.805	1.862	1.947	2.027
Group V, Polyolester, 4.1 cSt	1.692	1.709	1.766	1.813	1.869	1.920
Group V, Polyolester, 4.4 cSt	2.321	2.227	1.927	1.946	1.972	1.997
Group V, Adipate Ester, 4 cSt	1.821	1.840	1.900	1.950	2.029	2.087
Group V PAG Blend, 4 cSt	1.540	1.569	1.622	1.666	1.718	1.766
Group V PAG, 4 cSt	2.842	1.654	1.678	1.727	1.780	1.831
Group V, Bio-based Polyester	4.042	2.051	1.927	1.995	2.065	2.118
Group V, Bio-based Di-ester	1.825	1.880	1.992	2.053	2.116	2.165
Group V, Bio-based Monoalcohol Ester A	1.754	1.813	1.911	1.999	2.089	2.166
Group V, Bio-based Monoalcohol Ester B	2.035	2.089	2.181	2.267	2.350	2.433

The specific heat capacity data presented in Table 8 is a subset of the full data that was captured for these samples as the test recorded the results for each sample from -40°C to 200°C in 5C increments. Only the selected temperatures (-25°C, 0°C, 40°C, 70°C, 100°C, and 130°C) were requested and hence listed in this report and data attachment.

The specific heat results showed generally an increase as the test temperature increased while others decreased and then increased between 0°C and 40°C.

Additionally, there were two Group V samples that showed a spike in specific heat at 0°C (results were 4.161 and 5.321 with * noted) that was outside the range of the other samples. Both results were checked and confirmed to be real results, likely due to some type of phase transition or kinetic event, such as de-waxing, that occurred around 0°C. This likely was a kinetic event that falls outside of the definition of specific heat. Sample Group V, Monoester, 4.2 cSt was retested and the rerun results brought the data more consistent with other Group V specific heat data. Additional heating and cooling would be needed to determine if this kinetic event was reversible. The range of results for this dataset was from 1.443 to 2.842, but up to 5.321 J/(g*degC) including the two spikes.

Figure 6 charts the Specific Heat Capacity vs Temperature for a subset of samples.



	-25°C	0°C	40°C	70°C	100°C	130°C
Group III B, 4 cSt	2.045	1.871	1.802	1.875	1.965	2.067
Group III+ A, 4 cSt	1.863	1.805	1.87	1.933	2.01	2.092
Group IV, 3 cSt	1.833	1.822	1.874	1.942	2.023	2.111
Group IV, 5 cSt	2.023	1.852	1.906	1.969	2.039	2.108
Group V, Monoester, 4.2 cSt	1.768	5.321	1.86	1.889	1.953	2.015
Group V, Polyolester, 4.1 cSt	1.692	1.709	1.766	1.813	1.869	1.92
Group V, Polyolester, 4.4 cSt	2.321	2.227	1.927	1.946	1.972	1.997
Group V, Adipate Ester, 4 cSt	1.821	1.84	1.9	1.95	2.029	2.087
Group V PAG Blend, 4 cSt	1.54	1.569	1.622	1.666	1.718	1.766
Group V PAG, 4 cSt	2.842	1.654	1.678	1.727	1.78	1.831
Group V, Bio-based Polyester	4.042	2.051	1.927	1.995	2.065	2.118
Group V, Bio-based Di-ester	1.825	1.88	1.992	2.053	2.116	2.165
Group V, Bio-based Monoalcohol Ester A	1.754	1.813	1.911	1.999	2.089	2.166
Group V, Bio-based Monoalcohol Ester B	2.035	2.089	2.181	2.267	2.35	2.433
Group V, Monoester, 4.2 cSt Rerun	2.51	2.225	1.88	1.947	2.033	2.115

Figure 6: Specific Heat Capacity vs Temperature Chart

See below Table 9: Specific Resistivity Results. NA was listed when result was >10.0E+15. Additionally, the complete data set for specific resistivity is reported in Appendix A.

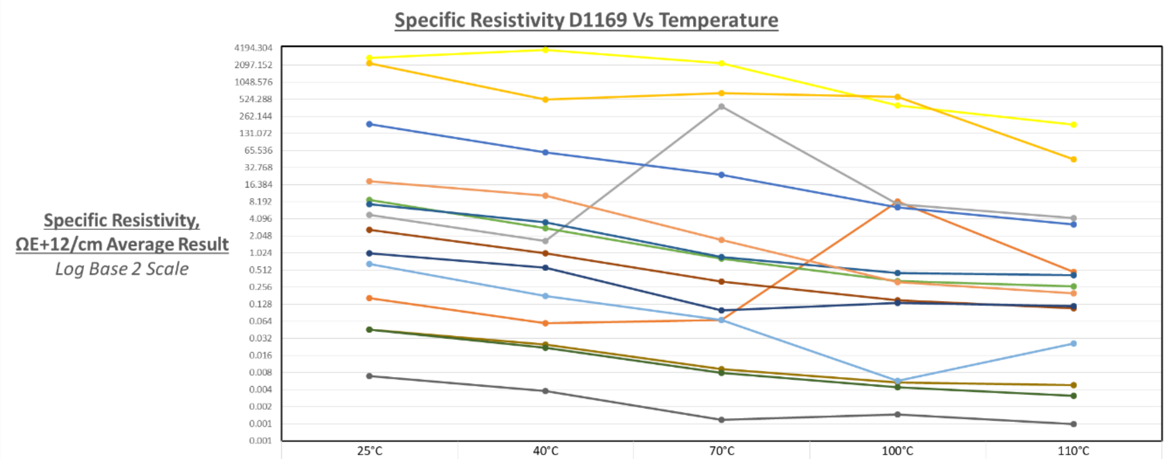
Table 9 Specific Resistivity Results						
ASTM D1169, Ωcm						
Sample		**25°C**	**40°C**	**70°C**	**100°C**	**110°C**
Group I, 4 cSt	Run1	284E+12	170E+12	67.4E+12	15.8E+12	4.34E+12
	Run2	336E+12	200E+12	64.7E+12	17.4E+12	4.67E+12
	AVG	310E+12	185E+12	66.1E+12	16.6E+12	4.51E+12
Group II+, 4 cSt	Run1	381E+12	213E+12	197E+12	134E+12	7.95E+12
	Run2	450E+12	342E+12	258E+12	177E+12	8.19E+12
	AVG	416E+12	278E+12	228E+12	156E+12	8.07E+12
Group III A, 4 cSt	Run1	87.2E+12	50.4E+12	64.9E+12	28.1E+12	19.8E+12
	Run2	103E+12	54.8E+12	76.3E+12	33.5E+12	20.5E+12
	AVG	95.1E+12	52.6E+12	70.6E+12	30.8E+12	20.2E+12
	Run3	4.38E+15	1.68E+15	880E+12	193E+12	90.5E+12
	Run4	4.75E+15	1.69E+15	1016E+12	202E+12	89.1E+12
	AVG	4.57E+15	1.69E+15	948E+12	198E+12	89.8E12
Group III B, 2 cSt	Run1	1.03E+15	571E+12	223E+12	71.3E+12	8.36E+12
	Run2	1.44E+15	728E+12	249E+12	75.2E+12	8.52E+12
	AVG	1.24E+15	650E+12	236E+12	73.3E+12	8.44E+12
Group III B, 3 cSt	Run1	378E+12	444E+12	15.7E+12	6.16E+12	2.66E+12
	Run2	675E+12	582E+12	16.1E+12	6.35E+12	2.85E+12
	AVG	527E+12	513E+12	15.9E+12	6.26E+12	2.76E+12
Group III B, 4 cSt	Run1	382E+12	427E+12	79.0E+12	7.39E+12	2.84E+12
	Run2	632E+12	623E+12	90.0E+12	7.35E+12	3.07E+12
	AVG	507E+12	525E+12	84.5E+12	7.37E+12	2.96E+12
	Run3	2.53E+15	3.95E+15	1.88E+15	402E+12	186E+12
	Run4	3.12E+15	NA	2.64E+15	430E+12	190E+12
	AVG	2.83E+15	NA	2.26E+15	416E+12	188E+12
Group III B, 6 cSt	Run1	2.72E+15	3.37E+15	682E+12	15.7E+12	6.75E+12
	Run2	NA	NA	904E+12	15.2E+12	6.73E+12
	AVG	NA	NA	793E+12	15.5E+12	6.74E+12
Group III B, 8 cSt	Run3	139E+12	220E+12	211E+12	40.9E+12	21.1E+12
	Run4	194E+12	412E+12	292E+12	64.9E+12	30.8E+12
	AVG	167E+12	316E+12	252E+12	52.9E+12	26.0E+12
Group III+ A, 4 cSt	Run1	581E+12	441E+12	215E+12	70.9E+12	11.0E+12
	Run2	906E+12	555E+12	243E+12	79.8E+12	11.1E+12
	AVG	746E+12	498E+12	229E+12	75.4E+12	11.1E+12
	Run3	370E+12	2.15E+15	720E+12	223E+12	128E+12
	Run4	264E+12	2.66E+15	774E+12	275E+12	135E+12
	AVG	317E+12	2.41+15	747E+12	249E+12	132E+12
Group III+ A, 8 cSt	Run1	101E+12	47.6E+12	57.3E+12	44.2E+12	9.36E+12
	Run2	120E+12	58.9E+12	72.9E+12	63.2E+12	9.81E+12
	AVG	111E+12	53.3E+12	65.1E+12	53.7E+12	9.59E+12
Sample		**25°C**	**40°C**	**70°C**	**100°C**	**110°C**
Group III+ B, 4 cSt	Run1	83.0E+12	27.0E+12	51.0E+12	340E+12	28.0E+12
	Run2	94.7E+12	29.5E+12	57.8E+12	430E+12	26.1E+12
	AVG	88.9E+12	28.3E+12	54.4E+12	385E+12	27.1E+12

	Run3	NA	NA	3.13E+15	134E+12	46.6E+12
	Run4	NA	NA	4.13E+15	140E+12	45.3E+12
	AVG	NA	NA	3.63E+15	137E+12	46.0E+12
Group IV, 3 cSt	Run3	2.66E+15	1.42E+15	533E+12	186E+12	99.5E+12
	Run4	3.57E+15	1.86E+15	759E+12	240E+12	121E+12
	AVG	3.12E+15	1.64E+15	646E12	213E+12	110E+12
Group IV, 5 cSt	Run1	2.28+E15	738E+12	701E+12	554E+12	46.0E+12
	Run2	3.59E+15	807E+12	805E+12	617E+12	46.4E+12
	AVG	2.94E+15	773E+12	753E+12	586E+12	46.2E+12
Group IV, 6 cSt	Run1	1.97E+15	985E+12	675E+12	333E+12	40.5E+12
	Run2	2.43E+15	853E+12	613E+12	351E+12	39.1E+12
	AVG	2.20E+15	919E+12	644E+12	342E+12	39.8E+12
Group IV, 8 cSt	Run1	1.88E+15	794E+12	508E+12	408E+12	48.9E+12
	Run2	2.12E+15	781E+12	530E+12	418E+12	47.9E+12
	AVG	2.00E+15	788E+12	519E+12	414E+12	48.4E+12
	Run3	3.05E+15	2.33E+15	1115E+12	365E+12	408E+12
	Run4	3.52E+15	2.32E+15	1008E+12	374E+12	389E+12
	AVG	3.29E+15	2.33E+15	1062E+12	370E+12	399E+12
Group IV, 65 cSt	Run1	NA	2.78E+15	897E+12	593E+12	102E+12
	Run2	6.04E+15	1.69E+15	573E+12	579E+12	109E+12
	AVG	NA	2.24E+15	735E+12	586E+12	106E+12
Group V Di-ester, 3.2 cSt	Run1	2.31E+12	900E+09	622E+09	335E+09	300E+09
	Run2	2.23E+12	882E+09	640E+09	332E+09	289E+09
	AVG	2.27E+12	891E+09	631E+09	334E+09	295E+09
Group V Monoester, 2.9 cSt	Run1	20.3E+12	8.34E+12	4.18E+12	2.21E+12	1.89E+12
	Run2	19.8E+12	8.14E+12	4.27E+12	2.23E+12	1.90E+12
	AVG	2.01E+12	8.24E+12	4.23E+12	2.22E+12	1.90E+12
Group V Monoester, 4.2 cSt	Run1	210E+12	65.3E+12	32.7E+12	6.52E+12	3.27E+12
	Run2	175E+12	56.4E+12	16.1E+12	6.52E+12	3.31E+12
	AVG	193E+12	80.9E+12	29.4E+12	6.52E+12	3.29E+12
Group V Monoester, 5.5 cSt	Run1	149E+12	88.5E+12	27.7E+12	8.80E+12	4.99E+12
	Run2	167E+12	93.0E+12	27.5E+12	9.06E+12	5.15E+12
	AVG	158E+12	90.8E+12	27.6E+12	8.93E+12	5.07E+12
Group V, Polyolester, 4.1 cSt	Run1	9.79E+12	3.10E+12	803E+09	331E+09	275E+09
	Run2	8.15E+12	2.50E+12	838E+09	331E+09	262E+09
	AVG	8.97E+12	2.80E+12	821E+09	331E+09	269E+09
Group V, Polyolester, 4.4 cSt	Run1	8.16E+12	3.66E+12	866E+09	490E+09	422E+09
	Run2	6.86E+12	3.52E+12	909E+09	462E+09	426E+09
	AVG	7.51E+12	3.59E+12	888E+09	476E+09	424E+09
Sample		**25°C**	**40°C**	**70°C**	**100°C**	**110°C**
Group V, Adipate Ester, 4 cSt	Run1	2.89E+12	1.04E+12	322E+09	151E+09	109E+09
	Run2	2.39E+12	988E+09	322E+09	152E+09	111E+09
	AVG	2.64E+12	1.02E+12	322E+09	152E+09	110E+09

Group V, PAG Blend, 4 cSt	Run1	7.01E+09	3.84E+09	1.17E+09	1.54E+09	1.05E+09
	Run2	6.83E+09	3.77E+09	1.21E+09	1.40E+09	945E+06
	AVG	6.92E+09	3.81E+09	1.19E+09	1.47E+09	998E+06
Group V, PAG, 4 cSt	Run1	46.8E+09	24.8E+09	8.96E+09	4.89E+09	4.28E+09
	Run2	45.1E+09	25.5E+09	9.53E+09	5.82E+09	5.47E+09
	AVG	46.0E+09	25.2E+09	9.25E+09	5.36E+09	4.88E+09
Group V, Bio-based Polyester	Run1	1.04E+12	562E+09	91.6E+09	138E+09	115E+09
	Run2	1.02E+12	571E+09	107E+09	136E+09	123E+09
	AVG	1.03E+12	5.67E+09	99.3E+09	137+09	119E+09
Group V, Bio-based Di-ester	Run1	45.5E+09	21.6E+09	7.88E+09	4.39E+09	3.23E+09
	Run2	46.1E+09	22.6E+09	8.06E+09	4.49E+09	3.04E+09
	AVG	45.8E+09	22.0E+09	7.97E+09	4.45E+09	3.14e+09
Group V, Bio-based Monoalcohol Ester A	Run1	711E+09	179E+09	66.9E+09	58.4E+09	27.2E+09
	Run2	666E+09	182E+09	68.3E+09	57.8E+09	25.9E+09
	AVG	689E+09	181E+09	67.6E+09	58.1E+09	26.6E+09
Group V, Bio-based Monoalcohol Ester B	Run1	18.8E+12	10.3E+12	1.72E+12	309E+09	200E+09
	Run2	19.0E+12	10.9E+12	1.79E+12	328E+09	203E+09
	AVG	18.9E+12	10.6E+12	1.76E+12	319E+09	202E+09

For the specific resistivity results, as the temperature increased, the specific resistivity generally decreases. The resistivity results were an average of two measurements for two runs for a total of four individual results. Only the run average results are reported in Table 8, the full data is reported in Appendix A for each run. For some samples, the results were out of range (>10.0E+15) for the instrument, and hence no averaged results were reported. Within each group, no trend was found when looking at increasing viscosity. Additionally, there was not a trend in resistivity results from Group I to Group IV. The reported results ranged from 945E6 to 6.04E15. The result for Group IV, 3 cSt sample at 70ºC did not trend with other results but the temperature and results were confirmed. For samples Group III B, 8 cSt and Group IV, 3 cSt original results were totally inconsistent with the rest in the same group and thus were not included in the report. Other retested results are shown in Table 9.

Figure 7 charts the Specific Resistivity vs Temperature for a subset of samples.



	25°C	40°C	70°C	100°C	110°C
Group III B, 4 cSt	2822.500	3913.333	2257.500	415.750	188.000
Group III+ A, 4 cSt	0.165	0.059	0.069	8.315	0.482
Group IV, 3 cSt	4.815	1.685	390.000	7.478	4.240
Group IV, 5 cSt	2295	517.505	677.750	585	46.150
Group V, Monoester, 4.2 cSt	192	60.825	24.375	6.520	3.285
Group V, Polyolester, 4.1 cSt	8.970	2.798	0.820	0.331	0.269
Group V, Polyolester, 4.4 cSt	7.505	3.588	0.883	0.456	0.424
Group V, Adipate Ester, 4 cSt	2.635	1.014	0.322	0.151	0.110
Group V PAG Blend, 4 cSt	0.007	0.004	0.001	0.001	0.001
Group V PAG, 4 cSt	0.046	0.025	0.009	0.005	0.005
Group V, Bio-based Polyester	1.031	0.566	0.100	0.137	0.119
Group V, Bio-based Di-ester	0.046	0.022	0.008	0.004	0.003
Group V, Bio-based Monoalcohol Ester A	0.668	0.180	0.068	0.006	0.027
Group V, Bio-based Monoalcohol Ester B	18.900	10.585	1.755	0.314	0.202

Figure 7: Specific Resistivity vs Temperature Chart

Conclusions

This test program looked to provide a large database of thermal and electrical properties at different temperatures of various base oils. Such a large data set is provided within this report.

As there are many ways to review and understand the data, limited analysis was conducted on the data. Commentary on trends was described in the Results section. Some repeat testing of samples were run where the original run results were not included, but other repeat test results show test method reproducibility of the method with these types of samples with more consistent data.

A few comments and suggestions if future testing is needed:

1. For future analysis with additional samples, it would be recommended to run each test in duplicate for all tests and samples to look at the variation of results. As different test temperatures were selected per test method, there could be variation in results not generally seen in some of the standardized test procedures which have limited test temperature range, and hence the ASTM test precision would not apply or be sufficient. Having each sample test per temperature run in duplicate could show if certain temperatures had greater variation than other temperatures. Also, as ASTM D1169 specific resistivity is a test method for insulating fluids, and not base oils, the variability may be different than listed in the test method precision due to the sample being outside of original test method scope and not included in the original matrix that generated the precision statement. Hence, setting up the test matrix, from the beginning, with repeat testing included, would better show the variation in specific resistivity results.

2. In order to minimize test variation, it would be suggested for future samples to arrive in one large batch and then testing all scheduled to run together. Multiple shipments over different time periods could allow for greater fluctuations in results inherent in using multiple instruments and technicians for testing.

3. It would be suggested to increase the sample volume for future tests to 1.2L to have sufficient volume for all tests and any re-running of tests, if needed. As mentioned in the Approach section, there was insufficient sample amount to run ASTM D1169 test with a new aliquot per run, the additional volume would be useful to properly measure the specific resistivity. Increasing the volume needed would also aid in any retesting that may be needed for other tests as well.

Overall, this study was able to provide a database of thermal and electrical properties for 29 base oils with a total of 1,073 data points.

List of References

ASTM D4052: Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter

ASTM D445: Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)

ASTM D7896: Standard Test Method for Thermal Conductivity, Thermal Diffusivity, and Volumetric Heat Capacity of Engine Coolants and Related Fluids by Transient Hot Wire Liquid Thermal Conductivity Method

ASTM E1269: Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry

ASTM D1169: Standard Test Method for Specific Resistance (Resistivity) of Electrical Insulating Liquids

Appendix A ASTM D1169 Specific Resistivity Results

Specific Restivity

*OOS-Out Of Spec

Sample	E1269		25°C			40°C			70°C			100°C			110°C		
	Ωcm		RHO+	RHO-	Avg Run 1/Avg Run 2	RHO+	RHO-	Avg Run 1/Avg Run 2	RHO+	RHO-	Avg Run 1/Avg Run 2	RHO+	RHO-	Avg Run 1/Avg Run 2	RHO+	RHO-	Avg Run 1/Avg Run 2
Group I, 4 cSt		**Run 1**	277E+12	290E+12	284E+12	155E+12	185E+12	170E+12	68.4E+12	66.3E+12	67.4E+12	15.9E+12	15.7E+12	15.8E+12	3.69E+12	4.98E+12	4.34E+12
		Run 2	336E+12	335E+12	336E+12	195E+12	205E+12	200E+12	62.9E+12	66.5E+12	64.7E+12	17.4E+12	17.4E+12	17.4E+12	4.02E+12	5.32E+12	4.67E+12
Group II+, 4 cSt		**Run 1**	389E+12	373E+12	381E+12	166E+12	260E+12	213E+12	138E+12	256E+12	197E+12	126E+12	141E+12	134E+12	4.59E+12	11.3E+12	7.95E+12
		Run 2	456E+12	444E+12	450E+12	302E+12	382E+12	342E+12	227E+12	288E+12	258E+12	179E+12	175E+12	177E+12	5.37E+12	11.0E+12	8.19E+12
Group III A, 4 cSt		**Run 1**	77.3E+12	97.1E+12	87.2E+12	42.9E+12	57.8E+12	50.4E+12	61.2E+12	68.5E+12	64.9E+12	26.5E+12	29.6E+12	28.1E+12	15.3E+12	24.3E+12	19.8E+12
		Run 2	100E+12	105E+12	103E+12	49.2E+12	60.3E+12	54.8E+12	76.3E+12	76.2E+12	76.3E+12	33.9E+12	33.1E+12	33.5E+12	17.2E+12	23.7E+12	20.5E+12
		Run 3	4.99E+15	3.77E+15	4.38E+15	1.37E+15	1.99E+15	1.68E+15	669E+12	1090E+12	880E+12	146E+12	240E+12	193E+12	71.9E+12	109E+12	90.5E+12
		Run 4	5.47E+15	4.03E+15	4.75E+15	1.41E+15	1.96E+15	1.69E+15	881E+12	1150E+12	1016E+12	163E+12	241E+12	202E+12	71.2E+12	107E+12	89.1E+12
Group III B, 2 cSt		**Run 1**	833E+12	1.18E+15	1.03E+15	466E+12	676E+12	571E+12	175E+12	271E+12	223E+12	64.9E+12	77.7E+12	71.3E+12	6.32E+12	10.4E+12	8.36E+12
		Run 2	1.34E+15	1.54E+15	1.44E+15	654E+12	802E+12	728E+12	204E+12	293E+12	249E+12	71.3E+12	79.0E+12	75.2E+12	6.84E+12	10.2E+12	8.52E+12
Group III B, 3 cSt		**Run 1**	191E+12	565E+12	378E+12	340E+12	548E+12	444E+12	18.5E+12	12.9E+12	15.7E+12	3.88E+12	8.44E+12	6.16E+12	2.60E+12	2.72E+12	2.66E+12
		Run 2	635E+12	714E+12	675E+12	557E+12	606E+12	582E+12	20.2E+12	12.0E+12	16.1E+12	4.09E+12	8.60E+12	6.35E+12	2.86E+12	2.84E+12	2.85E+12
Group III B, 4 cSt		**Run 1**	289E+12	475E+12	382E+12	299E+12	554E+12	427E+12	81.7E+12	76.2E+12	79.0E+12	4.08E+12	10.7E+12	7.39E+12	2.50E+12	3.18E+12	2.84E+12
		Run 2	585E+12	678E+12	632E+12	534E+12	712E+12	623E+12	102E+12	77.9E+12	90.0E+12	4.40E+12	10.3E+12	7.35E+12	2.82E+12	3.32E+12	3.07E+12
		Run 3	2.51E+15	2.54E+15	2.53E+15	4.49E+15	3.41E+15	3.95E+15	2.12E+15	1.64E+15	1.88E+15	384E+12	419E+12	402E+12	164E+12	208E+12	186E+12
		Run 4	3.14E+15	3.10E+15	3.12E+15	>10.0E+15	3.84E+15	OOS	3.53E+15	1.74E+15	2.64E+15	432E+12	428E+12	430E+12	175E+12	205E+12	190E+12
Group III B, 6 cSt		**Run 1**	1.35E+15	4.09E+15	2.72E+15	3.21E+15	3.52e+15	3.37E+15	795E+12	569E+12	682E+12	8.59E+12	22.9E+12	15.7E+12	6.16E+12	7.33E+12	6.75E+12
		Run 2	>10.0E+15	5.49E+15	OOS	>10.0E+15	4.18E+15	OOS	1.21E+15	598E+12	904E+12	9.25E+12	21.2E+12	15.2E+12	6.21E+12	7.24E+12	6.73E+12
Group III B, 8 cSt		**Run 3**	131E+12	147E+12	139E+12	187E+12	253E+12	220E+12	162E+12	260E+12	211E+12	31.2E+12	50.6E+12	40.9E+12	16.4E+12	25.7E+12	21.1E+12
		Run 4	177E+12	211E+12	194E+12	376E+12	447E+12	412E+12	240E+12	344E+12	292E+12	56.6E+12	73.1E+12	64.9E+12	27.0E+12	34.6E+12	30.8E+12
Group III+ A, 4 cSt		**Run 1**	526E+12	635E+12	581E+12	371E+12	510E+12	441E+12	189E+12	240E+12	215E+12	71.0E+12	70.8E+12	70.9E+12	8.95E+12	13.0E+12	11.0E+12
		Run 2	901E+12	911E+12	906E+12	522E+12	588E+12	555E+12	230E+12	256E+12	243E+12	83.4E+12	76.2E+12	79.8E+12	9.38E+12	12.9E+12	11.1E+12
		Run 3	584E+12	155E+12	370E+12	2.32E+15	1.97E+15	2.15E+15	691E+12	748E+12	720E+12	207E+12	238E+12	223E+12	111E+12	145E+12	128E+12
		Run 4	228E+12	299E+12	264E+12	3.10E+15	2.21E+15	2.66E+15	828E+12	719E+12	774E+12	289E+12	260E+12	275E+12	123E+12	147E+12	135E+12
Group III+ A, 8 cSt		**Run 1**	94.8E+12	108E+12	101E+12	42.2E+12	52.9E+12	47.6E+12	50.9E+12	63.6E+12	57.3E+12	39.8E+12	48.5E+12	44.2E+12	7.61E+12	11.1E+12	9.36E+12
		Run 2	115E+12	124E+12	120E+12	56.7E+12	61.1E+12	58.9E+12	66.9E+12	78.9E+12	72.9E+12	61.2E+12	65.2E+12	63.2E+12	7.71E+12	11.9E+12	9.81E+12
Group III+ B, 4 cSt		**Run 1**	76.6E+12	89.4E+12	83.0E+12	23.6E+12	30.4E+12	27.0E+12	44.7E+12	57.3E+12	51.0E+12	391E+12	289E+12	340E+12	15.6E+12	40.4E+12	28.0E+12
		Run 2	92.7E+12	96.6E+12	94.7E+12	26.9E+12	32.1E+12	29.5E+12	52.8E+12	62.8E+12	57.8E+12	551E+12	309E+12	430E+12	17.5E+12	34.6E+12	26.1E+12
		Run 3	>10.0E+15	6.66E+15	OOS	>10.0E+15	4.49E+15	OOS	4.39E+15	1.86E+15	3.13E+15	98.5E+12	169E+12	134E+12	41.0E+12	52.2E+12	46.6E+12
		Run4	>10.0E+15	6.77E+15	OOS	>10.0E+15	4.54E+15	OOS	6.34E+15	1.92E+15	4.13E+15	107E+12	173E+12	140E+12	44.0E+12	46.6E+12	45.3E+12
Group IV, 3 cSt		**Run 3**	1.88E+15	3.44E+15	2.66E+15	1.27E+15	1.56E+15	1.42E+15	398E+12	668E+12	533E+12	155E+12	216E+12	186E+12	81.9E+12	117E+12	99.5E+12
		Run 4	2.94E+15	4.20E+15	3.57E+15	1.79E+15	1.92E+15	1.86E+15	689E+12	828E+12	759E+12	231E+12	249E+12	240E+12	110E+12	131E+12	121E+12
Group IV, 5 cSt		**Run 1**	1.71E+15	2.84E+15	2.28+E15	499E+12	977E+12	738E+12	689E+12	713E+12	701E+12	748E+12	359E+12	554E+12	37.7E+12	54.2E+12	46.0E+12
		Run 2	1.77E+15	2.86E+15	3.59E+15	593E+12	1.02E+15	807E+12	851E+12	758E+12	805E+12	866E+12	367E+12	617E+12	39.4E+12	53.3E+12	46.4E+12
Group IV, 6 cSt		**Run 1**	1.22E+15	2.72E+15	1.97E+15	489E+12	1.48E+15	985E+12	526E+12	823E+12	675E+12	391E+12	275E+12	333E+12	31.8E+12	49.2E+12	40.5E+12
		Run 2	1.81E+15	3.05E+15	2.43E+15	496E+12	1.21E+15	853E+12	513E+12	713E+12	613E+12	435E+12	268E+12	351E+12	32.2E+12	46.0E+12	39.1E+12
Group IV, 8 cSt		**Run 1**	1.26E+15	2.50E+15	1.88E+15	468E+12	1.12E+15	794E+12	438E+12	577E+12	508E+12	520E+12	295E+12	408E+12	41.3E+12	55.8E+12	48.9E+12
		Run 2	1.69E+15	2.55E+15	2.12E+15	511E+12	1.05E+15	781E+12	488E+12	572E+12	530E+12	530E+12	305E+12	418E+12	41.2E+12	54.5E+12	47.9E+12
		Run 3	1.81E+15	4.29E+15	3.05E+15	1.89E+15	2.77E+15	2.33E+15	839E+12	1390E+12	1115E+12	319E+12	410E+12	365E+12	466E+12	349E+12	408E+12
		Run 4	2.96E+15	4.08E+15	3.52E+15	1.99E+15	2.64E+15	2.32E+15	805E+12	1210E+12	1008E+12	327E+12	421E+12	374E+12	431E+12	347E+12	389E+12
Group IV, 65 cSt		**Run 1**	>10.0E+15	6.78E+15	NA	2.75E+15	2.81E+15	2.78E+15	1.02E+15	774E+12	897E+12	849E+12	337E+12	593E+12	107E+12	97.3E+12	102E+12
		Run 2	6.67E+15	5.41E+15	6.04E+15	1.40E+15	1.98E+15	1.69E+15	493E+12	652E+12	573E+12	795E+12	362E+12	579E+12	119E+12	98.8E+12	109E+12
Group V Di-ester, 3.2 cSt		**Run 1**	2.01E+12	2.60E+12	2.31E+12	749E+09	1.05E+12	900E+09	425E+09	819E+09	622E+09	278E+09	391E+09	335E+09	239E+09	360E+09	300E+09
		Run 2	1.94E+12	2.52E+12	2.23E+12	773E+09	991E+09	882E+09	437E+09	843E+09	640E+09	278E+09	386E+09	332E+09	231E+09	346E+09	289E+09
Group V Monoester, 2.9 cSt		**Run 1**	18.9E+12	21.7E+12	20.3E+12	7.55E+12	9.12E+12	8.34E+12	3.24E+12	5.11E+12	4.18E+12	1.94E+12	2.48E+12	2.21E+12	1.55E+12	2.22E+12	1.89E+12
		Run 2	17.7E+12	21.8E+12	19.8E+12	7.39E+12	8.89E+12	8.14E+12	3.29E+12	5.24E+12	4.27E+12	2.04E+12	2.42E+12	2.23E+12	1.66E+12	2.13E+12	1.90E+12
Group V Monoester, 4.2 cSt		**Run 1**	215E+12	204E+12	210E+12	60.6E+12	70.0E+12	65.3E+12	39.2E+12	26.2E+12	32.7E+12	6.10E+12	6.94E+12	6.52E+12	2.95E+12	3.58E+12	3.27E+12
		Run 2	162E+12	187E+12	175E+12	49.8E+12	62.9E+12	56.4E+12	14.4E+12	17.7E+12	16.1E+12	6.00E+12	7.04E+12	6.52E+12	2.96E+12	3.65E+12	3.31E+12
Group V Monoester, 5.5 cSt		**Run 1**	141E+12	156E+12	149E+12	67.9E+12	109E+12	88.5E+12	22.1E+12	33.3E+12	27.7E+12	8.70E+12	8.90E+12	8.80E+12	4.26E+12	5.72E+12	4.99E+12
		Run 2	160E+12	174E+12	167E+12	76.0E+12	110E+12	93.0E+12	22.2E+12	32.8E+12	27.5E+12	9.02E+12	9.09E+12	9.06E+12	4.50E+12	5.80E+12	5.15E+12
Group V, Polyolester, 4.1 cSt		**Run 1**	9.38E+12	10.2E+12	9.79E+12	2.66E+12	3.53E+12	3.10E+12	476E+09	1.13E+12	803E+09	284E+09	378E+09	331E+09	224E+09	326E+09	275E+09
		Run 2	7.71E+12	8.59E+12	8.15E+12	2.19E+12	2.81E+12	2.50E+12	525E+09	1.15E+12	838E+09	283E+09	378E+09	331E+09	217E+09	307E+09	262E+09
Group V, Polyolester, 4.4 cSt		**Run 1**	7.83E+12	8.48E+12	8.16E+12	2.93E+12	4.38E+12	3.66E+12	662E+09	1.07E+12	866E+09	409E+09	489E+09	490E+09	357E+09	487E+09	422E+09
		Run 2	6.22E+12	7.49E+12	6.86E+12	2.94E+12	4.10E+12	3.52E+12	688E+09	1.13E+12	909E+09	415E+09	509E+09	462E+09	358E+09	494E+09	426E+09
Group V, Adipate Ester, 4 cSt		**Run 1**	2.70E+12	3.07E+12	2.89E+12	821E+09	1.26E+12	1.04E+12	253E+09	391E+09	322E+09	133E+09	168E+09	151E+09	89.3E+09	128E+09	109E+09
		Run 2	2.08E+12	2.69E+12	2.39E+12	806E+09	1.17E+12	988E+09	254E+09	390E+09	322E+09	134E+09	170E+09	152E+09	91.8E+09	131E+09	111E+09
Group V PAG Blend, 4 cSt		**Run 1**	7.33E+09	6.77E+09	7.01E+09	3.91E+09	3.77E+09	3.84E+09	1.19E+09	1.14E+09	1.17E+09	1.65E+09	1.43E+09	1.54E+09	1.09E+09	1.00E+09	1.05E+09
		Run 2	6.90E+09	6.75E+09	6.83E+09	3.79E+09	3.74E+09	3.77E+09	1.23E+09	1.19E+09	1.21E+09	1.49E+09	1.31E+09	1.40E+09	994E+06	896E+06	945E+06
Group V PAG, 4 cSt		**Run 1**	48.6E+09	45.0E+09	46.8E+09	24.8E+09	24.7E+09	24.8E+09	8.99E+09	8.93E+09	8.96E+09	5.12E+09	4.66E+09	4.89E+09	4.36E+09	4.20E+09	4.28E+09
		Run 2	45.6E+09	44.5E+09	45.1E+09	25.6E+09	25.4E+09	25.5E+09	9.66E+09	9.40E+09	9.53E+09	6.17E+09	5.46E+09	5.82E+09	5.70E+09	5.23E+09	5.47E+09
Group V, Bio-based Polyester		**Run 1**	790E+09	1.29E+12	1.04E+12	388E+09	735E+09	562E+09	80.1E+09	103E+09	91.6E+09	114E+09	162E+09	138E+09	102E+09	128E+09	115E+09
		Run 2	813E+09	1.23E+12	1.02E+12	425E+09	716E+09	571E+09	98.3E+09	117E+09	107E+09	111E+09	160E+09	136E+09	108E+09	137E+09	123E+09
Group V, Bio-based Di-ester		**Run 1**	46.8E+09	44.2E+09	45.5E+09	21.6E+09	21.5E+09	21.6E+09	8.08E+09	7.67E+09	7.88E+09	4.44E+09	4.33E+09	4.39E+09	3.36E+09	3.10E+09	3.23E+09
		Run 2	46.5E+09	45.7E+09	46.1E+09	23.1E+09	22.0E+09	22.6E+09	8.33E+09	7.79E+09	8.06E+09	4.59E+09	4.38E+09	4.49E+09	3.20E+09	2.88E+09	3.04E+09
Group V, Bio-based Monoalcohol Ester A		**Run 1**	561E+09	781E+09	711E+09	165E+09	193E+09	179E+09	62.8E+09	71.0E+09	66.9E+09	52.6E+09	64.2E+09	58.4E+09	25.8E+09	28.5E+09	27.2E+09
		Run 2	570E+09	761E+09	666E+09	169E+09	194E+09	182E+09	64.1E+09	72.4E+09	68.3E+09	51.7E+09	63.8E+09	57.8E+09	25.1E+09	26.6E+09	25.9E+09
Group V, Bio-based Monoalcohol Ester B		**Run 1**	18.5E+12	19.1E+12	18.8E+12	9.64E+12	10.9E+12	10.3E+12	1.75E+12	1.69E+12	1.72E+12	259E+09	343E+09	309E+09	149E+09	251E+09	200E+09
		Run 2	18.0E+12	20.0E+12	19.0E+12	10.3E+12	11.5E+12	10.9E+12	1.83E+12	1.75E+12	1.79E+12	293E+09	362E+09	328E+09	157E+09	249E+09	203E+09