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Executive Summary

Purpose

The US Army has successfully used silicone brake fluid (SBF) over traditional poly-glycol brake fluid (PBF) since 1980 in most ground vehicle platforms due to its long life and corrosion protection. SBF now faces a modern compatibility issue: it is incompatible with anti-lock braking systems (ABS). To improve safety, some ground vehicle platforms including High Mobility Multipurpose Wheeled Vehicle (HMMWV) and Joint Light Tactical Vehicle (JLTV) are transitioning to the use of ABS. Therefore, the US Army has a need to implement a PBF solution without revisiting the corrosion and vapor lock problems that plagued the Army prior to 1980.

This report is in support of the Brake Fluid Standardization for Anti-Lock Braking Systems (BFABS) project of the CCDC GVSC Ground Systems Fluids and Fuels (GSFF) research project. The objective of the BFABS project is to evaluate a series of PBF for use in ABS and define military-specific fluid requirements to safeguard Army ground vehicle brake systems in all operational environments.

Approach

The effort detailed in this report identified 13 commercially-available PBF candidates via market survey, internet research, and communication with industry experts. Selected candidates conformed to several different commercial performance specifications and were classified as one of four PBF types: Department of Transportation (DOT) 3, DOT 4, International Organization for Standardization (ISO) 4925 Class 6, and DOT 5.1.

DOT 3 brake fluids are low cost and have a lower boiling point than other types of brake fluid, but tend to absorb water less quickly. DOT 4 brake fluids are the most commonly used fluids in Europe, are costlier than a DOT 3, but boast a higher boiling point and better low temperature viscosity properties. DOT 5.1 brake fluids are high performance PBFs designed to meet the requirements of SBF and are costlier still, but also tend to absorb water more quickly. ISO 4925 Class 6 fluids are advertised to have the high boiling point properties of a DOT 5.1, as well as improved low temperature viscosity performance like a DOT 4. HMMWV and JLTV are currently using fluids that conform to DOT 5.1 and DOT 4, respectively, and therefore were also selected as test candidates in this study.

All candidates underwent experimental testing to determine key characteristics of ABS-compatible brake fluid including vapor lock prevention, low temperature viscosity, and water absorption. This was done via experimental investigations of boiling point as a function of water content, water absorption over time, and low temperature viscosity of humidified brake fluid. Routine conformance testing was also performed in accordance with (IAW) SAE J1704 (JUL2016)



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and MIL-PRF-46176B, such as corrosion, kinematic viscosity, rubber swell, low temperature fluidity, and effect on rubber.

Results and Discussion

Four major performance criteria were identified during data analysis and literature research: corrosion protection, vapor lock prevention, low temperature viscosity, and water absorption. Candidates were evaluated using the above criteria and ranked in order to select the top five candidates, all of which were DOT 5.1 or ISO 4925 Class 6 candidates. These candidates were selected for their outstanding performance in vapor lock prevention and low temperature viscosity even when humidified. HMMWV currently uses a DOT 5.1 which was one of the top five candidates, while JLTV currently uses a DOT 4 which had poor corrosion protection, vapor lock prevention and low temperature viscosity and was not selected as one of the top five candidates.

Next Steps

In the next phase of the BFABS project, simulated service testing on the five down selected candidates will be performed to determine ABS compatibility. The BFABS project will conclude with the establishment of a standard, such as a military performance specification or commercial item description, to be used in procuring commercial brake fluids for use in ABS-equipped military ground vehicles.



Acknowledgements

The US Army CCDC GVSC, Force Projection Technology (FPT) in Warren, MI administered the project; Phase IIb testing was performed at the Fuel & Lubricants Laboratory (FLL) under FPT. ABIC International Consultants, Inc., located in Fairfield, NJ, performed Phase IIa testing during the period September 2018 through August 2019. Mr. Eric Sattler served as the CCDC GVSC contracting officer's technical representative. The authors would like to acknowledge the contribution of ABIC's technical and administrative support staff. In addition, special recognition goes out to Talia Marie Sebastian, PhD., Jill M. Bramer, Patsy A. Muzzell, and James S. Dusenbury, PhD., for their essential review of the report draft; their feedback was critical to showcasing the large amount of work that went into this effort.



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Background

Since 1980, Army brake fluid use has been governed by MIL-PRF-46176, which prompted the replacement of three different polyglycol brake fluids (PBF) used at the time with a single fluid, silicone brake fluid (SBF) [1]. Prior to 1980, PBF was designated for general use (under VV-B-680), arctic use (MIL-H-13910B), and vehicle storage (MIL-P-46046A) [2]–[4]. Logistically, sustaining three different fluids to service the large array of ground vehicles in a range of environments worldwide proved difficult. Practically, these fluids, along with the brake system hardware at the time, could not sustain operation in high-humidity environments due to the PBFs' hygroscopic, or water absorbing properties. As PBF absorbs water, it hinders the fluid's ability to prevent corrosion in the brake hardware, as well as lowers the boiling point, thereby increasing the risk of vapor lock and brake system failure [5]–[7]. Continued use of fluids under VV-B-680 were resulting in both operational failures and hardware deterioration, prompting the use of SBF under MIL-PRF-46176 in 1980 [8].

The adoption of SBF has been successful in large part due to the fluid's inability to absorb water, its high boiling point, and low temperature viscosity performance. Additionally, the switch from three fluids to one helped improve the Army's logistical brake fluid footprint; SBF's non-hygroscopic nature effectively negated the need for regular fluid changes as it significantly reduced hardware corrosion potential [9]. At the time of implementation, SBF was expected to move further into the commercial brake fluid market share. While it has since proved successful for the United States Postal Service as well as in classic car enthusiast market, the fluid's price, as well as concerns of air entrapment and system corrosion due to free water, has prevented widespread implementation [10]–[12].

To further complicate matters, the advent of Anti-lock Braking Systems (ABS) in the 1990s has caused many brake fluid manufacturers to state that SBF was incompatible with ABS due to air entrapment, rubber incompatibility, and poor lubricity. Research conducted by the US Army confirmed the reports from industry [12], [13]. SBF's poor lubricity and system elastomer incompatibilities has shown that use in ABS is not optimal, although air entrapment was not observed to pose a problem.

Currently, as modern US Army ground vehicle platforms such as HMMWV and JLTV are transitioning to the use of ABS, the US Army has a need to implement a brake fluid solution without revisiting the problems that plagued the Army's use of PBF in the past [14].

This report is in support of the BFABS project of the CCDC GVSC Ground Systems Fluids and Fuels (GSFF) research program. The objective of the BFABS project is to identify and evaluate a brake



fluid for use in ABS and define military-specific fluid requirements to safeguard Army ground vehicle brake systems in all environments. Stakeholders in this research effort include the HMMWV and JLTV offices under Program Executive Office Combat Support & Combat Service Support (PEO CS&CSS), as well as Defense Logistics Agency – Aviation (DLA-A), who manages the supply chain for military procurements of Class IIIP – packaged Petroleum, Oil and Lubricant (POL) products.

The benchtop testing effort detailed in this report was designed to aid in the identification of promising brake fluid solutions by determining key characteristics of ABS-compatible brake fluids and down-selecting brake fluid test candidates for simulated service testing. The approach detailed in this report will describe the routine benchtop testing of brake fluid candidates to serve as a baseline. Additionally, a more experimental approach was performed to measure performance in areas including vapor lock prevention, water absorption, and humidified low temperature viscosity.

Objective

1. Select test candidates from market survey results
2. Baseline test candidate performance in benchtop testing
3. Down select test candidates for simulated service testing based on performance criteria
 - a. Corrosion Protection
 - b. Low Temperature Viscosity
 - c. Water Absorption
 - d. Vapor Lock Prevention

Approach

To accomplish the objective, GVSC conducted four phases:

- I. Market Survey
- II. Laboratory Benchtop Testing
 - a. Routine & Experimental (ABIC International Consultants, Inc.)
 - b. Experimental (FLL)
- III. Candidate Performance Criteria
- IV. Candidate Down Selection

Phase I – Market Survey

GVSC developed a market survey to identify commercial PBF on the market; information of primary interest was specification conformance, service interval, low temperature performance, and global distribution ability. The Procurement Network (PROCNET) and Federal Business Opportunities (FedBizOpps) posted this market survey for brake fluid manufacturers to respond



to with potential candidates for 39 days. GVSC received four market survey responses from three companies during the posting period. Following the conclusion of the market survey, GVSC reached out to those known industry contacts who did not respond to the initial posting. From here, GVSC was able to identify ten products from six additional companies. Market survey responses were published to the Defense Technical Information Center (DTIC) under accession number AD1070186. In total, the market survey identified 14 products from nine companies.

Market Survey Results Guiding Fluid Candidate Selection

Based on results gathered from the industry market survey, contacts within the industry, and internet research, GVSC was able to identify and select fluid candidates for Phase II testing. Selected candidates fell into one of four different types of brake fluid: DOT 3, DOT 4, ISO 4925 Class 6, and DOT 5.1. Inclusion of a broad range of brake fluid types, detailed below, ensures coverage of the most widely-used types of brake fluid available internationally in the commercial market today:

DOT 3 BRAKE FLUIDS are the most commonly used fluids in the US and conform to the Department of Transportation's (DOT) Federal Motor Vehicle Safety Standard (FMVSS) 116 [15]. These fluids are low cost and have a lower boiling point than other types of brake fluid, but tend to absorb water less quickly. They also typically conform to SAE J1703 [16].

DOT 4 BRAKE FLUIDS are the most commonly used fluids in Europe and also conform to the DOT's FMVSS 116. These fluids are costlier than DOT 3's but boast a higher boiling point and better low temperature viscosity properties. They also typically conform to SAE J1704 [17].

DOT 5.1 BRAKE FLUIDS are high performance PBF designed to meet the requirements of FMVSS 116 DOT 5 brake fluids, which are silicone based. These fluids are more costly than DOT 4's, but have the highest dry boiling point of all commercial PBF. They also typically conform to SAE J1705 [18].

ISO 4925 CLASS 6 BRAKE FLUIDS (hereafter "ISO 6") are higher performance versions of DOT 4 fluids and referred to by various naming conventions e.g. "Super DOT 4", "DOT 4 Plus", and "DOT 4 Low Viscosity" [19]. These fluids conform to ISO 4925 and are advertised to have the high boiling point properties of a DOT 5.1, as well as improved low temperature viscosity performance. They also typically conform to SAE J1704.

A total of seven different manufacturers were represented in the candidate pool (Table 1). The two remaining manufacturers did not have their fluids selected from lack of information and difficulties in procurement. Color designations in Table 1 are used to denote fluid types and are



not representative of performance. These colors are used for the presentation of testing results throughout this report as an easy way to identify differences between fluid types.

Table 1. Test Candidate Information		
Candidate Code	Specification Conformance	Selection Justification
DOT 3 A	SAE J1703	Interest due to marketing as a “low viscosity” DOT 3 fluid; advertised to have better viscosity performance while maintaining low water absorption of DOT 3.
DOT 4 A	SAE J1704	General use DOT 4, used by many OEMs.
DOT 4 B	SAE J1704	General use DOT 4, used by many OEMs.
DOT 4 C	SAE J1704	Fluid currently being used in ABS-equipped JLTV.
DOT 5.1 A	SAE J1705	Fluid currently being used in ABS-equipped HMMWV.
DOT 5.1 B	SAE J1705	General use DOT 5.1; available for worldwide shipment.
DOT 5.1 C	SAE J1705	General use DOT 5.1; available for worldwide shipment.
DOT 5.1 D	SAE J1705	Low viscosity DOT 5.1; advertised to match the low viscosity performance of DOT 4 Low Viscosity (LV) / ISO Class 6 while maintaining high boiling point inherent to DOT 5.1.
DOT 5.1 E	SAE J1705	Specialty DOT 5.1 said to have improved low temperature viscosity and lubricity performance.
ISO 6 A	SAE J1704	DOT 4 LV, widely used.
ISO 6 B	SAE J1704	DOT 4 LV, widely used.
ISO 6 C	ISO 4925 Class 6	ISO 4925 Class 6, shipped and used worldwide.
ISO 6 D	SAE J1704	DOT 4 LV under ISO 4925 Class 6, sometimes marketed as a "DOT 6"; This fluid supposedly has all the benefits of DOT 4 and DOT 5.1 without the drawbacks.
RM-71	SAE J1704	Control fluid

All fluid candidates were procured between July and August 2018, with the exception of DOT 4 C, which was added in April 2019 following discussions with technical points of contact from the JLTV office. RM-71 (defined in SAE J1704) was used as a control fluid for FLL experimental testing.



Phase II – Laboratory Benchtop Testing

Laboratory benchtop testing was performed at the CCDC GVSC Fuels & Lubricants Laboratory (FLL) and at ABIC International Consultants, Inc (hereafter ABIC). ABIC is a 3rd party test laboratory chosen to perform both conformance and experimental benchtop testing on the candidates for testing that was unable to be performed at the FLL. ABIC was chosen via full and open contract for their expertise in brake fluid testing. Testing was broken out between the two labs as follows:

- ABIC conformance testing
 - Conformance to SAE J1704 (JUL2016) performance requirements
 - Conformance to MIL-PRF-46176B performance requirements (Viscosity & low temperature fluidity at -55°C only)
- ABIC experimental testing
 - Wet viscosity investigation
- FLL experimental testing
 - Study 1: Equilibrium reflux boiling point (ERBP) of PBF as a function of water content
 - Study 2: Water absorption of PBF as a function of time

Phase IIa – Laboratory Benchtop Testing: ABIC

ABIC performed conformance testing for all test procedures in SAE J1704 as well as two tests selected from MIL-PRF-46176: viscosity and low temperature fluidity at -55°C. These were the only tests selected from MIL-PRF-46176 since all other benchtop tests are identical to those found in SAE J1704; only the pass/fail requirements differ. Appendix C provides the complete set of conformance tests performed for each candidate. Candidate ISO 6 D was not tested by ABIC due to funding constraints.

ABIC also performed a wet viscosity investigation to determine the effect of water content on kinematic viscosity as a function of temperature. Candidate ISO 6 D was again not tested by ABIC due to funding constraints.

Conformance tests that were of particular interest are expanded upon below.

Viscosity

Kinematic viscosity (hereafter “viscosity”) is defined as a fluid’s resistance to flow at a particular temperature; for brake fluids, having a high viscosity at low temperatures means that braking power feels “sluggish” [20]. Viscosity was performed IAW ASTM D445 at three temperatures: -55°C, -40°C, and 100°C [21]. All commercial brake fluids must pass specification requirements at -40°C, and 100°C; the US Army requires testing down to -55°C.



Corrosion

Corrosion testing is performed to observe wear metal corrosion weight loss on a number of typical metals used in a brake system including cast iron, tinned iron, aluminum, steel, brass, and copper. Brake fluids that are well-formulated to resist system corrosion induced by the ingestion of water typically have low levels of metal weight loss. Wear metal corrosion under wet and dry conditions was performed IAW SAE J1704 §5.6.1 and 5.6.2, respectively. The wet corrosion test is the more severe of the two as it tests the fluid mixed with 5% water.

Rubber Swell

Examination of rubber swell on brake cups is performed as a part of the wet and dry corrosion tests IAW SAE J1704 §5.6.1 and 5.6.2, respectively. Cups are examined for decrease in hardness and volume swell. Both Styrene Butadiene Rubber (SBR) and Ethylene Propylene Diene Monomer (EPDM) cups were tested; these elastomers are chosen as they represent the compounds typically used in brake systems [22].

Low Temperature Fluidity

Low temperature fluidity subjects the test fluid to storage at a low temperature for a set amount of time. This test is used to identify fluids that are unstable at low temperatures by examining them post-test for signs of high viscosity, sludging, sedimentation, crystallization, or stratification. Fluidity and Appearance at Low Temperature was performed IAW SAE J1704 §5.7 and MIL-PRF-46176 §4.3.6.2.2 at -40 and -55°C, respectively.

Effect on Rubber

This test was performed IAW SAE J1704 §5.11 on SBR cups to discern candidate compatibility with rubber under a high temperature soak. Cups are examined post-test for disintegration, sloughing, and changes in both hardness and base diameter. Testing on EPDM was not performed as that test has since been suspended as of the JUL2016 revision of SAE J1704.

Wet Viscosity Investigation

Brake fluid viscosities when humidified at -55°C, -40°C, and 100°C were also investigated. This data was of interest since brake fluids in operation absorb water from the environment, therefore observations of viscosity on dry fluids do not provide an accurate picture of how fluids behave in a brake system. Understanding how wet brake fluids increase their viscosities at lower temperatures can provide a clear indication of fluids that would pose a risk when operating in arctic environments.

To complete the investigation, candidates were first humidified IAW SAE J1704 §5.2.1, such that the reference fluid (SAE RM-71) reached 3.7% water content in the same environment. Post-



humidification, samples were run IAW ASTM D445 at the designated temperatures to determine their kinematic viscosities.

Phase IIb – Laboratory Benchtop Testing: FLL

GVSC performed laboratory benchtop testing on 13 brake fluid candidates (Table 1). Testing was performed in the Fuels and Lubricants Laboratory (FLL) from September 2018 to July 2019. The objective of this testing was to characterize the performance of each candidates boiling point as a function of water content, as well as the performance of their water absorption over time.

The testing included the following protocols conducted on the candidates in Table 1:

- ASTM D1120-17 – Standard Test Method for Boiling Point of Engine Coolants [23]
- ASTM D6304-16^{e1} Procedure C – Standard Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration [24]
- SAE J1704 (JUL16) §5.2.1 (modified) – Humidification Procedure [17]

Study 1: Equilibrium Reflux Boiling Point (ERBP) of PBF as a Function of Water Content

The objective of this study was to characterize the quantitative performance of the candidate brake fluids' ERBP as a function of water content by weight. ERBP is defined as the temperature of a fluid when it reaches an equilibrium between liquid and vapor state at a constant reflux rate IAW the method. A brake fluid's ERBP will decrease as water is absorbed. The wet ERBP test, as defined in SAE J1704, has the user obtain the ERBP of the humidified test fluid after a reference fluid (RM-71) has absorbed 3.7% water in the same humidified environment. As such, this test does not fairly compare how candidates' boiling points differ at the same water content because they are not all tested at 3.7% water. This study aimed to objectively compare the candidates' ERBP via direct injection of water.

ERBP was measured IAW ASTM D1120; water content of the candidates during test was measured IAW ASTM D6304, which uses a Karl Fischer titrator. All fluid candidates had their initial ERBP and water content measured (as received). The candidates' water content was then raised via direct injection from zero to four percent water by weight at approximately 0.5% increments for a total of nine data points. Following direct injection, each sample had their ERBP and water content measured to produce a boiling point curve as a function of water content. Distilled water used for direct injections conformed to ASTM D1193-06 (Reapproved 2018) Type IV [25]. A step-by-step procedure is described in Appendix A. Figure 1 and Figure 2 show the apparatus used to conduct ASTM D1120 and ASTM D6304, respectively.



Figure 1. Test apparatus for ASTM D1120-17 ERBP.
Heaters: Ful-Kontrol 750W (left), and
Glas-Col 230W (right)
Thermocouples: VWR Traceable RTD Platinum

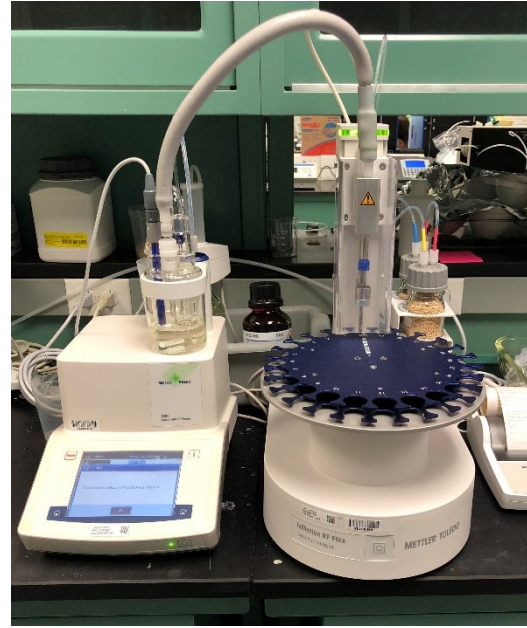


Figure 2. Test apparatus for ASTM D6304-16e1,
Procedure C.
Hardware: Mettler Toledo C30SX (left), and
InMotion KF Flex Oven Autosampler (right)

Study 2: Water Absorption of PBF as a Function of Time

The objective of this study was to characterize the candidate brake fluids' water absorption as a function of time. All fluid candidates had their initial water content measured IAW ASTM D6304. A modified version of the Humidification procedure in SAE J1704 was performed (Appendix B); three glass test jars, two with the fluid candidate and one of RM-71 reference fluid, were placed in a sealed desiccator filled with 350mL distilled water. The entire apparatus was placed in an oven at $50 \pm 1^\circ\text{C}$ for 24 hours. During normal working hours, each test jar was sampled via syringe every hour and had its water content measured. Two different desiccators were run for each fluid candidate; one in the morning to collect samples from hours zero through eight, and one in the afternoon to collect samples from hours 16 through 24 the following day. A step-by-step procedure is described in Appendix B.



Results

Phase IIa – Laboratory Benchtop Testing: ABIC

Tables 2-5 below show data for the following tests that were deemed most critical to brake fluid performance:

- Viscosity at -40°C and -55°C
- Corrosion (5% water and dry)
- Rubber Swell (SBR) for hardness decrease and base diameter increase
- Rubber Swell (EPDM) for hardness decrease and volume increase
- Low Temperature Fluidity for time it takes for an air bubble to travel to the top at -40°C and -55°C
- Effect on Rubber (SBR) at 120°C for base diameter increase.

Cells marked in yellow are passing values but close to their respective limits; red cells represent specification failures.



Table 2. DOT 3 Candidate Benchtop Results		
J1703 Test	J1703 Requirements	DOT 3 A
Viscosity @ -40°C (mm ² /s), max	1500	616
Viscosity @ -55°C (mm ² /s)	Not Required ¹	4706
Corrosion (5% Water)	See Appendix C	Pass ²
Corrosion (dry)	See Appendix C	Pass ²
Rubber Swell (SBR) ³		
<i>hardness decrease, IRHD, max</i>	15	4
<i>base diameter increase, mm, max</i>	1.4	0.02
Rubber Swell (EPDM) ³		
<i>hardness decrease, IRHD, max</i>	10	1
<i>volume increase, %</i>	≤ 10	+1
Low Temp Fluidity - time for air bubble to travel to the top ¹		
<i>at -40°C, seconds</i>	≤ 10	2
<i>at -55°C, seconds</i>	Not Required ¹	4
Effect on Rubber (SBR) @ 120°C		
<i>Hardness decrease, IRHD</i>	0-15	3
<i>Base diameter increase, mm</i>	0.15 - 1.4	0.58

¹MIL-PRF-46176 requirement for Viscosity at -55°C is a max of 900 mm²/s and for Low Temp Fluidity - time for air bubble to travel to the top the requirement is 10 seconds [1]

²Full data and requirements in Appendix C

³Rubber Swell is performed as a part of the corrosion test. Data shown are results from the wet corrosion test. Data on rubber swell from the dry corrosion test is shown in Appendix C



Table 3. DOT 4 Candidates Benchtop Results

J1704 Test	J1704 Requirements	DOT 4 A	DOT 4 B	DOT 4 C
Viscosity @ -40°C (mm ² /s), max	1500	1100	1407	1355
Viscosity @ -55°C (mm ² /s)	Not Required ¹	11780	13906	15733
Corrosion (5% Water)	See Appendix C	Pass ²	Pass ²	Pass ²
Corrosion (dry)	See Appendix C	Pass ²	Pass ²	Pass ²
Rubber Swell (SBR) ³				
<i>hardness decrease, IRHD, max</i>	15	1	6	1
<i>base diameter increase, mm, max</i>	1.4	0.07	0.27	0.05
Rubber Swell (EPDM) ³				
<i>hardness decrease, IRHD, max</i>	10	1	1	1
<i>volume increase, %</i>	≤ 10	+1	+1	+1
Low Temp Fluidity - time for air bubble to travel to the top ¹				
<i>at -40°C, seconds</i>	≤ 10	2	2	2
<i>at -55°C, seconds</i>	Not Required ¹	13	6	5
Effect on Rubber (SBR) @ 120°C				
<i>Hardness decrease, IRHD</i>	0-15	4	10	5
<i>Base diameter increase, mm</i>	0.15 - 1.4	0.43	0.83	0.45

¹MIL-PRF-46176 requirement for Viscosity at -55°C is a max of 900 mm²/s and for Low Temp Fluidity - time for air bubble to travel to the top the requirement is 10 seconds [1]

²Full data and requirements in Appendix C

³Rubber Swell is performed as a part of the corrosion test. Data shown are results from the wet corrosion test. Data on rubber swell from the dry corrosion test is shown in Appendix C



Table 4. DOT 4 LV/ISO Class 6 Candidates Benchtop Results

J1704 LV Test	J1704 LV Requirements	ISO 6 A	ISO 6 B	ISO 6 C
Viscosity @ -40°C (mm ² /s), max	750	536	690	610
Viscosity @ -55°C (mm ² /s)	Not Required ¹	4588	6156	5357
Corrosion (5% Water)	See Appendix C	Pass ²	Pass ²	Pass ²
Corrosion (dry)	See Appendix C	Pass ²	Pass ²	Pass ²
Rubber Swell (SBR) ³				
<i>hardness decrease, IRHD, max</i>	15	3	1	3
<i>base diameter increase, mm, max</i>	1.4	0.02	0.00	0.02
Rubber Swell (EPDM) ³				
<i>hardness decrease, IRHD, max</i>	10	2	1	1
<i>volume increase, %</i>	≤ 10	+1	+1	+1
Low Temp Fluidity - time for air bubble to travel to the top ¹				
<i>at -40°C, seconds</i>	≤ 10	2	2	1
<i>at -55°C, seconds</i>	Not Required ¹	12	6	6
Effect on Rubber (SBR) @ 120°C				
<i>Hardness decrease, IRHD</i>	0-15	4	4	5
<i>Base diameter increase, mm</i>	0.15 - 1.4	0.78	0.66	0.55

¹MIL-PRF-46176 requirement for Viscosity at -55°C is a max of 900 mm²/s and for Low Temp Fluidity - time for air bubble to travel to the top the requirement is 10 seconds [1]

²Full data and requirements in Appendix C

³Rubber Swell is performed as a part of the corrosion test. Data shown are results from the wet corrosion test. Data on rubber swell from the dry corrosion test is shown in Appendix C



Table 5. DOT 5.1 Candidates Benchtop Results

J1705 Test	J1705 Requirements	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E
Viscosity @ -40°C (mm ² /s), max	900	836	837	684	893	611
Viscosity @ -55°C (mm ² /s)	Not Required ¹	8584	7755	6660	8761	5653
Corrosion (5% Water)	See Appendix C	Pass ²	Pass ²	Pass ²	Pass ²	Pass ²
Corrosion (dry)	See Appendix C	Pass ²	Pass ²	Pass ²	Pass ²	Pass ²
Rubber Swell (SBR) ³						
<i>hardness decrease, IRHD, max</i>	15	2	4	2	3	3
<i>base diameter increase, mm, max</i>	1.4	0.12	0.02	0.07	0.05	0.02
Rubber Swell (EPDM) ³						
<i>hardness decrease, IRHD, max</i>	10	1	1	1	1	1
<i>volume increase, %</i>	≤ 10	+1	+	+1	+1	+1
Low Temp Fluidity - time for air bubble to travel to the top ¹						
<i>at -40°C, seconds</i>	≤ 10	2	1	2	2	1
<i>at -55°C, seconds</i>	Not Required ¹	6	7	11	10	7
Effect on Rubber (SBR) @ 120°C						
<i>Hardness decrease, IRHD</i>	0-15	4	10	4	4	5
<i>Base diameter increase, mm</i>	0.15 - 1.4	0.66	1.09	0.60	0.58	0.71

¹MIL-PRF-46176 requirement for Viscosity at -55°C is a max of 900 mm²/s and for Low Temp Fluidity - time for air bubble to travel to the top the requirement is 10 seconds [1]

²Full data and requirements in Appendix C

³Rubber Swell is performed as a part of the corrosion test. Data shown are results from the wet corrosion test. Data on rubber swell from the dry corrosion test is shown in Appendix C

Viscosity

While all candidates met their respective viscosity requirements at -40°C, candidates DOT 4 B, ISO 6 B, DOT 5.1 A, and DOT 5.1 D were all close to the limit for their respective requirements listed in Tables 2-5. All candidates failed to meet the MIL-PRF-46176B requirement for viscosity at -55°C (900 mm²/s). The lowest viscosity observed at -55°C was 4,588 mm²/s for ISO 6 A, or just over five times the allowable limit for MIL-PRF-46176B.

Corrosion

All candidates met their respective weight loss requirements under both wet and dry conditions. Figure 3 shows wet corrosion results with limit lines for the SAE J1704 limits¹, as well as the MIL-PRF-46176 limits. Only one candidate, DOT 4 C, came within 0.1 mg of failing the weight loss limits set in MIL-PRF-46176 for brass.

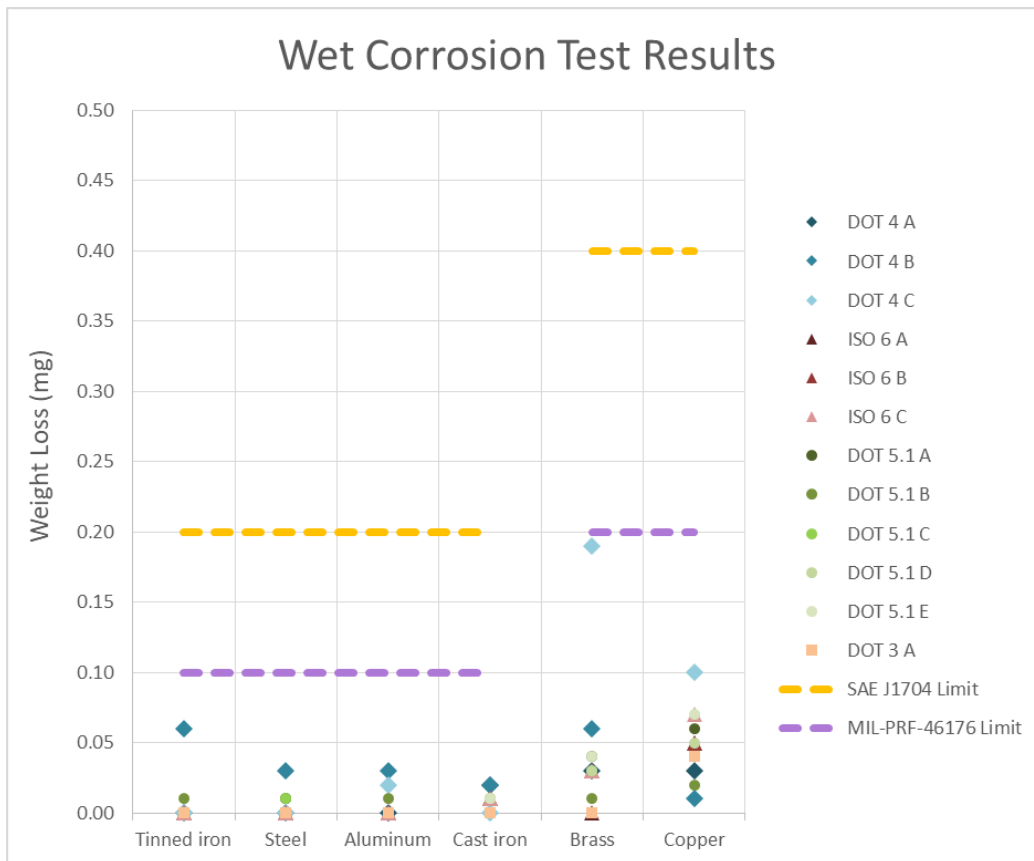


Figure 3. Wet Corrosion Test Results. Limit lines are pulled from SAE J1704 and MIL-PRF-46176.

¹ SAE J1704 limits for corrosion weight loss are identical to the limits in SAE J1703, SAE J1705, and ISO 4925 Class 6.



Rubber Swell

All candidates met requirements and had almost no change in their rubber hardness or volume, both for EPDM and SBR. Even for the wet corrosion test, the more severe of the two that were run, there was little to no delineation between candidates' performance.

Low Temperature Fluidity

Candidates DOT 4 A and DOT 5.1 C did not meet the requirement in MIL-PRF-46176 at -55°C; DOT 5.1 D was right at the requirement limit. All other candidates passed. Performance was identical on the test at -40°C for all candidates, while DOT 3 A performed the best on the test at -55°C.

Effect on Rubber

All candidates passed the requirements in their respective specifications. DOT 5.1 B had a larger decrease in hardness and base diameter increase than nearly any other test candidate; however, it still passed the test. DOT 4 B also saw a large hardness decrease.

Wet Viscosity Investigation

Viscosity did not change between candidates as received (hereafter "dry") and candidates post-humidification (hereafter "wet") at 100°C. At -40°C, viscosities increased anywhere from 30% to 80% between dry and wet candidates. At -55°C, a large change is noted in all candidates, where viscosities were observed to range between 31% and 96%. Figure 4 shows the increase in viscosities for DOT 5.1 A when dry and wet; figures for the remaining candidates are found in Appendix D. Figure 5 and Figure 6 show the wet viscosities of all candidates at -40°C and -55°C. DOT 3 A was the only candidate to pass its respective dry viscosity limit at -40°C when wet. Additionally, ABIC measured the water content of the wet candidates; total water content absorbed by each candidate is shown in Figure 7. These data points were used to compare to the results produced in Phase IIb Study 2.

Full results of this investigation can be found in Appendix D.

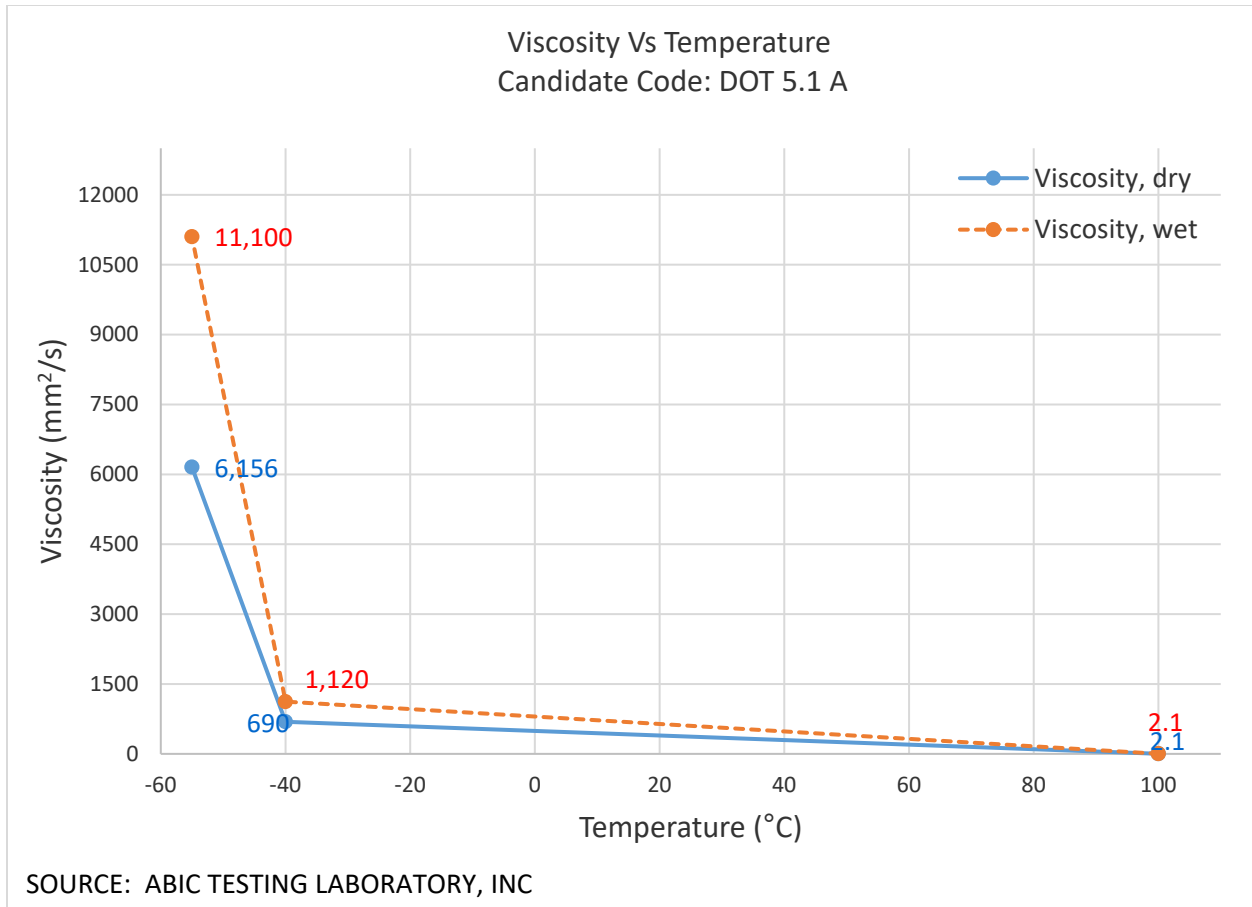


Figure 4. Viscosity vs Temperature of DOT 5.1 A, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.

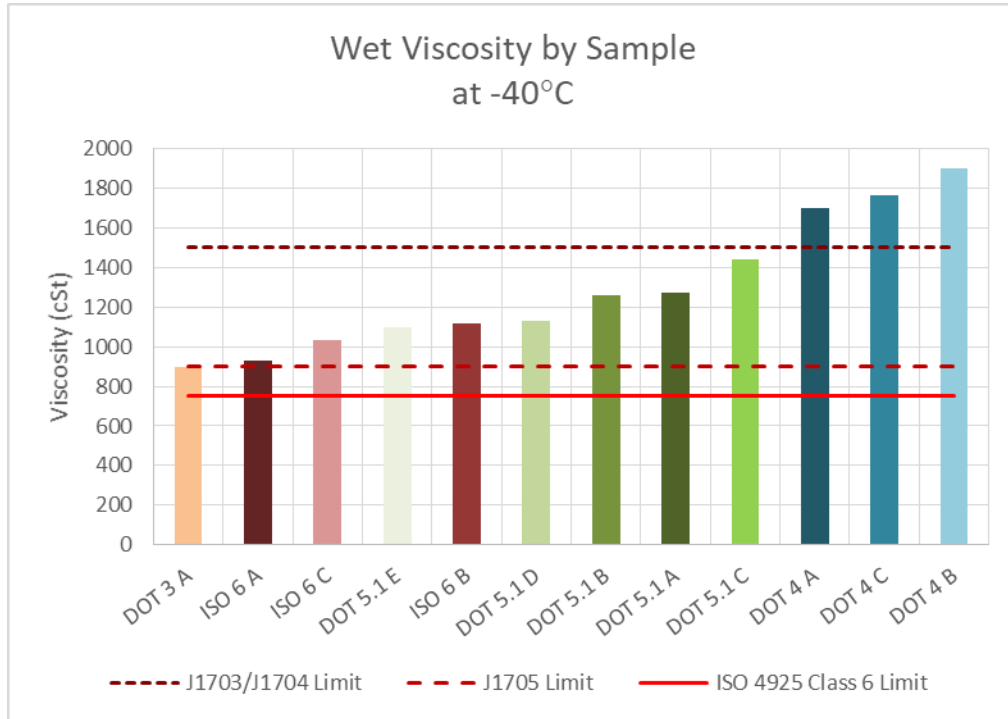


Figure 5. Wet Viscosity by Sample at -40°C
Limit lines for the specification limits (max) are shown in red.

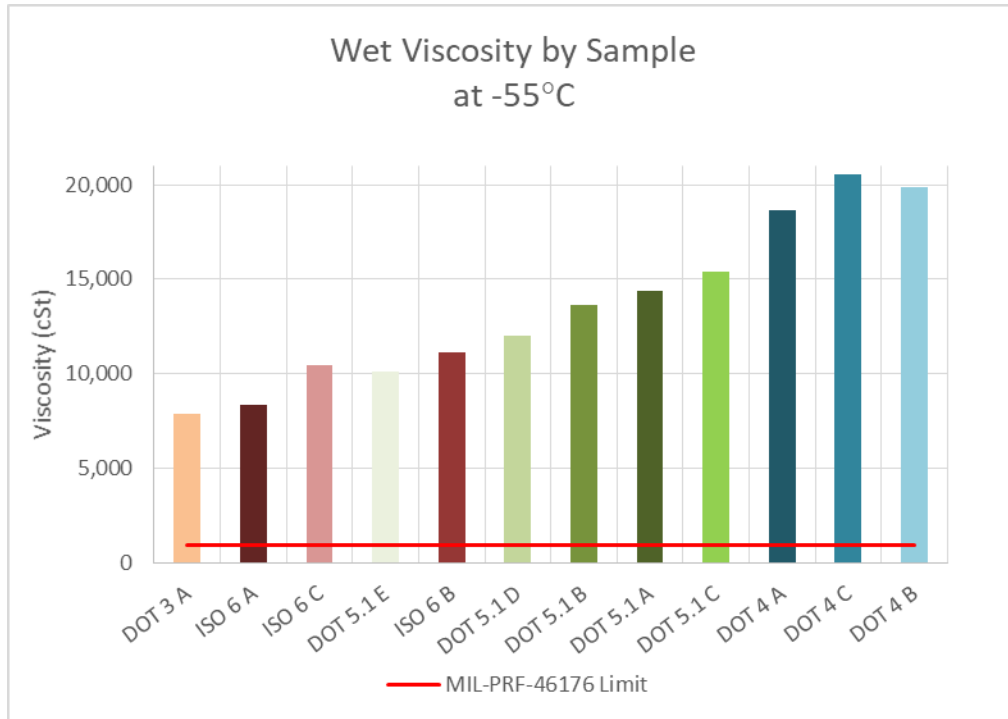


Figure 6. Wet Viscosity by Sample at -55°C.
The limit line for MIL-PRF-46176 (max) is shown in red.

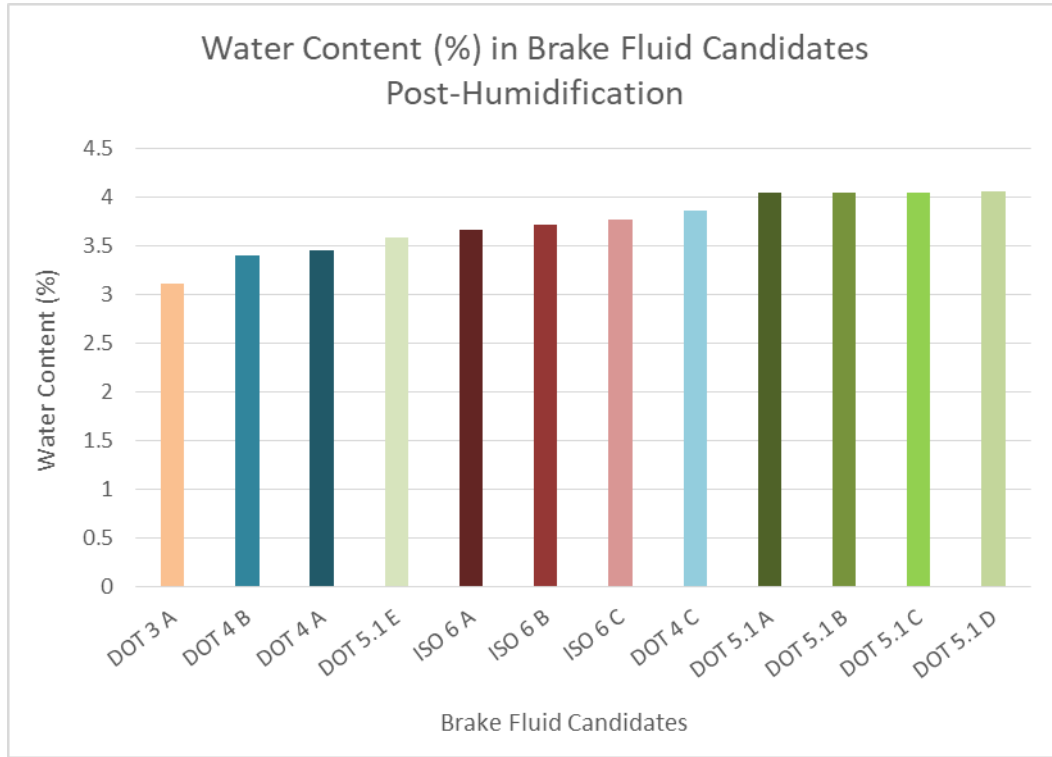


Figure 7. Change in Water Content in Brake Fluid Candidates Post-Humidification (ABIC).

Phase IIb – Laboratory Benchtop Testing: FLL

Study 1: Equilibrium Reflux Boiling Point (ERBP) of PBF as a Function of Water Content

Charted results are shown below in Figure 8.

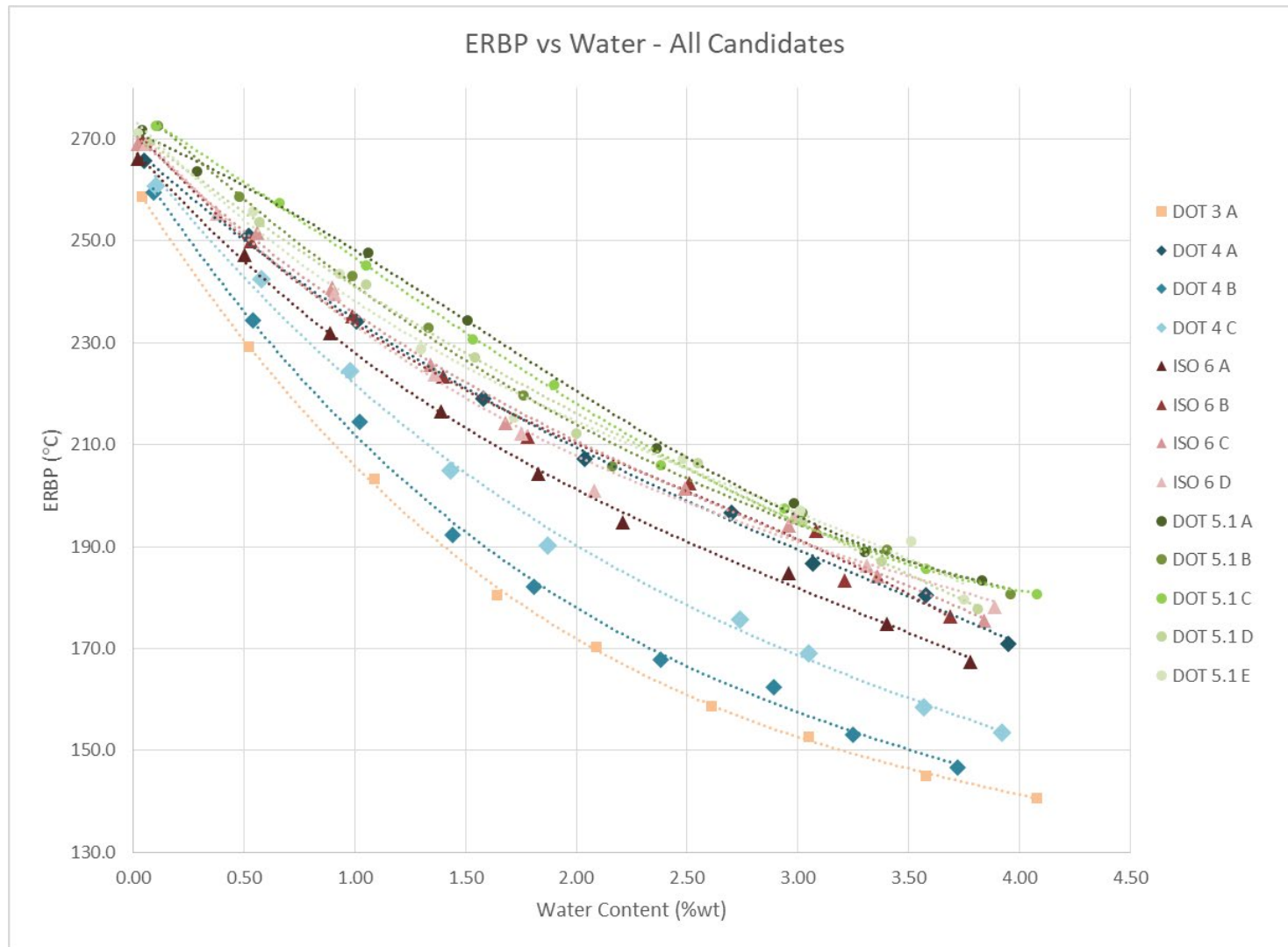


Figure 8. ERBP Data for All Candidates.
 Each data point is an average of duplicate data. Fluid types are differentiated by symbol and color.
 Trendlines are 3rd order polynomials with an r-squared of >0.995.



Candidates behaved as expected based on their respective fluid types; DOT 5.1 performed best for dry and wet BP, followed by ISO 6, then DOT 4, and finally DOT 3. The higher the water content observed, the clearer the delineation between the different fluid types. DOT 4 B and DOT 4 C performed only marginally better than the DOT 3 fluid and markedly worse than DOT 4 A.

Study 2: Water Absorption of PBF as a Function of Time

Charted results are shown below in Figure 9, with a zoomed-in version of results shown in Figure 10.

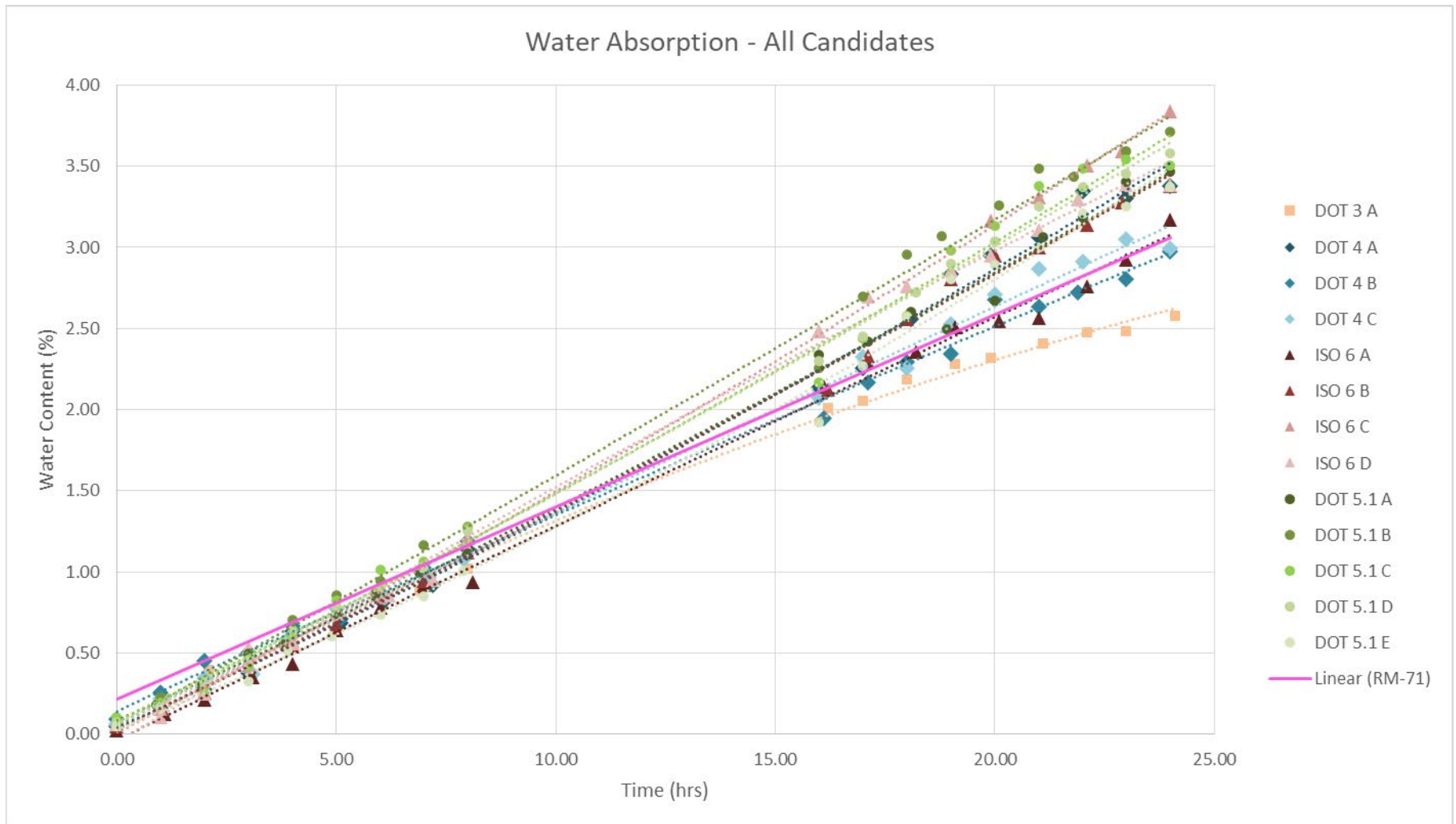


Figure 9. Water Absorption Data for All Candidates.
 Each data point is an average of quadruplicate data. Data were also adjusted to account for deviation in the reference fluid water pick-up.
 Fluid types are differentiated by symbol and color.
 Trendlines are 2nd order polynomials with an $R^2 > 0.995$. The RM-71 linear trendline is an average of all RM-71 data.

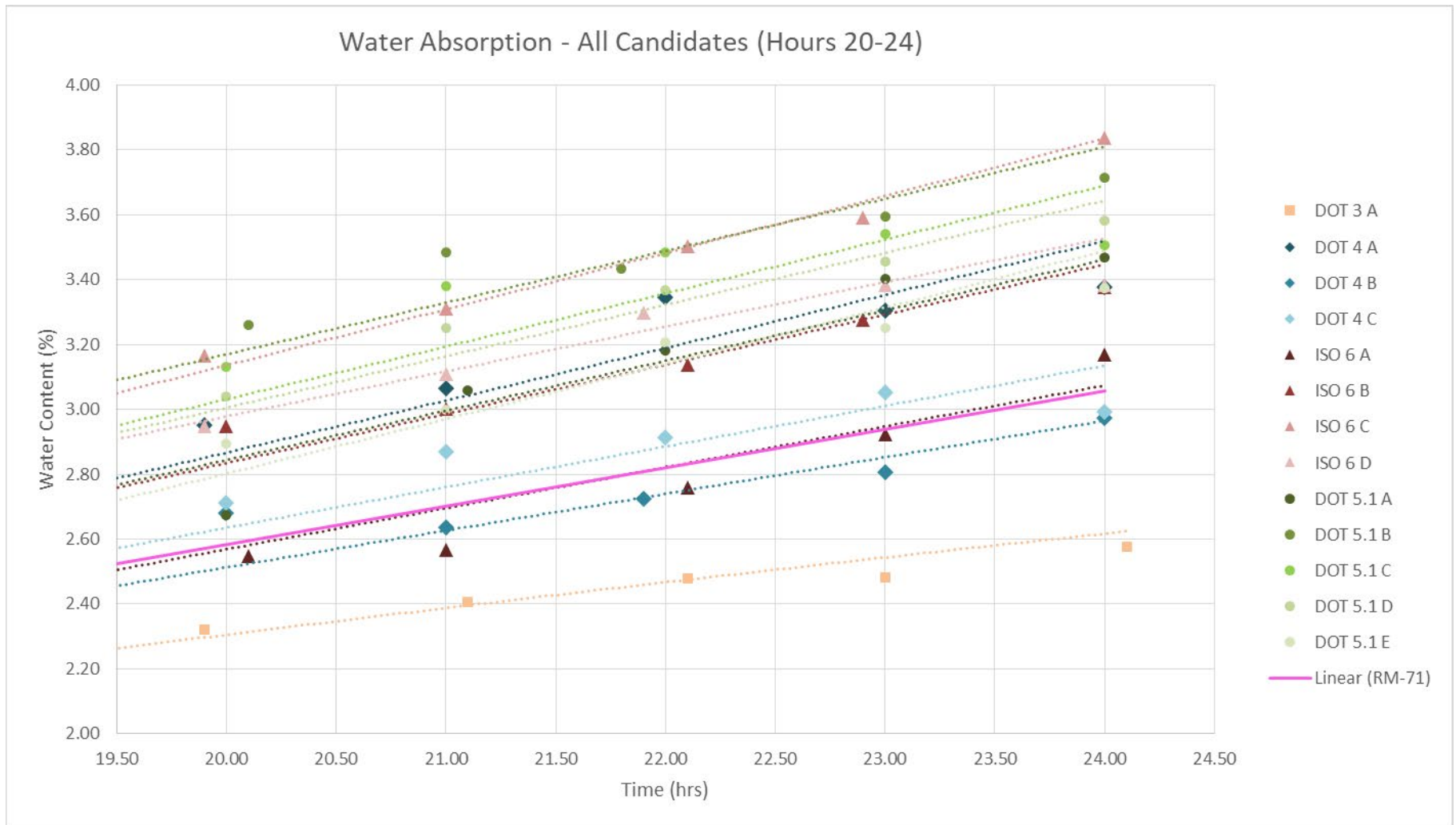


Figure 10. Zoom in of hours 20-24 in Figure 9.
Clear delineation of water absorption between fluid types is apparent.



The general trend observed was that DOT 5.1 candidates absorbed the most water followed by ISO 6 candidates, DOT 4 candidates, and lastly the DOT 3 candidate which absorbed the least amount of water. Outliers included ISO 6 A, which absorbed less water on par with DOT 4 candidates, and DOT 4 A, which absorbed more water on par with ISO 6 candidates. It was also observed that DOT 3 A water absorption was nonlinear and began to taper off after reaching 1.5% water. No other candidates exhibited this behavior.

Typically for the humidification procedure in SAE J1704, the reference fluid reaches 3.7% water within 24 hours, however, this test procedure did not cause it to absorb more than 3% water. This is believed to be caused by running the test with three jars per desiccator rather than two as in the original procedure.

Discussion

Once all testing had concluded, the data was analyzed in order to identify performance criteria which would allow the candidates to be most clearly ranked and further down selected. In FY20, the BFABS project is scheduled to test the top five candidate in a simulated service test rig to evaluate ABS performance².

Phase III – Candidate Performance Criteria

Candidates were assessed using four different performance criteria identified in the objectives:

- a. Corrosion Protection
- b. Low Temperature Viscosity
- c. Water Absorption
- d. Vapor Lock Prevention

Each criterion was given its own grading scale from zero to four, with four being the most desirable, as described in the corresponding sections below. Each criterion was weighted based on their relative importance for military use and are listed in order of increasing importance.

Criterion A: Corrosion Protection

PBF's hygroscopic properties introduce the risk of system deterioration if proper corrosion inhibitors are not employed [26]. Historically, system corrosion has plagued military ground vehicles in storage, as water-laden brake fluid would be observed to rust out brake lines. It was in the interest of this study to examine candidate corrosion protection properties to ensure that future Army use of PBF would not repeat these issues.

Results were noteworthy in that every candidate passed not only their respective specification limits on both the wet and dry corrosion tests, but also the much stricter limits on metal weight loss imposed by MIL-PRF-46176.

² Candidate ISO 6 D was not included in the down selection analysis since a full data set could not be obtained.



This criterion was weighted as the least impactful performance metric since there was such little differentiation between the candidates. Commercial brake fluids have evolved since the 1970s in terms of corrosion prevention to match the military’s current requirements of SBF. These advances have vastly reduced the risk to the Army for moving back to using PBF in ABS applications. Requirements in Table 6 were based on requirements for the wet corrosion test listed in FMVSS 116 and MIL-PRF-46176. All but one candidate received a value of 4; DOT 4 C scored a 3 because of nearly failing the MIL-PRF-46176 requirements for brass weight loss.

Table 6. Criterion A: Corrosion Protection	
Score	Requirement
0	Candidate failed to meet wet corrosion weight loss requirements in FMVSS 116.
1	Candidate nearly met wet corrosion weight loss requirements in FMVSS 116.
2	Candidate met wet corrosion weight loss requirements in FMVSS 116, but failed to meet requirements in MIL-PRF-46176B.
3	Candidate met wet corrosion weight loss requirements in MIL-PRF-46176B.
4	Candidate exceeded wet corrosion weight loss requirements in MIL-PRF-46176B.

Criterion B: Low Temperature Viscosity

At low temperatures many brake fluids exhibit high kinematic viscosity which can translate to sluggish brake response, longer stopping distance, and uneven braking between wheel circuits. Previous work showed that test drivers experienced sluggish brake response with fluids at 800 cSt and dangerous driving conditions at 2000 cSt; this study was performed with a vehicle at room temperature and a test fluid that had its viscosity artificially elevated [27]. Another study performed on a vehicle in arctic conditions showed that brake fluids with viscosities up to 1480 cSt had no adverse effect on braking performance [28]. These studies were considered in setting criterion requirements below.

All commercial brake fluid specifications contain requirements for low temperature viscosity at -40°C of a dry brake fluid, yet none require testing the fluid when humidified. While all candidates passed their dry viscosity limits at -40°C, all but DOT 3 A exceeded those limits when humidified as described in the wet viscosity investigation. It is not fair to compare dry viscosity limits with wet viscosity performance since those limits were not set with wet viscosity performance in mind. However, testing humidified fluid is arguably a better representation of a



worst-case scenario for brake fluid performance, as exhibited in the inclusion of the wet corrosion and wet ERBP tests in the aforementioned specifications.

Table 7 shows the requirements used to score the candidates based on their wet viscosity performance at -40°C . Performance at -55°C was not used to rank the candidates due to the unlikelihood of vehicle brake system operation at that temperature. Though operational temperatures of Army ground vehicles can go as low as -55°C , vehicle operation has stringent cold-start requirements that would likely heat the brake fluid enough pre-operation to mitigate the high viscosities seen at -55°C [29].

This criterion was weighted as the second most important because of the risk of sluggish or imbalanced brake performance in cold environments. Requirements in Table 7 were set based on the risks associated with having a high viscosity at -40°C . At a viscosity of greater than 2000 cSt, a fluid would receive a score of 0 since previous vehicle testing demonstrated dangerous driving conditions would be observed. At a viscosity of less than 800 cSt for a score of 4, there is little risk of sluggish brake performance. The even separation of scores in between were used to delineate the candidates' performance. The DOT 3, DOT 5.1, and ISO 6 candidates scored a 2 or 3, while all DOT 4 candidates scored a 1 because of their very high viscosity at -40°C .

The argument can be made that it is inequitable to rank these candidates' wet viscosity performance when humidified since, as observed in water absorption data in Phase IIa and IIb, the candidates do not have the same water content post-humidification. Though wet viscosity data for the candidates' with identical water content were not collected, it is reasonable to infer the candidates' expected viscosity performance based on the water absorption data obtained in Phase IIa and IIb. As shown in Table 14 in Appendix D, candidates DOT 3 A, DOT 4 A, and DOT 4 B all absorbed noticeably less than 3.7% water; if they had been corrected to 3.7% water, their viscosities at -40°C would be expected to increase. Similarly, candidates DOT 5.1 A through D absorbed closer to 4.0% water; if they had been corrected, their viscosities would be expected to decrease. The remaining candidates all absorbed around 3.7% water and would not see much of a correction. All in all, collecting these data would not noticeably affect the rating of each candidate nor influence the downselection in Phase IV.



Table 7. Criterion B: Low Temperature Viscosity	
Score	Requirement
0	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, has a wet viscosity at -40°C of > 2000 cSt
1	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, 1600 cSt ≤ wet viscosity at -40°C < 2000 cSt
2	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, 1200 cSt ≤ wet viscosity at -40°C < 1600 cSt
3	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, 800 cSt ≤ wet viscosity at -40°C < 1200 cSt
4	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, has a wet viscosity at -40°C of < 800 cSt

Criterion C: Water Absorption

Water absorption is likely the most wide-reaching aspect of a PBF as it ties directly to all other criteria. As the fluid absorb water, it introduces the risk of corrosion, lowers the ERBP that can cause vapor lock, and increases the low temperature viscosity to produce sluggish system response. Ultimately, how quickly a brake fluid picks up water determines how often the fluid must be changed to mitigate these risks.

Table 8 shows the requirements used to score the candidates based on the amount of water they absorbed when humidified by ABIC. Humidification testing outlined in Phase IIb Study 2 was not used to score the candidates despite producing similar results; data on the RM-71 reference fluid showed that running the test for a fixed amount of time was not as accurate as running until the reference fluid absorbed the same amount of water each run. Though the data was corrected to account for this factor, ABICs humidification data was felt by GVSC to be a more fair representation of comparing the candidates’ water absorption to each other.

This criterion was also weighted as the second most important (tied with low temperature viscosity) due in part to its relationship to all of the other criteria, but also to the fact that the largest safety risk from water ingestion can be mitigated by requiring a shorter fluid change interval. Requirements in Table 8 were set based on the risks associated with absorbing large amounts of water in a humid environment. When a fluid absorbs more than 4.5% water during humidification, it would receive a score of 0 since it poses a high risk of needing a very short fluid change interval. When a fluid absorbs less than 3.0% water for a score of 4, there is little risk of



needing a short change interval to mitigate corrosion, vapor lock, and low temperature problems. The even separation of scores in between were used to delineate the candidates' performance. All but one DOT 5.1 candidate scored a 1 on water absorption, while DOT 5.1 E, DOT 4 C, and the ISO 6 candidates scored a 2. DOT 3 A, DOT 4 A, and DOT 4 B absorbed the least amount of water and scored a 3.

Table 8. Criterion C: Water Absorption	
Score	Requirement
0	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, absorbed > 4.5% water when measured IAW ASTM D445.
1	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, absorbed 4.0% < water ≤ 4.5%.
2	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, absorbed 3.5% < water ≤ 4.0%.
3	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, absorbed 3.0% < water ≤ 3.5%.
4	Candidate, when humidified IAW SAE J1704 (JUL2016) §5.2.1, absorbed < 3.0% water when measured IAW ASTM D445.



Criterion D: Vapor Lock Prevention

When brake fluid reaches its boiling point, the normally incompressible fluid produces a very compressible gas phase. This manifests in the brake system as a weak or spongy brake pedal until no braking power can be produced at all resulting in full brake system failure [5]. There have been several cases over the years of injuries and fatalities as the result of brake fluid vapor lock [7].

Commercial brake fluids are often advertised by their wet ERBP, since that represents a worst-case scenario for potential vapor lock; as reported, wet ERBP states the fluids' boiling point when humidified to the point that a reference fluid hits 3.7% water. Many commercial specifications set a wet ERBP limit of at least 155°C, which is slightly above the maximum temperature of 146°C observed in brake fluids during a cross-country field test performed in 1970 on passenger vehicles in the US [30]. Unfortunately, historical data has shown that the wet ERBP test overestimates the vapor lock temperature of the fluid and it not representative of when it can actually occur in a vehicle under high temperature conditions [27]. Therefore, a fluid which claims a wet ERBP of 155°C may actually experience vapor lock at a lower temperature in a vehicle.

Vapor lock prevention is of the utmost important to Army implementation of an ABS-compatible brake fluid since it poses the greatest risk to the life of the user. As such, it was weighted the most important out of the four criteria stated.

Candidates were scored according to the requirements in Table 9. Requirements in Table 9 were set based on the risks associated with having a low boiling point. At a wet ERBP of less than 150°C, a fluid would receive a score of 0 since it is below all commercial ERBP specification requirements and close to the maximum temperature seen in cross-country vehicle tests. At a wet ERBP of over 180°C for a score of 4, there is little risk of vapor lock. The even separation of scores in between were used to delineate the candidates' performance. All DOT 5.1 candidates received a score of 4. The DOT 3 and two of the DOT 4 candidates scored 1 or below because of their low ERBP to the point that vapor lock at high water content would be a significant risk.

Table 9. Criterion D: Vapor Lock Prevention	
Score	Requirement
0	Candidate, when wetted to 3.7% water, ERBP ≤ 150°C.
1	Candidate, when wetted to 3.7% water, 150°C < ERBP ≤ 160°C.
2	Candidate, when wetted to 3.7% water, 160°C < ERBP ≤ 170°C.
3	Candidate, when wetted to 3.7% water, 170°C < ERBP ≤ 180°C.
4	Candidate, when wetted to 3.7% water, ERBP > 180°C.



Phase IV – Candidate Down Selection

Table 10 shows all candidates’ scores for the criteria identified above and their respective weighting. Total performance score (TPS) is on a scale from zero to ten, with ten being the highest and most desirable score available for a candidate. The total performance score is further broken down into low-medium-high risk to identify candidates with the lowest risk for operation in ABS-equipped Army ground vehicles. Risk levels were broken out as follows:

- Low risk – TPS > 7
- Medium risk – 5 ≤ TPS ≤ 7
- High Risk – TPS < 5

Table 10. Candidate Down Selection Results										
Candidate Code	Corrosion Protection		Low Temp Performance		Water Absorption		Vapor Lock Prevention		Total Performance Score	Level of Risk
	Weight	0.25	Weight	0.625	Weight	0.625	Weight	1.00		
	Score	Total	Score	Total	Score	Total	Score	Total		
DOT 5.1 E	4	1.0	3	1.9	2	1.3	4	4.0	8.1	Low
DOT 5.1 D	4	1.0	3	1.9	1	0.6	4	4.0	7.5	Low
ISO 6 B	4	1.0	3	1.9	2	1.3	3	3.0	7.1	Low
ISO 6 C	4	1.0	3	1.9	2	1.3	3	3.0	7.1	Low
DOT 5.1 A	4	1.0	2	1.3	1	0.6	4	4.0	6.9	Medium
DOT 5.1 B	4	1.0	2	1.3	1	0.6	4	4.0	6.9	Medium
DOT 5.1 C	4	1.0	2	1.3	1	0.6	4	4.0	6.9	Medium
DOT 4 A	4	1.0	1	0.6	3	1.9	3	3.0	6.5	Medium
ISO 6 A	4	1.0	3	1.9	2	1.3	2	2.0	6.1	Medium
DOT 3 A	4	1.0	3	1.9	3	1.9	0	0.0	4.8	High
DOT 4 C	3	0.8	1	0.6	2	1.3	1	1.0	3.6	High
DOT 4 B	4	1.0	1	0.6	3	1.9	0	0.0	3.5	High

DOT 5.1 A, B, and C all performed similarly, resulting in tied scores. Budget constraints for funding in FY20 limited the number of candidates that could be selected for the next phase of testing to only five; therefore, a decision had to be made between the three DOT 5.1 fluids with the same (tied) ranking scores. GVSC chose DOT 5.1 A to be the candidate that moves on to ABS simulated rig testing because of its use in HMMWV, whereas DOT 5.1 B and C are not currently being used by the military.

No DOT 4 fluids will move on for further testing because of their poor performance in low temperature viscosity and vapor lock prevention. This includes the fluid currently selected by



JLTV. Though the DOT 4 candidates scored well on water absorption, their high likelihood of vapor lock and large low temperature viscosities introduce more risk than GVSC would recommend to the vehicle platform managers for user safety. While the DOT 3 candidate performed better than most other candidates in water absorption and low temperature viscosity, its very low ERBP is similarly too high of a safety risk to recommend for Army ground vehicle use.

The top five candidates moving on to ABS simulated service rig testing in FY20 are: DOT 5.1 E, DOT 5.1 D, ISO 6 B, ISO 6 C and DOT 5.1 A.

Conclusions

The objective of this report was to evaluate a series of PBF for use in ABS to safeguard Army ground vehicle brake systems in all operational environments. Thirteen candidates underwent routine and experimental benchtop testing and were graded on their performance in four key areas: corrosion protection, low temperature viscosity, water absorption, and vapor lock prevention. Of the candidates, five were selected to move on to simulated service testing for their outstanding performance in vapor lock prevention and low temperature viscosity even when humidified; all of them were classified as either DOT 5.1 or ISO 6 candidates:

- DOT 5.1 E
- DOT 5.1 D
- ISO 6 B
- ISO 6 C
- DOT 5.1 A (HMMWV fluid)

JLTV currently uses a DOT 4 which exhibited poor vapor lock prevention and low temperature viscosity and was not selected.

Next Steps

Prior to moving on to simulated service testing, GVSC will maintain communications with stakeholders via in person meetings and e-mail correspondence. GVSC has plans to meet with JLTV technical personnel in November 2019 to provide an update of work accomplished in FY19. This includes a discussion of why the fluid currently used by JLTV (DOT 4 C) did not move forward in the BFABS project and how this can impact their fluid use going forward.

GVSC has begun work with its Government Owned, Contractor Operated (GOCO) lab at Southwest Research Institute (SwRI) to design and fabricate an ABS simulated service rig, the design of which was approved by GVSC in August 2019. SwRI will then develop a method to determine the operational suitability of brake fluid in ABS under different environmental conditions, including at extreme temperatures. This method shall differentiate between brake



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fluids that are compatible with an ABS and those that are not. These efforts will allow for a wide range of testing capabilities in order to evaluate the life and performance of brake fluids in a testing environment that is a close approximation to field service.

At the conclusion of simulated service testing, GVSC will evaluate and use the results to create a military performance specification or CID for PBF use in ABS-equipped Army ground vehicles.



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Appendix

Appendix A: Phase IIb Study 1 Procedure

Study 1: ERBP of PBF as a Function of Water Content

1. Prior to any ERBP test, run RM-71 reference fluid (known ERBP) to verify test apparatus.
2. Run ASTM D1120 (ERBP) in duplicate on candidates as received to get ERBP at zero-water.
3. Run ASTM D6304 (Water Content) in duplicate on candidates to get zero-water data.
4. Calculate amount of distilled water necessary to direct inject into candidates to produce 120mL samples at 0.5% water; 120mL is necessary for duplicate ERBP runs.
5. Repeat step 3 at 0.5% increments until calculations are known to produce samples up to 4% water (total of eight 120mL samples per candidate).
6. Use a disposable syringe and balance to direct inject the amount of distilled water determined in steps 3 and 4 into 120mL samples of candidates until all candidates are produced for testing. Mix each sample with a magnetic stir bar for 30s prior to testing.
7. Use a disposable syringe to pull ~ 3 mL of sample from each sample and set aside in 1.5mL glass vials for water content testing.
8. Run ASTM D1120 (ERBP) in duplicate on all samples (13 candidates x 8 samples x duplicate = 208 total runs)
9. Use the vials produced in step 7 and run in ASTM D6304 (Water Content) in duplicate to determine water content of each sample run in ERBP.
10. Plot data produced in steps 2, 3, 8 and 9 to generate ERBP vs water content curves for each candidate.



Appendix B: Phase IIb Study 2 Procedure

Study 2: Water Absorption of PBF as a Function of Time

Setup: Run SAE J1704 (JUL2016) §5.2.1 on each candidate modified as follows (**bold** are additions, ~~strikethrough~~ are removed):

1. Lubricate the ground-glass joint of a 250 mm (9.89 in) I.D. bowl-form desiccator having matched tubulated glass cover and fitted with a No. 8 rubber stopper **or equivalent ground glass stopper**
2. Pour 450 mL \pm 10 mL (15.22 oz \pm 0.34 oz) of distilled water into the desiccator and insert a perforated porcelain plate (Coors No. 60456 or equivalent).
3. Immediately place **two** open RM-49 corrosion test jars **each** containing 350 mL \pm 5 mL of the test brake fluid into the desiccator
4. Place a ~~second~~ **third** open RM-49 corrosion test jar containing 350 mL \pm 5 mL of TEGME (triethylene glycol monomethyl ether, brake fluid grade-Appendix E) (RM-71) into the same desiccator. ~~The water content of the TEGME control fluid at the start of exposure shall have been adjusted to 0.50% \pm 0.05% by weight (Karl Fischer analysis or equivalent).~~ **Place a thermocouple in the oven next to the desiccator.**
5. Replace desiccator cover and insert at once into an ~~ASTM E 145, Type II A,~~ forced ventilation oven set at 50 °C \pm 1 °C (122 °F \pm 1.8 °F)

Running the test

1. At the start of test and every 60 \pm 10 minutes thereafter, use a syringe through the desiccator top to remove up to 4mL from each test jar and place into separate sealed 1.5mL vials for water content testing, making note of the time at which the sample was removed and marking down the sample designation as defined on the humidification datasheet. Take down temperature measurement.
2. Terminate test after minimum 8 data points have been taken.
3. Each sample should be run in a desiccator twice: one test should begin at the beginning of the work day (Desiccator A), while the second test should begin at the end of the work day (Desiccator B). The second test does not need to have a zero hour sample taken.
4. Run hourly samples pulled in step 1 via ASTM D6304 (Water Content) in duplicate.
5. Plot the data produced in steps 1 and 4 to generate water content vs time curves for each candidate.

Appendix C: Phase IIa Laboratory Benchtop Testing: 3rd Party Data for All Candidates

Table 11. Corrosion Test Specification Requirements							
Corrosion	SAE J1703		SAE J1704		SAE J1705	ISO 4925 Class 6	MIL-PRF-46176B
			Standard Fluid	Low Viscosity Fluid			
	100°C for 120 hours		100°C for 120 hours		100°C for 120 hours	100°C for 120 hours	100°C for 120 hours
	DRY SBR (RM-03a) and EPDM (RM-69)	WET SBR (RM-03a) and EPDM (RM-69)	DRY SBR (RM-03a) and EPDM (RM-69)	WET SBR (RM-03a) and EPDM (RM-69)	SBR (RM-03a) (humidified fluid)	SBR Cups (wet test)	SBR Cups (humidified fluid)
a) metal test strips shall not show weight changes exceeding the following limits	max weight change permissible, mg/cm ²		max weight change permissible, mg/cm ²		max weight change permissible, mg/cm ²	max weight change permissible, mg/cm ²	max weight change permissible, mg/cm ²
Steel, tinned iron, cast iron	± 0.2		± 0.2		0.1	± 0.2	0.1 (and carbon steel)
Aluminum	± 0.1		± 0.1		0.1	± 0.1	0.1
Brass, Copper	± 0.4		± 0.4		0.2	± 0.4	0.2
b) metal test strip appearance after test	no pitting or roughness outside contact area; staining and discoloration is permitted		no pitting or roughness outside contact area; staining and discoloration is permitted		no pitting or roughness outside contact area; staining and discoloration is permitted	no pitting or roughness outside contact area, staining or discoloration permitted	shall not be pitted nor etched after exposure to brake fluid
c) Wet-water brake fluid	no gelling after test		no gelling after test		no gelling at 23°C	no gel	no gelling at 25±5°C
d) crystal deposits	no crystalline deposit		no crystalline deposit		no crystalline-type of deposit shall form and adhere to either the glass jar walls or surface of the metal strips	none adhering crystals	no crystal deposits
e) sedimentation of the water-wet brake fluid	0.1% max		0.1% max		0.1% max	max 0.1%	0.1% max
f) pH value of water-wet brake fluid	7.0 to 11.5		7.0 - 11.5		Not Required	10 to 11.5	Not Required
g) appearance at end of the test	no blisters or sloughing		no blisters or sloughing		no blisters or sloughing indicated by carbon black separation on the surface of the rubber cup	no blisters or carbon black separation at surface, no sloughing, blisters, or other disintegration	shall show no sloughing, tackiness, blisters, or any other form of disintegration
h) Hardness at end of the test	Not Required	SBR 15 IRHD, max EPDM 10 IRHD, max	Not Required	SBR 15 IRHD, max EPDM 10 IRHD, max	shall not decrease by more than 15 degrees	max decrease 15 IRHD	shall not exceed 15 points after exposure to the brake fluid
i) base diameter		SBR 1.4mm max increase		SBR 1.4mm max increase	shall not increase by more than 1.4mm	max increase 1.4mm	shall not be less than 0.03mm and not more than 1.40 mm
j) volume change		EPDM volume increase 0 to 10 %		EPDM volume increase 0 to 10 %	Not Required	max increase 16%	Not Required



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Table 12. ABIC Benchtop Testing Data for All Candidates

Tests	DOT 3 A	DOT 4 A	DOT 4 B	DOT 4 C	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E	ISO 6 A	ISO 6 B	ISO 6 C	Control Fluid
<u>Original Equilibrium Reflux Boiling Point (°C)</u>	269	267°C	260	252	273°C	270	269	273	270	264	268	267	246
<u>Wet Equilibrium Reflux (°C)</u>	153	171°C	157	158	184°C	181	177	180	176	171	175	172	153
<u>Viscosity</u>													
@ -40°C (mm ² /s)	616	1100	1407	1355	836	837	684	893	611	536	690	610	239
@ 100°C (mm ² /s)	2.2	2.2	2.2	2.2	2.3	2.2	2	2	2.1	1.9	2.1	2.0	1.36
@ -55°C (mm ² /s)	4706	11,780	13906	15733	8584	7755	6660	8761	5653	4588	6156	5357	1568
<u>pH</u>	8.8	7.5	8.7	8.7	7.3	7.2	7.1	7.1	7.2	7.5	7.5	7.5	8.8
<u>Brake Fluid Stability</u>													
High Temp Stability	No change	No change	No change	No change	-1°C	No change	No change	No change	No change	No change	No change	No change	1°C
Chemical Stability	No change	2°C	1°C	No change	-1°C	No change	-3°C	-2°C	No change	No change	No change	3°C	No change
<u>Corrosion (5% Water)</u>													
<u>Weight change in mg./sq. cm.</u>													
Tinned iron	0.00	0.00	0.06	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Steel	0.00	0.00	0.03	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Aluminum	0.00	0.00	0.03	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cast iron	0.00	0.02	0.02	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00
Brass	0.00	0.03	0.06	0.19	0.04	0.01	0.03	0.03	0.04	0.00	0.03	0.03	0.00
Copper	0.04	0.03	0.01	0.10	0.06	0.02	0.04	0.05	0.07	0.05	0.05	0.07	0.04
Metals pitted not roughened to an extent discernible to the naked eye outside area of contact	None	None	None	None	None	None	None	None	None	None	None	None	None

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Tests	DOT 3 A	DOT 4 A	DOT 4 B	DOT 4 C	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E	ISO 6 A	ISO 6 B	ISO 6 C	Control Fluid
Gelling of fluid/water, mixture at 23°C ± 5°C	None	None	None	None	None	None	None	None	None	None	None	None	None
Crystalline deposit on glass jar walls or on metal strips	None	None	None	None	None	None	None	None	None	None	None	None	None
Sedimentation, percent	None	None	None	None	None	None	None	None	None	None	None	None	None
pH of water/fluid mixture	8.6	7.3	8.6	8.5	7.3	7.1	7.1	7.1	7.5	7.6	7.6	7.5	8.6
<u>SBR Cups</u>													
Hardness decrease	4 IRHD	1 IRHD	6 IRHD	1 IRHD	2 IRHD	4 IRHD	2 IRHD	3 IRHD	3 IRHD	3 IRHD	1 IRHD	3 IRHD	4 IRHD
Disintegration as evidenced by blisters	None	None	None	None	None	None	None	None	None	None	None	None	None
Sloughing as indicated by carbon black separation	None	None	None	None	None	None	None	None	None	None	None	None	None
Base diameter increase	0.02	0.07	0.27	0.05	0.12	0.02	0.07	0.05	0.02	0.02	0.00	0.02	0.02
<u>EPDM</u>													
Hardness decrease	1 IRHD	1 IRHD	1 IRHD	1 IRHD	1 IRHD	1 IRHD	1 IRHD	1 IRHD	1 IRHD	2 IRHD	1 IRHD	1 IRHD	2 IRHD
Disintegration as evidenced by blisters	None	None	None	None	None	None	None	None	None	None	None	None	None
Sloughing as indicated by carbon black separation	None	None	None	None	None	None	None	None	None	None	None	None	None
Volume swell percent	+1%	+1%	+1%	+1%	+1%	+1%	+1%	+1%	+1%	+1%	+1%	+1%	+1%
<u>Corrosion (Dry)</u>													
<i>Weight change in mg./sq. cm.</i>													
Tinned iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Steel	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Aluminum	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cast iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00

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Tests	DOT 3 A	DOT 4 A	DOT 4 B	DOT 4 C	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E	ISO 6 A	ISO 6 B	ISO 6 C	Control Fluid
Brass	0.01	0.01	0.01	0.19	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00
Copper	0.01	0.00	0.01	0.10	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Metals pitted not roughened to an extent discernible to the naked eye outside area of contact	None	None	None	None	None	None	None	None	None	None	None	None	None
Gelling of fluid/water, mixture at 23°C ± 5°C	None	None	None	None	None	None	None	None	None	None	None	None	None
Crystalline deposit on glass jar walls or on metal strips	None	None	None	None	None	None	None	None	None	None	None	None	None
Sedimentation, percent	None	None	None	None	None	None	None	None	None	None	None	None	None
pH of water/fluid mixture	8.4	7.4	8.6	8.5	7.3	7.2	7.1	7.1	8.4	7.4	7.5	8.4	8.6
<u>SBR Cups</u>													
Disintegration as evidenced by blisters	None	None	None	None	None	None	None	None	None	None	None	None	None
Sloughing as indicated by carbon black separation	None	None	None	None	None	None	None	None	None	None	None	None	None
<u>EPDM</u>													
Disintegration as evidenced by blisters	None	None	None	None	None	None	None	None	None	None	None	None	None
Sloughing as indicated by carbon black separation	None	None	None	None	None	None	None	None	None	None	None	None	None
<u>Fluidity and Appearance at Low Temps</u>													
<u>@-40°C</u>													
Stratification, sedimentation, sludging or crystallization	None	None	None	None	None	None	None	None	None	None	None	None	None

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Tests	DOT 3 A	DOT 4 A	DOT 4 B	DOT 4 C	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E	ISO 6 A	ISO 6 B	ISO 6 C	Control Fluid
Time for air bubble to travel to top	2 seconds	2 seconds	2 Sec	2 sec	2 seconds	1 sec	2 sec	2 sec	1 sec	2 seconds	2 sec	1 sec	1 sec
Appearance of sample after warming to room temp	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
@-50°C													
Stratification or sedimentation, sludging or crystallization	None	None	None	None	None	None	None	None	None	None	None	None	None
Time for air bubble to travel to top	3 sec	7 sec	4 sec	3 sec	4 seconds	5 sec	4 sec	5 sec	5 sec	3 sec	4 sec	3 sec	3 sec
Appearance of sample after warming to room temp	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
@ -55°C													
Stratification or sedimentation, sludging or crystallization	None	None	None	None	None	None	None	None	None	None	None	None	None
Discerability of hiding power test chart lines	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable	Discernable
Time for air bubble to travel to top	4 sec	13 sec	6 sec	5 sec	6 seconds	7 sec	11 Sec	10 sec	7 sec	5 sec	6 sec	6 sec	4 sec
Appearance of sample after warming to room temp	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
<u>Water Tolerance</u>													
@-40°C													
Stratification or sedimentation, sludging or crystallization	None	None	None	None	None	None	None	None	None	None	None	None	None

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Tests	DOT 3 A	DOT 4 A	DOT 4 B	DOT 4 C	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E	ISO 6 A	ISO 6 B	ISO 6 C	Control Fluid
Time for air bubble to travel to top	1 sec	1 sec	1 sec	1 sec	2 seconds	1 sec	1 sec	2 sec	1 sec	1 sec	1 sec	1 sec	1 sec
Appearance of sample after warming to room temp	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity	Regains original clarity and fluidity
@60°C													
Stratification	None	None	None	None	None	None	None	None	None	None	None	None	None
Sedimentation, percent	None	None	None	None	None	None	None	None	None	None	None	None	None
<u>Compatibility</u>													
@-40°C													
Discernibility of black contrast lines	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable	Clearly discernable
Stratification or sedimentation	None	None	None	None	None	None	None	None	None	None	None	None	None
@60°C													
Stratification	None	None	None	None	None	None	None	None	None	None	None	None	None
Sedimentation, percent	None	None	None	None	None	None	None	None	None	None	None	None	None
<u>Resistance to Oxidation</u>													
Pitting or roughening of metal strips discernable to naked eye	None	None	None	None	None	None	None	None	None	None	None	None	None
Gum deposited on metal strips	None	None	None	None	None	None	None	None	None	None	None	None	None
Weight loss in mg./sq. cm.													
Aluminum	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Cast iron	0.03	0.03	0.03	0.02	0.04	0.01	0.02	0.04	0.03	0.01	0.01	0.02	0.01
<u>Effect on Rubber</u>													
@120°C													
SBR													

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Tests	DOT 3 A	DOT 4 A	DOT 4 B	DOT 4 C	DOT 5.1 A	DOT 5.1 B	DOT 5.1 C	DOT 5.1 D	DOT 5.1 E	ISO 6 A	ISO 6 B	ISO 6 C	Control Fluid
Hardness increase	None	None	None	None	None	None	None	None	None	None	None	None	None
Hardness decrease	3 IRHD	4 IRHD	10 IRHD	5 IRHD	4 IRHD	10 IRHD	4 IRHD	4 IRHD	5 IRHD	4 IRHD	4 IRHD	5 IRHD	3 IRHD
Base diameter increase	0.58	0.43 mm	0.83	0.45	0.66 mm	1.09	0.60 mm	0.58 mm	0.71 mm	0.78	0.66 mm	0.55	0.58
Disintegration as evidenced by blisters	None	None	None	None	None	None	None	None	None	None	None	None	None
Sloughing as indicated by carbon black separation	None	None	None	None	None	None	None	None	None	None	None	None	None

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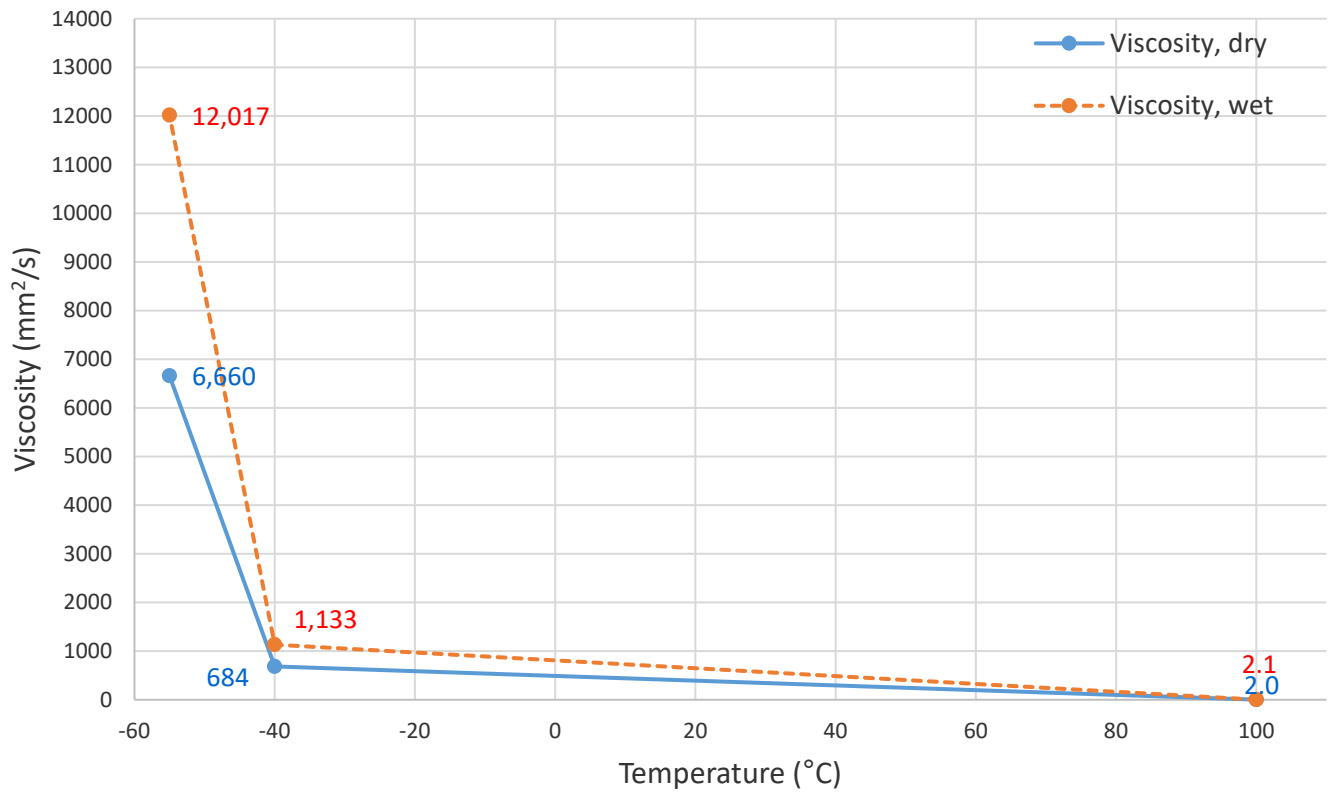
Appendix D: Phase IIa Wet Viscosity Investigation Data for All Candidates

Table 13. Low Temperature Viscosity After Humidification (mm²/s)			
Code	Water Absorption (%)	Viscosity at -40°C	Viscosity at -55°C
DOT 3 A	3.11	897	7,847
DOT 4 A	3.46	1,698	18,670
DOT 4 B	3.40	1,898	19,889
DOT 4 C	3.86	1,763	20,542
DOT 5.1 A	4.04	1,274	14,386
DOT 5.1 B	4.05	1,259	13,646
DOT 5.1 C	4.05	1,442	15,380
DOT 5.1 D	4.14	1,133	12,017
DOT 5.1 E	3.58	1,097	10,128
ISO 6 A	3.67	927	8,318
ISO 6 B	3.72	1,120	11,100
ISO 6 C	3.77	1,035	10,478



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Viscosity Vs Temperature
Candidate Code: DOT 3 A



SOURCE: ABIC TESTING LABORATORY, INC

Figure 11. Viscosity vs Temperature of DOT 3 A, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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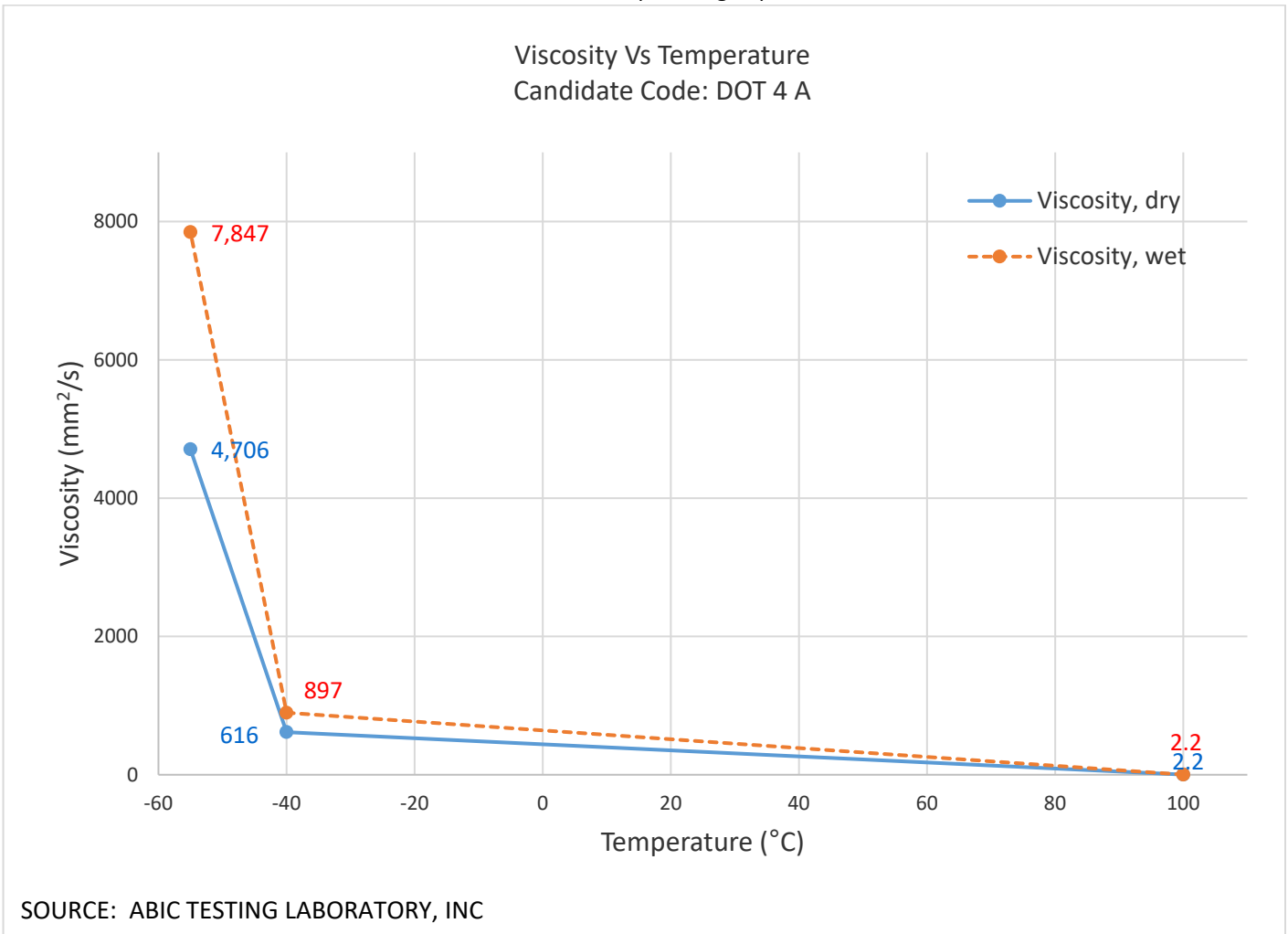


Figure 12. Viscosity vs Temperature of DOT 4 A, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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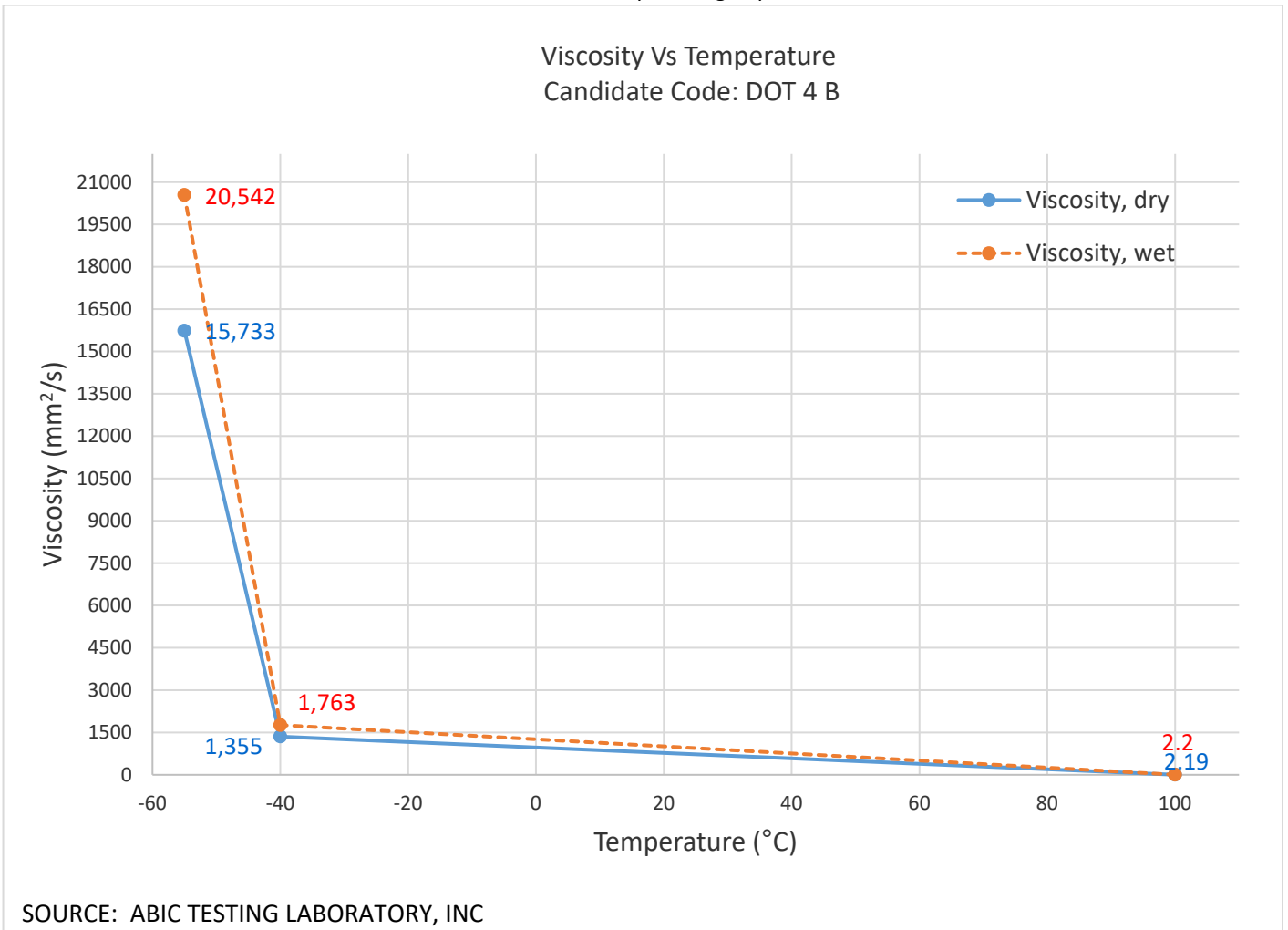


Figure 13. Viscosity vs Temperature of DOT 4 B, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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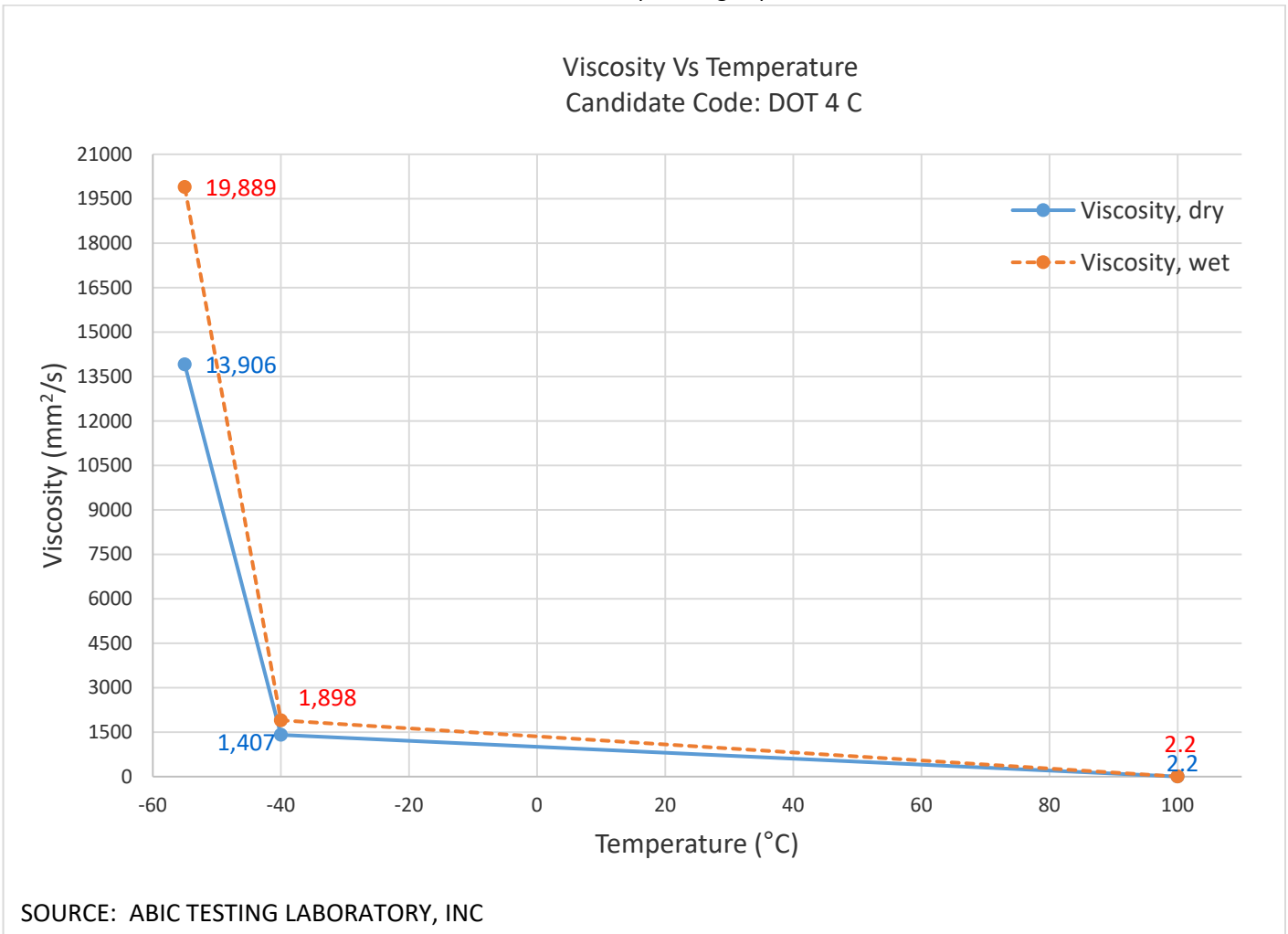


Figure 14. Viscosity vs Temperature of DOT 4 C, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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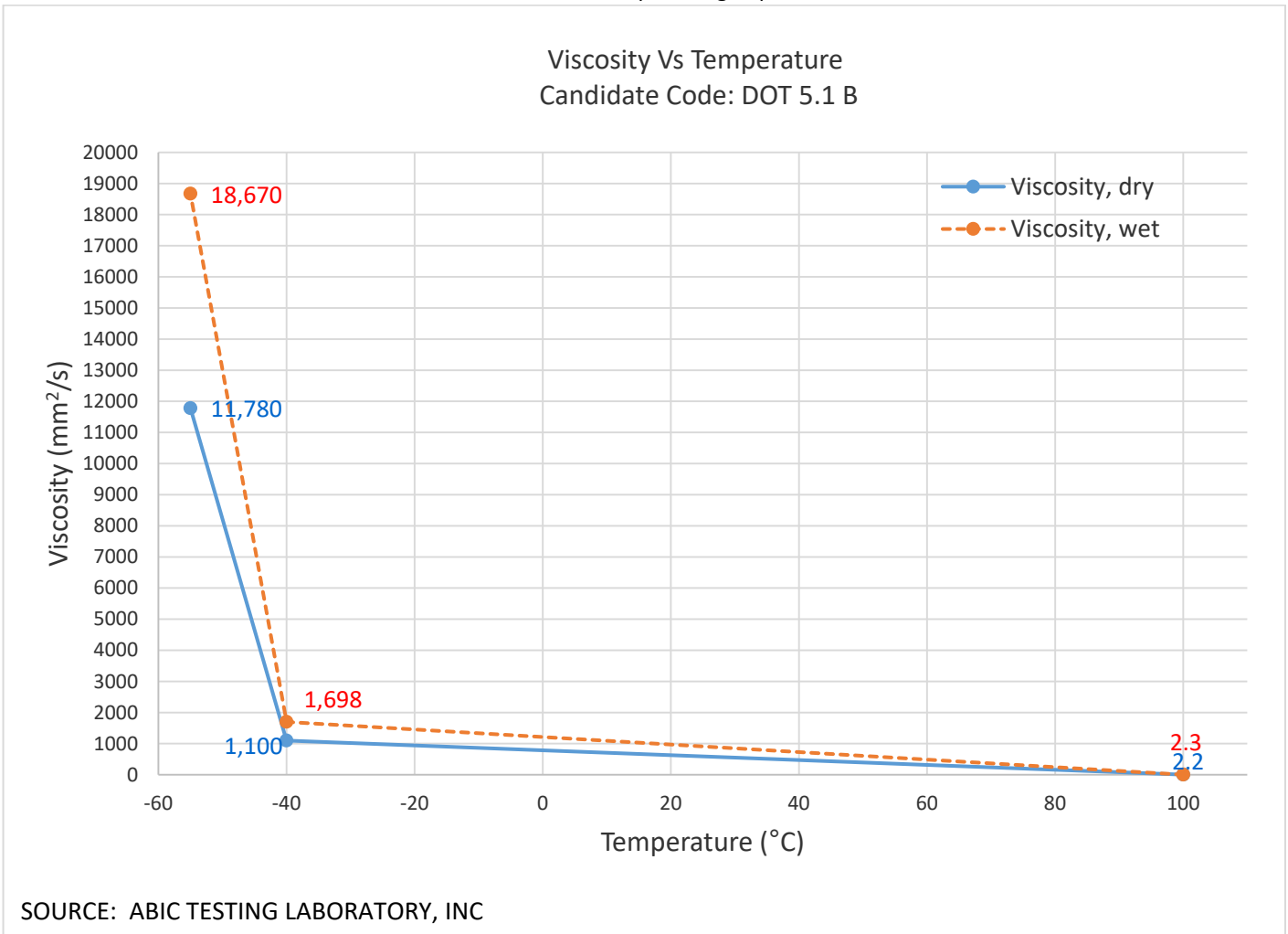


Figure 15. Viscosity vs Temperature of DOT 5.1 B, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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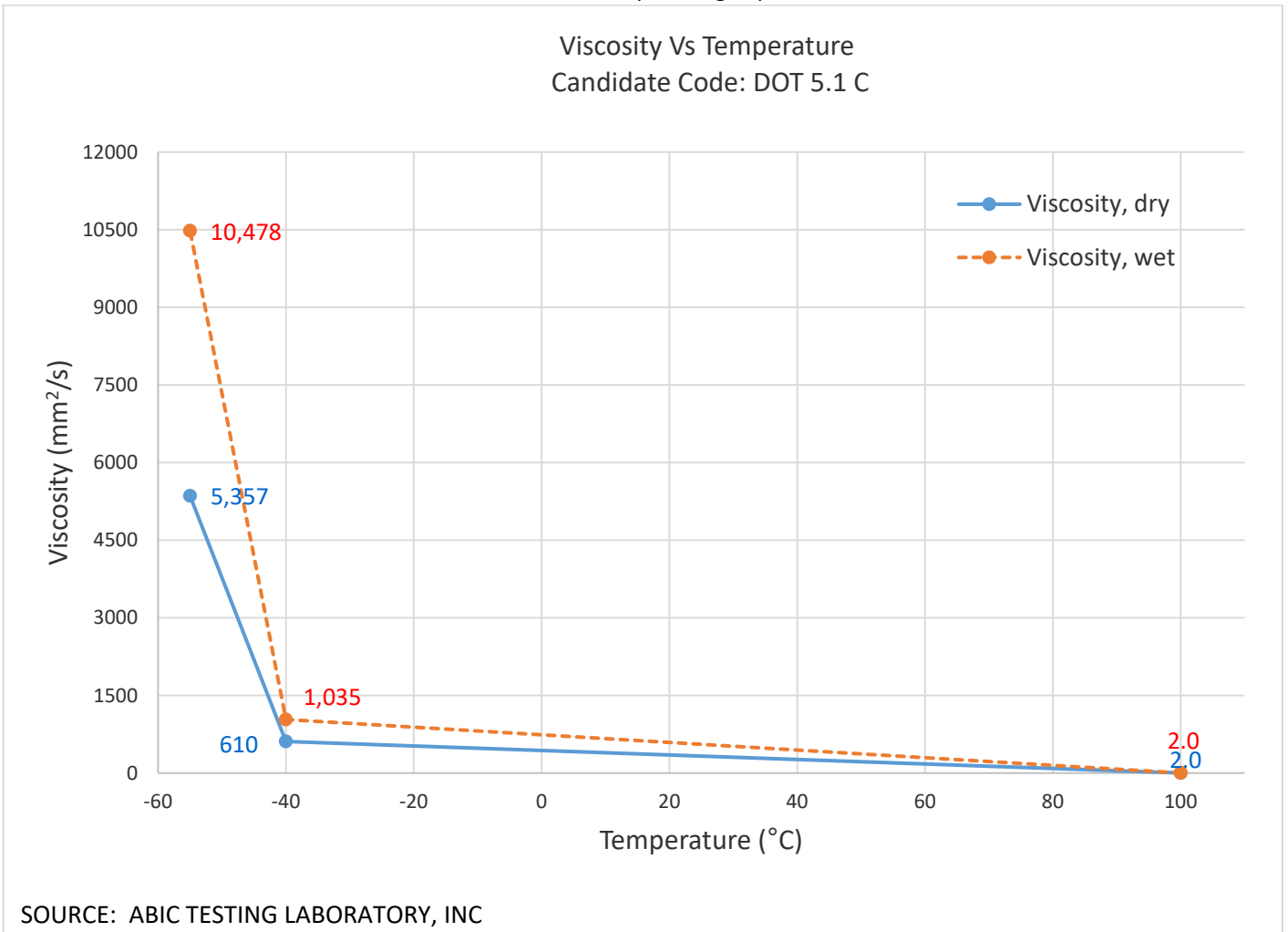
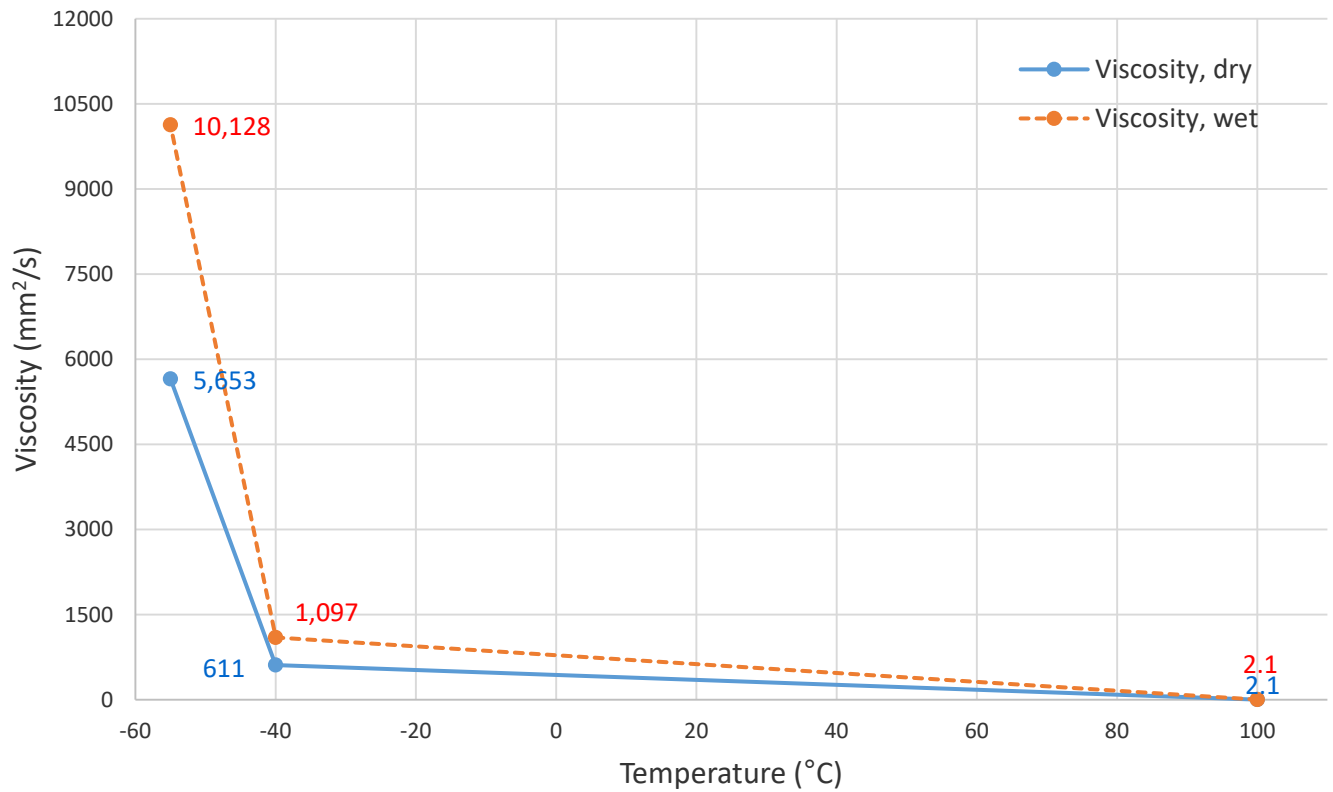


Figure 16. Viscosity vs Temperature of DOT 5.1 C, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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Viscosity Vs Temperature
Candidate Code: DOT 5.1 D

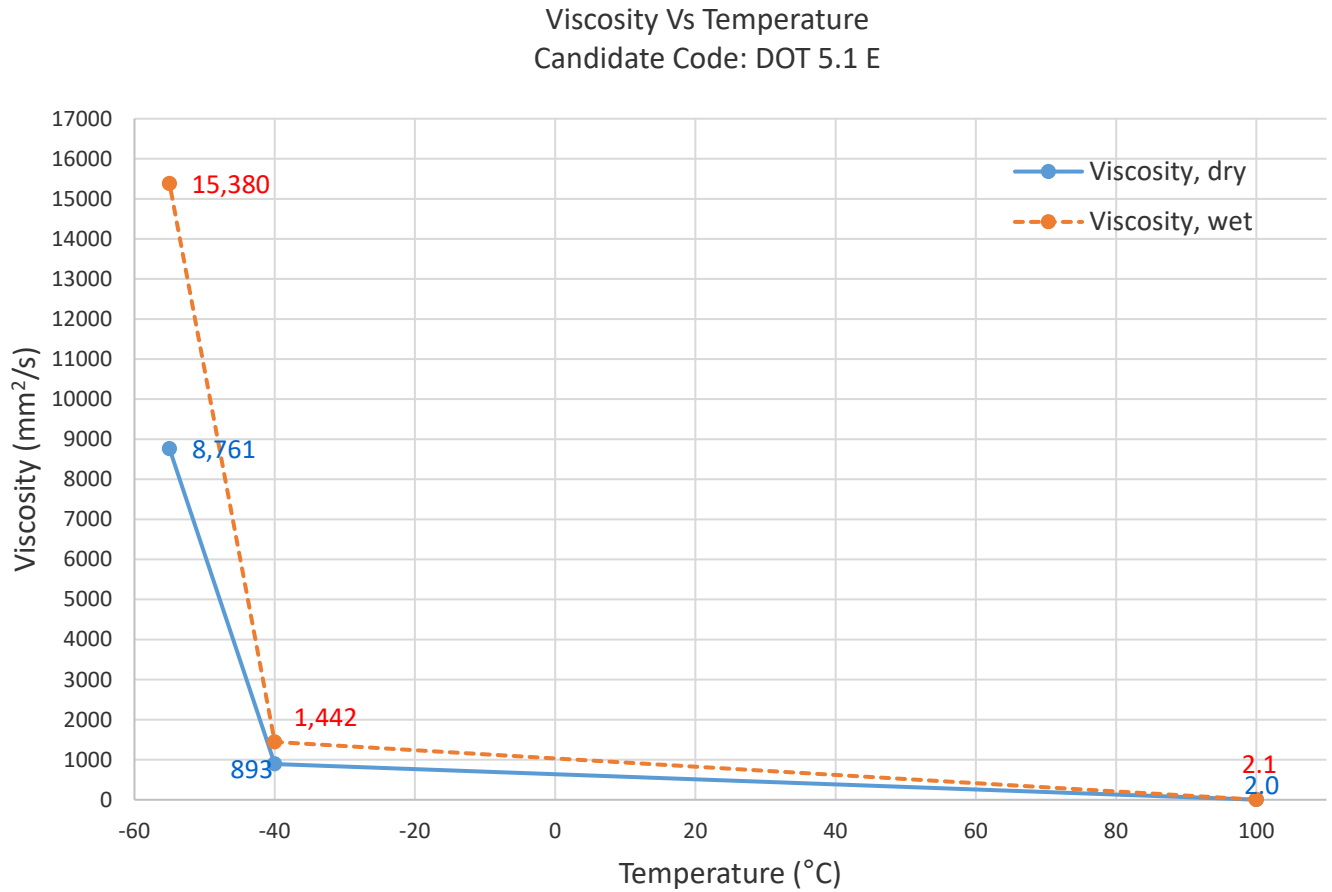


SOURCE: ABIC TESTING LABORATORY, INC

Figure 17. Viscosity vs Temperature of DOT 5.1 D, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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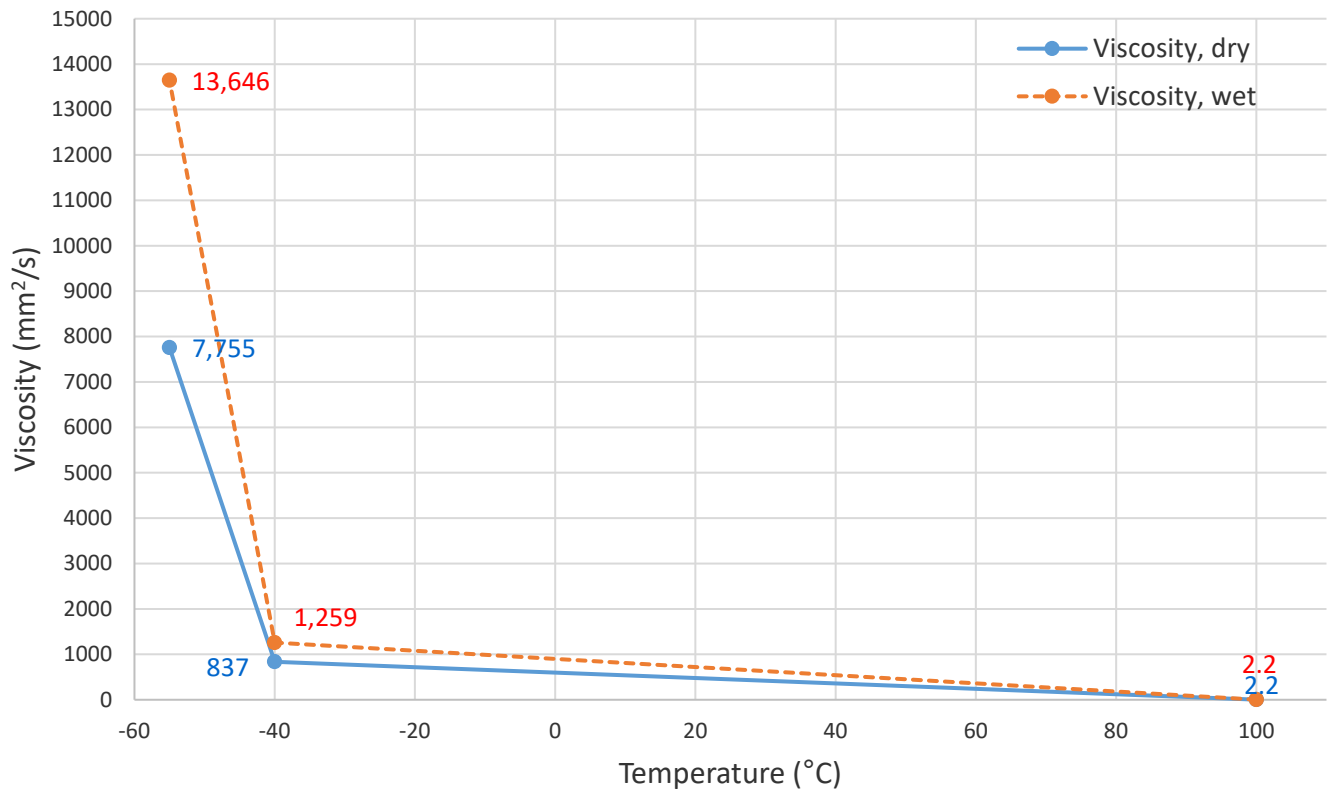
SOURCE: ABIC TESTING LABORATORY, INC

Figure 18. Viscosity vs Temperature of DOT 5.1 E, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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Viscosity Vs Temperature
Candidate Code: ISO 6 A



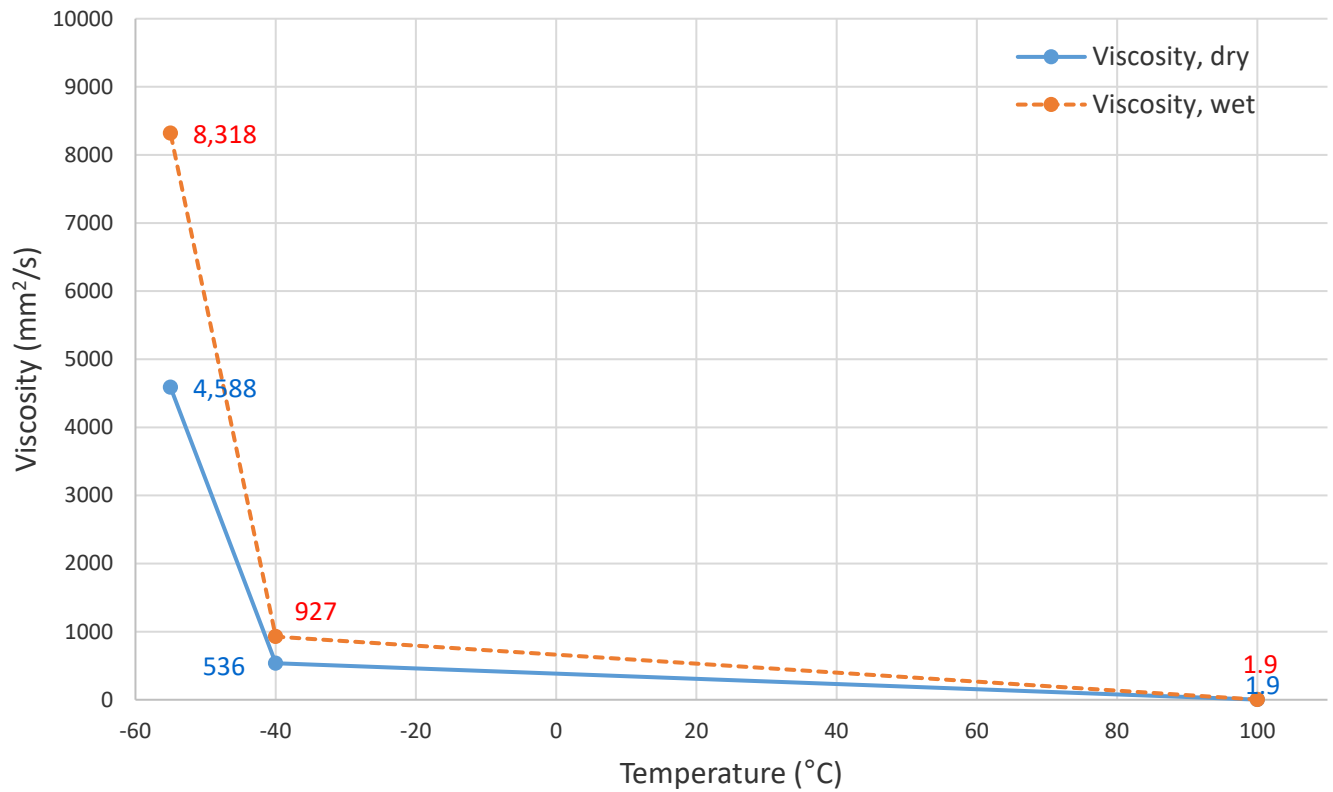
SOURCE: ABIC TESTING LABORATORY, INC

Figure 19. Viscosity vs Temperature of ISO 6 A, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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Viscosity Vs Temperature
Candidate Code: ISO 6 B



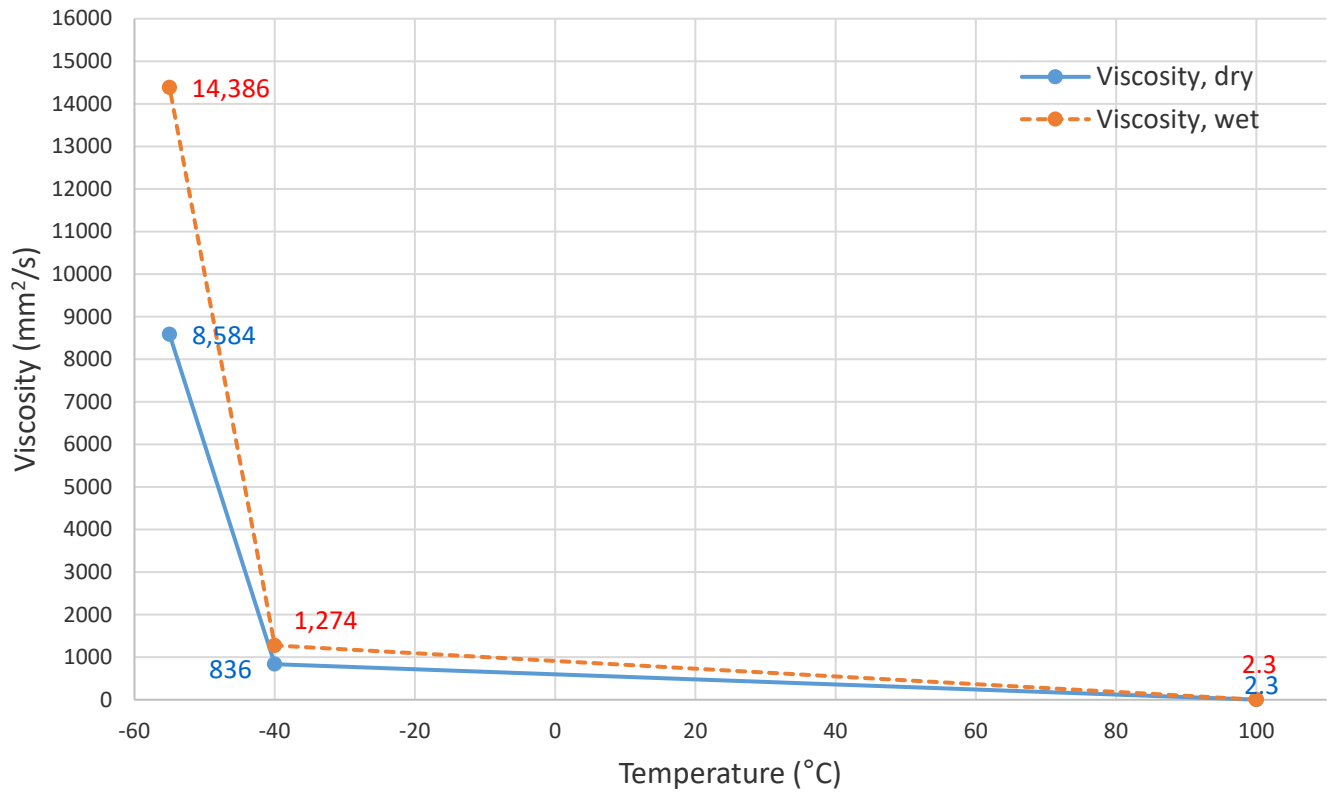
SOURCE: ABIC TESTING LABORATORY, INC

Figure 20. Viscosity vs Temperature of ISO 6 B, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



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Viscosity Vs Temperature
Candidate Code: ISO 6 C



SOURCE: ABIC TESTING LABORATORY, INC

Figure 21. Viscosity vs Temperature of ISO 6 C, dry and wet.
No change in viscosity is observed at 100°C but rises sharply at -40 and -55°C.



Appendix E: Acronyms

ABIC – ABIC International Consultants Inc.
ABS – Anti-lock Braking Systems
ASTM – ASTM International
BF – Brake Fluid
BFABS – Brake Fluid Standardization for Anti-lock Braking Systems
BP – Boiling Point
CCDC – Combat Capabilities Development Command
cSt – Centistoke
DLA-A – Defense Logistics Agency - Aviation
DOT – Department of Transportation
DTIC – Defense Technical Information Center
EPDM – Ethylene propylene diene monomer
ERBP – Equilibrium Reflux Boiling Point
FedBizOpps – Federal Business Opportunities
FLL – Fuels and Lubricants Laboratory
FMVSS – Federal Motor Vehicle Safety Standards
FPT – Force Projection Technology
GOCO – Government Owned, Contractor Operated
GVSC – Ground Vehicle Systems Center
GSFF – Ground System Fluids and Fuels
HMMWV – High Mobility Multipurpose Wheeled Vehicle
IAW – In accordance with
IRHD – International Rubber Hardness Degrees
ISO – International Organization for Standardization
JLTV – Joint Light Tactical Vehicle
LV – Low viscosity
MIL-PRF – Military performance specification
OEM – Original Equipment Manufacturer
PBF – Polyglycol Brake Fluid
POL – Petroleum, Oil, and Lubricant
PEO CS&CSS – Program Executive Office, Combat Support & Combat Service Support
PROCNET – Procurement Network
QC – Quality Control
SAE – SAE International
SBF – Silicone Brake Fluid
SBR – Styrene Butadiene Rubber
SwRI – Southwest Research Institute
TEGME – Tetraethylene glycol dimethyl ether
TPS – Total Performance Score