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SILICONE BRAKE FLUID COMPATIBILITY WITH ANTI-LOCK BRAKING SYSTEMS FOR IDENTIFYING FUTURE MILITARY BRAKE FLUID REQUIREMENTS

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ABSTRACT
Since the 1980s, the US Army has been successfully utilizing silicone brake fluid (SBF) to protect military ground vehicle brake systems from corrosion in a variety of environments. Currently, the US Army is focusing its ground vehicle brake system efforts on safety by executing a hardware technology upgrade to anti-lock braking systems (ABS). SBF has been purported by many ABS manufacturers to be incompatible with ABS; however, to date no literature exist to prove these claims. Therefore, the work therein investigated these claims by testing SBF versus traditional glycol-based brake fluid in a commercial ABS utilizing a pump and dump cycle approach to simulate ABS actuation. As expected, failure of SBF was observed at 20,000 cycles, while no failure was observed for the traditional fluid. The failure of SBF was investigated and identified to be related to the lower lubricity of SBF in relation to the traditional fluid, as well as SBF incompatibility with internal ABS elastomers. This paper presents the results of these analyses, so as to help ensure a smooth transition to ABS use in military ground vehicles.

BACKGROUND
Currently, the US Army is executing a hardware technology upgrade to focus on soldier safety through the implementation of anti-lock braking systems (ABS) in military ground vehicles [1]. ABS have long been a staple in the commercial vehicle market and when paired with modern brake controller systems like Traction Control Systems (TCS), Brake Assist, and Electronic Stability Control (ESC), have increased vehicle stability and decreased the incidence of crashes [2].

INTRODUCTION
US military brake systems face many challenges different from their commercial counterparts. While US military vehicles may experience lower mileage, they often operate in very hot or cold environments, and/or sit for long periods of time, which can lead to corrosion. Prior to 1980, the US

military used three different glycol-based brake fluids: one for general use, one for low temperatures, and one for long-term storage. However, the need for frequent fluid changes caused by thermal breakdown of brake fluids, as well as corrosion in vehicles that stood unused for too long, resulted in logistics problems for this three-fluid approach [3]. In the 1980s, the US military began utilizing a Silicone Brake Fluid (SBF) under MIL-PRF-46176 as a common fluid across all ground systems to combat these logistics and corrosion problems. Since then, the use of SBF has mitigated thermal breakdown thereby extending the length of time between fluid changes, and has helped to eliminate the ingestion of water that normally leads to corrosion due to silicone's hydrophobicity [3]. Drawbacks however, to the use of SBF, include increased price and potential incompatibility issues with other commercial glycol-based brake fluids. As well, SBF has long been purported to be incompatible with ABS.

Commercial ABS manufacturers recommend commercial specialty fluids for use with their systems; however, as previously discussed, these fluids do not address the challenges of US military ground vehicles, most notably the prevention of thermal breakdown in desert operation, and long-term corrosion. Commercial ABS manufacturers do not recommended the use of SBF with ABS due to concerns that these fluids would degrade the system performance and life. As well, there have been reports of possible high temperature degradation of SBF in ABS that have led to deposition and filter plugging, and subsequent ABS filter collapse. Specific concerns that have been identified include: SBF immiscibility with water that may lead to performance issues and corrosion, as well as the formation of particulate matter that will plug filters and damage components [4].

This study aims to investigate commercial ABS manufacturer claims concerning compatibility of SBF in ABS and to determine the root cause, if any, of fluid failure. The approach was to design an ABS test stand unit to simulate SBF use in an ABS environment and subsequently evaluate SBF performance through physical and chemical analyses on the ABS test stand unit hardware and used SBF. A reference fluid, similar to those recommended by commercial ABS manufactures, was selected and subjected to the same operating and evaluation criteria for comparison in a separate ABS test stand unit.

EXPERIMENTAL

TEST FLUID SELECTION

Two brake fluids were selected for analysis, SBF and DOT III [5]. SBF is a silicone based fluid, similar to DOT V, but meets the MIL-PRF-46176 Specification [6]. The SBF was purchased from the Qualified Product List (QPL) for the MIL-PRF-46176 Specification. Purchasing SBF directly from the QPL guarantees the fluid is representative of brake fluid being purchased by the US Army depots in the field. The DOT III is a polyethylene glycol based fluid, and was purchased from a commercial supplier.

TEST STAND DESIGN

To reproduce conditions of heavy duty ABS use, an ABS test stand was designed (Figure 1). The ABS test stand unit consisted of independent front and rear breaking circuits. Each breaking circuit had an electric motor that drove a pumping element used to maintain braking pressure, a gas charged accumulator to store circuit pressure, and a pressure transducer for measurement and control. Each circuit also had two independent wheel circuits, right and left, which contained two servo valves for each wheel. One servo valve was responsible for controlling pressurized fluid to the brake calipers, while the second servo valve was responsible for brake release and relieving caliper circuit pressure back to the reservoir. The brake circuit was initiated by pressure from the master cylinder through the

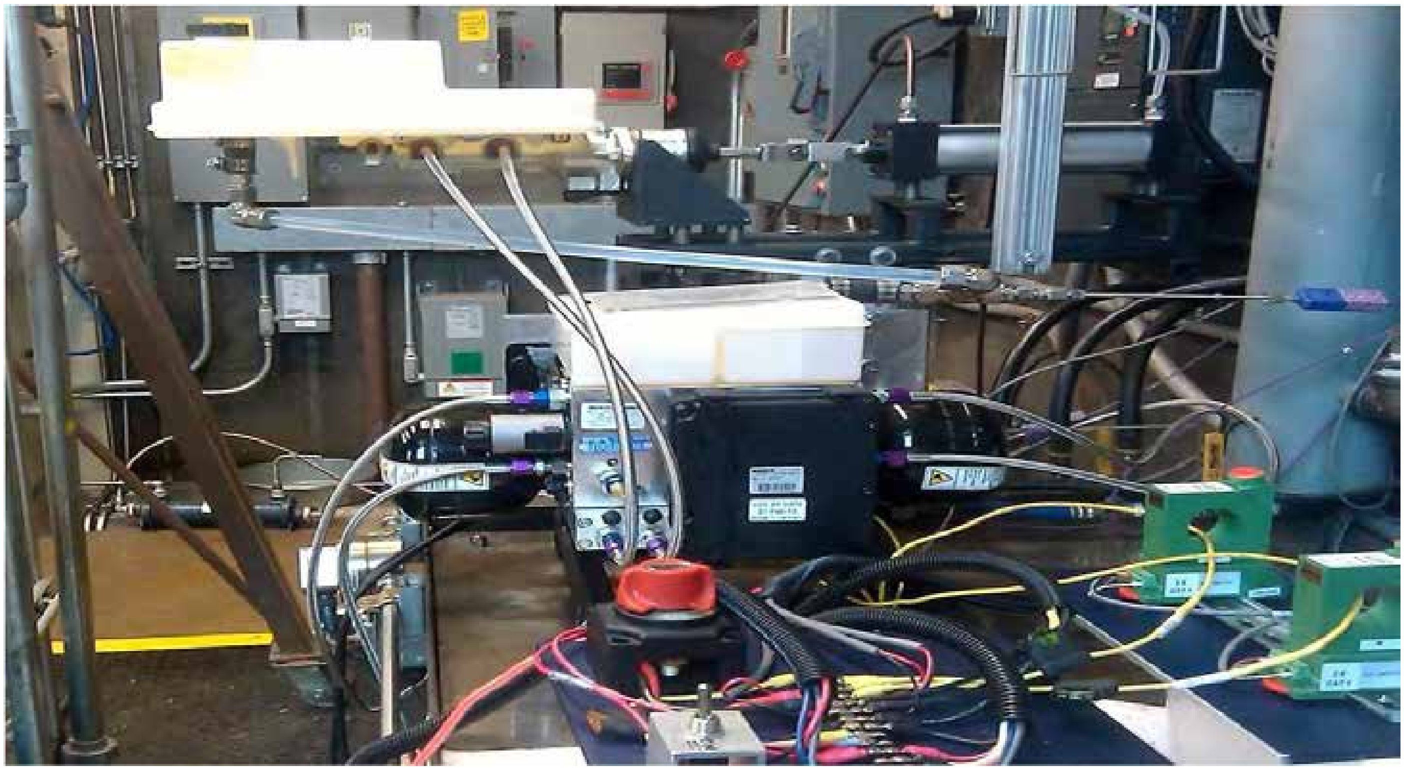

Figure 1. Anti-Lock Brake System Test Stand Unit

relay valves. An Electronic Control Unit (ECU) monitored the system pressures and controlled the motors to maintain accumulator pressure and servo valves. An exploded view of a typical ABS configuration is shown in Figure 2.

A service software tool was utilized to control the ABS test stand without the need for wheel sensors. In short, the ECU software was used to dump the accumulator pressure. This then resulted in venting the brake fluid across a filter, shearing the fluid, and returning back to the reservoir. This action then triggered the ECU to turn on the pump motors to raise the system pressure again and cycle the fluid. This "pump and dump" cycle was to be repeated until deposition was observed to occur on the pump inlet filter mesh screen and/or the pump inlet filter mesh screen collapsed.

This scheme was devised to cycle the fluid through the system as a means to monitor the development of residue deposits in a shortened time interval; it resulted in greater pressure fluctuations and more motor operational time than a conventional master cylinder and brake approach. A Polyethylene Terephthalate (PET) viewing window, compatible with both fluids, was machined into the hydraulic reservoir to allow for the monitoring of residue deposition on the pump inlet filter mesh screen and/or pump inlet filter mesh screen fidelity.

TEST STAND SETUP

In the likelihood that the manufacturer of the ABS test stand units used DOT III fluid to validate the system build, the ABS test stand unit used for the evaluation of SBF was flushed with SBF several times. The SBF unit was then filled with SBF. The DOT III test stand unit was simply filled with DOT III fluid.

TEST STAND OPERATION

Both the SBF and DOT III ABS test stand units were subjected to the pump and dump cycling

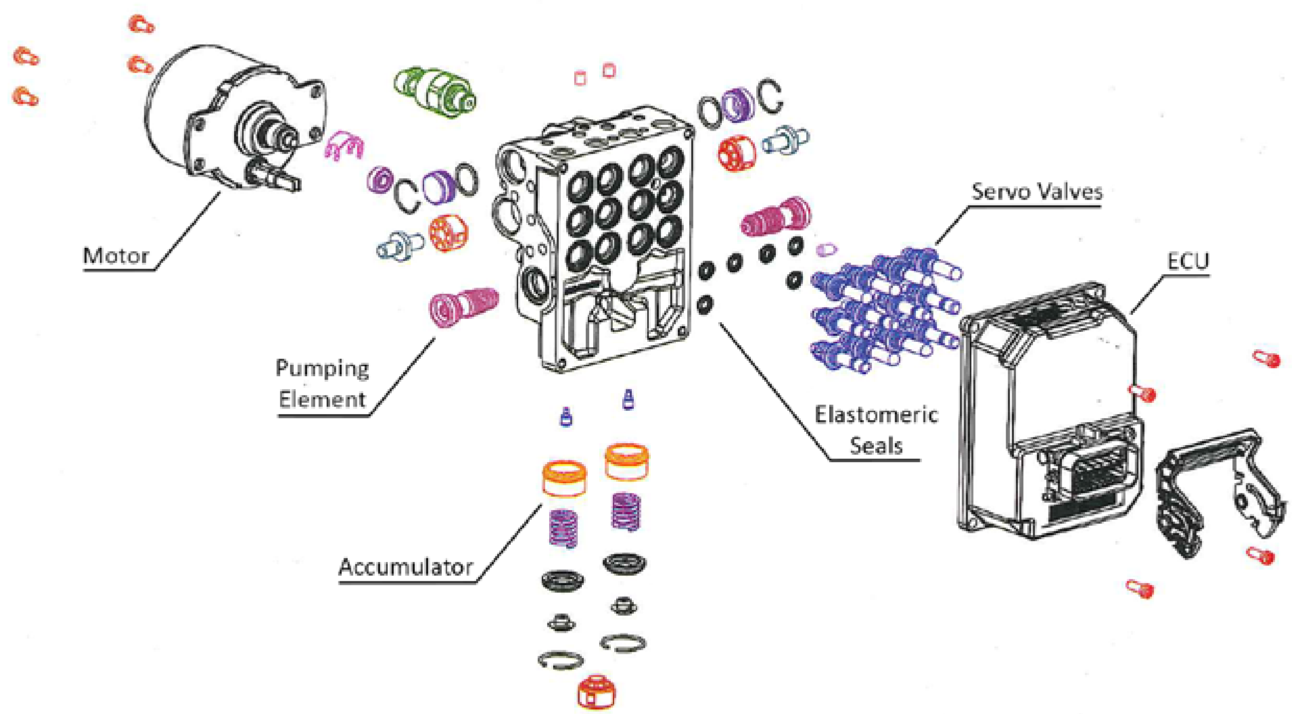

Figure 2. Detail view of ABS components. [7]

scheme identified above in the ABS test stand design. Since previous reports by the manufacturer indicated that SBF would break down before the DOT III, the testing on the SBF ABS test stand unit was conducted first. At the conclusion of SBF testing, determined as SBF failure in the ABS test stand unit, the DOT III ABS test stand was then run the same length to ensure results could be adequately compared. As previously noted, fluid fidelity was monitored throughout testing through visible inspection of the pump inlet filter mesh screens. Unlike DOT III, which is a clear amber fluid, SBF is an opaque purple fluid; therefore, it was not possible to inspect the pump filter mesh screen through the inspection window during testing. To inspect the pump inlet filter mesh screens of the SBF ABS test stand, the system was halted, the SBF was removed and reserved, and the filter was then inspected. After inspection, the SBF fluid was returned to the unit and testing commenced.

TEST STAND TEARDOWN

At the conclusion of testing, both the SBF and DOT III ABS test stand units were disassembled. Physical inspection of the internal components of each ABS test stand unit for wear, deposits, and particle accumulations was conducted to include: two pumping elements, eleven elastomeric seals, and ten servo valve filters per unit. Chemical analyses were performed on both new and tested SBF and DOT III fluids, as well as the servo valve filters, elastomer seals, deposits and particle accumulations on pump inlet filter mesh screens.

RESULTS AND DISCUSSION

SBF was allowed to run until residue build up was observed on the pump inlet filter mesh screen or filter fidelity was observed to be in questionable state. After 7,000 pump and dump cycles were accumulated with the SBF, a dark ink-like viscous fluid was observed to cover the pumping inlet filter mesh, believed to be dye from the fluid, but no particulate was observed. This ink-like fluid was scraped off and observed under high magnification. Examination revealed dark and metallic particles were suspended in the fluid. The sample was subjected to Scanning Electron Microscope (SEM) elemental analysis and the surface of the sample appeared to be primarily silicon, while the particles were primarily silicon and iron. Testing was then commenced, as the filter of the SBF ABS test stand unit did not appear compromised.

Testing continued until 11,000 cycles were accumulated. Examination revealed no evidence of particulate formation in the SBF reservoir; however, the ink-like fluid was again observed on the pumping inlet filter mesh, thicker in appearance, but again the pumping inlet filter media was not observed to be compromised. The ink-like fluid was again examined by SEM elemental analysis and revealed dark metallic particles again were primarily silicon. Testing again commenced as the filter of the SBF ABS test stand unit did not appear compromised.

Once the test stand had reached 15,000 cycles the reservoir was drained and evidence of particulate formation in the SBF reservoir was observed. There was no sufficient particulate evidenced to form that would cause compromise of the pumping inlet filter mesh, but particulate was analyzed again by SEM elemental analysis and revealed again that the dark metallic particles were again primarily silicon.

At 20,000 cycles, it was finally observed that the filter media appeared to be collapsing. Figure 3 details the filter media after 20,000 cycles. From the figure it can be observed that the pumping inlet filter mesh screen at 20,000 cycles was covered with particulate laden viscous fluid and had wrinkling likely due to elevated differential pressure due to particulate deposition. Although spot checking during cycling revealed deposit and metallic particulate build up, the filter fidelity had not yet been compromised. This observation indicated that metal particles were present within the fluid, suggesting that deposit and metallic particulate wear were occurring within the ABS test stand unit. Testing on the SBF ABS test stand unit was then halted. The SBF ABS test stand unit was then decommissioned and subjected to physical analysis of the components and chemical analysis of the 20,000 cycle fluid and servo valve filters, elastomer seals, deposits and particle accumulations on pump inlet filter mesh screens.

Figure 3. Pumping filter inlet mesh screen after 20,000 pump and dump cycles with SBF.

Testing then proceeded with 20,000 cycles of the reference DOT III fluid on the DOT III ABS test stand unit. As previously mentioned, this length was chosen to allow data sets to be easily compared between the SBF and DOT III test stands. The DOT III fluid was observed to complete 20,000 cycles of testing without any evidence of deposition on the pumping inlet filter mesh screens, although the fluid was observed to darken slightly; this was likely due to oxidation.

PHYSICAL ANALYSIS

The pumping elements, front and rear, of each ABS test stand unit, SBF and DOT III, were disassembled to expose the plunger and barrel. Both front and rear plunger and barrel were imaged under high magnification for wear analysis. Figures 4 and 5 display the overall condition of both the pumping (left) and follower (right) ends the front plunger of both the SBF and DOT III ABS test stand units respectively. The DOT III front plunger was observed to have less polish. Wear was observed on the follower end of the SBF front plunger, as well as distress to the elastomeric seal. In comparison, very little distress was observed on the elastomeric seal of the DOT III front plunger. Figure 6 and 7 display the overall condition of both the pumping (left) and follower (right) end of the rear plunger of both the SBF and DOT III ABS test stand units respectively. Wear was observed on both the pumping and the follower end of the SBF unit, while the DOT III was again observed to have very little polishing. As well, more distress to the SBF rear plunger elastomer seal was observed, while very little distress was observed for the elastomer seal of the DOT III rear plunger.

Figures 8 and 9 display the cross-sectioned barrels of both the SBF and DOT III front plunger respectively. Wear from the SBF front plunger follower section was observed, while the corresponding barrel of the DOT III was observed to have very little wear from the DOT III front plunger follower. Elastomer distress was observed for the SBF unit front plunger. Debris from the SBF front plunger and barrel wear at the follower end is believed to be the cause for the elastomer distress. Figures 10 and 11 display the cross-sectioned barrels of both the SBF and DOT III rear plunger respectively. Wear and material transfer from the SBF front plunger follower section was again observed, while the corresponding barrel of the DOT III was again observed to have very little wear. As well, elastomer seal distress was again observed for the SBF unit rear plunger. Debris from the SBF rear plunger and barrel is again believed to be the cause for the elastomer distress.

Figure 4. SBF front plunger. Pumping end (left), follower end (right).

Figure 5. DOT III front plunger. Pumping end (left), follower end (right).

Figure 6. SBF rear plunger. Pumping end (left), follower end (right).

Figure 7. DOT III rear plunger. Pumping end (left), follower end (right).

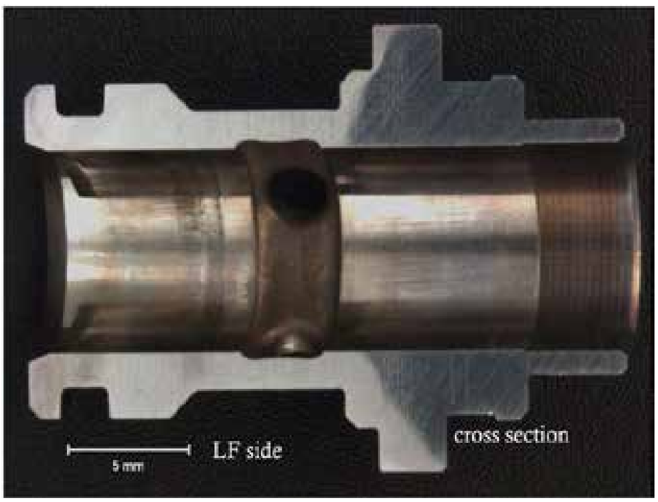

Figure 8. SBF front plunger barrel cross section.

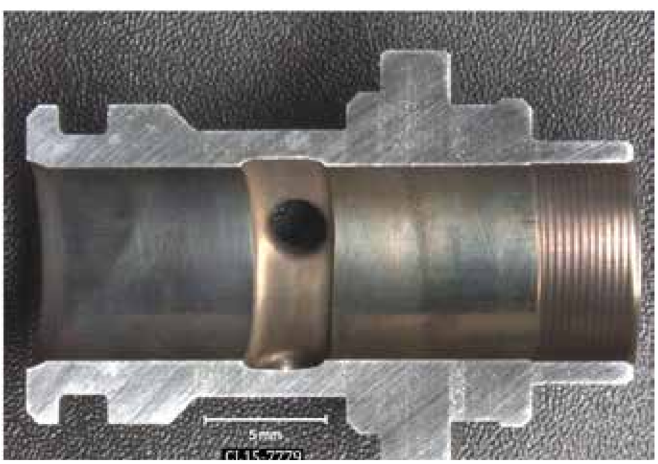

Figure 9. DOT III front plunger barrel cross section.

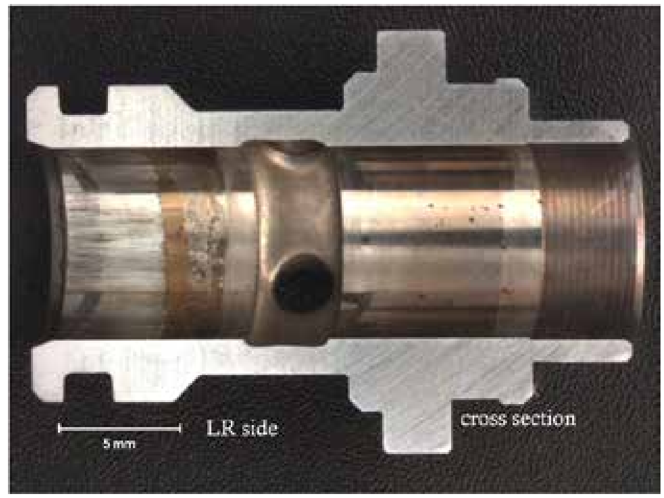

Figure 10. SBF rear plunger barrel cross section.

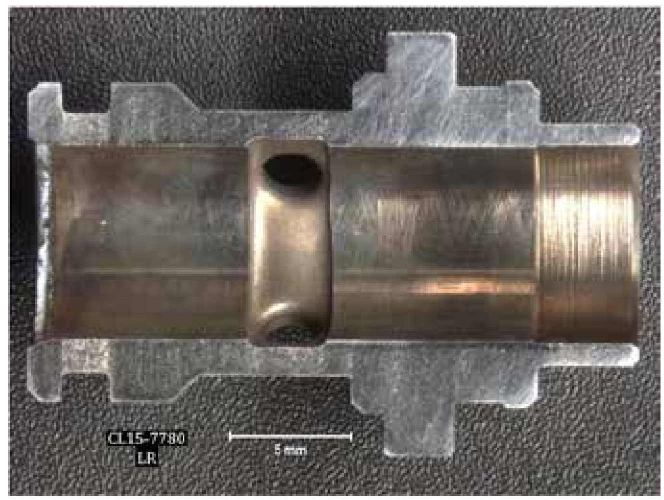

Figure 11. DOT III rear plunger barrel cross section.

CHEMICAL ANALYSIS

The lubricity of SBF was studied using ASTM D5001-10 Ball-on-Cup Lubricity Evaluator (BOCLE) [8] and ASTM D6079-11 High Frequency Reciprocating Rig (HFRR) [9] tests and compared to DOT III. New and used SBF and DOT III were subjected to these tests at 60 °C. The results are shown in Table 1. These tests were developed to study the lubricity of aviation and diesel fuels; however use here is justified since the tests are ultimately used to evaluate boundary lubrication properties, which are relevant in other vehicle hardware such as brake systems. The results

Brake Fluid	ASTM D5001 BOCLE, mm	ASTM D6078 HFRR, mm
DOT III	.511	.338
Cycled DOT III	.483	.302
SBF	.535	.281
Cycled SBF	.521	.430
Fresh SBF	.665	.361

Table 1. BOCLE and HFRR bench wear test results.

of both tests suggests that SBF is slightly less lubricious, which could explain the increased wear seen on the system pumping plungers and corresponding barrels that match these results.

Chemical inspection of the used SBF, as well as the solid residue recovered from the reservoir filter was analyzed by Fourier Transform Infrared (FTIR) spectroscopy and compared to new SBF. Figure 12 overlays the spectra for each. The following spectral bands were found in the residue (green band) only: 1593.63 cm-1, indicating a C-C aromatic stretch, 1562.09 cm-1, indicating N-O asymmetric aromatic stretch, and 1399.14 cm-1 and 1370.75 cm-1, indicating N=O bends. These bands likely point to the presence of nitrile based compounds typically found in elastomers. Chemical inspection of the elastomeric seals by FTIR spectroscopy was conducted and compared to the solid residue recovered from the reservoir filter; however, the spectra did not reveal any nitrile spectra bands. X-ray Diffraction (XRD) analysis was then conducted to determine the exact identity of the solid residue found in the reservoir filter. The spectra identified the deposit as silane based compound, therefore, the possibility of brake fluid polymerization was eliminated. Although, the SBF reservoir residue sample did contain a fluid that did not evaporate in vacuum; therefore, it is not certain if the XRD spectra detected the residual fluid or the residue itself. Since the XRD spectra did not appear to contain any elastomeric compounds, this fluid was deemed to be either silicone grease or residual silicone brake fluid.

Chemical inspection of the used SBF on the servo valve filters was also analyzed by FTIR spectroscopy and compared to the spectra for new SBF. Figure 13 overlays the spectra for each. The following spectra bands were found on the servo valves only: 3296.91 cm-1, indicating the presence of an O-H peak corresponding to water, 1631.50 cm-1, indicating a C=C peak corresponding to alkenes, 1531.36 cm-1, indicating a C=C peak corresponding to aromatic compounds, and multiple peaks around 1463.01 cm-1, indicating presence of C-H peak corresponding to alkanes. This spectra was compared to the spectra of FTIR analysis conducted on the eleven elastomer seals from within the ABS test stand unit. These peaks indicate the probability of Styrene-Butadiene elastomers (SBR) elastomeric seal contents. The C=C alkene peak corresponds to the butadiene chain, and the C=C aromatic peak corresponds to the phenyl group of the SBR structure. This indicates that there is likely SBR elastomeric residue on the servo valves.

SEM images of the servo valve filtered residue revealed presence of threaded structures in addition to the solid agglomerate residue, indicative of the physical presence of elastomer/polymer threads. XRD analysis of the filtered residue indicated the presence of two chemical structures, 1,4-diphenyl-1,3-butadiene, which is likely indicative of the presence of SBR, and N-phenylmaleimide, which is used for grafting polymers at low concentrations also likely indicative of SBR.

The eleven elastomer seals within the ABS test stand units were analyzed by FTIR to determine the possible source of SBR release. Analysis revealed that the Parking Brake Supply and Relay Valve Seal, as well as the Pump Plunger Dynamic Seal and Reservoir Seal could contain SBR elastomer, with the Pump Plunger Seal being the most likely source from which SBR elastomer could have been leached into the brake fluid.

To determine whether the presence of elastomer residue was due to fluid-elastomer incompatibility, static soak and dynamic seal elastomer tests were conducted. The static elastomer tests were conducted at room temperature and at 40 °C, and the dynamic elastomer tests were conducted at

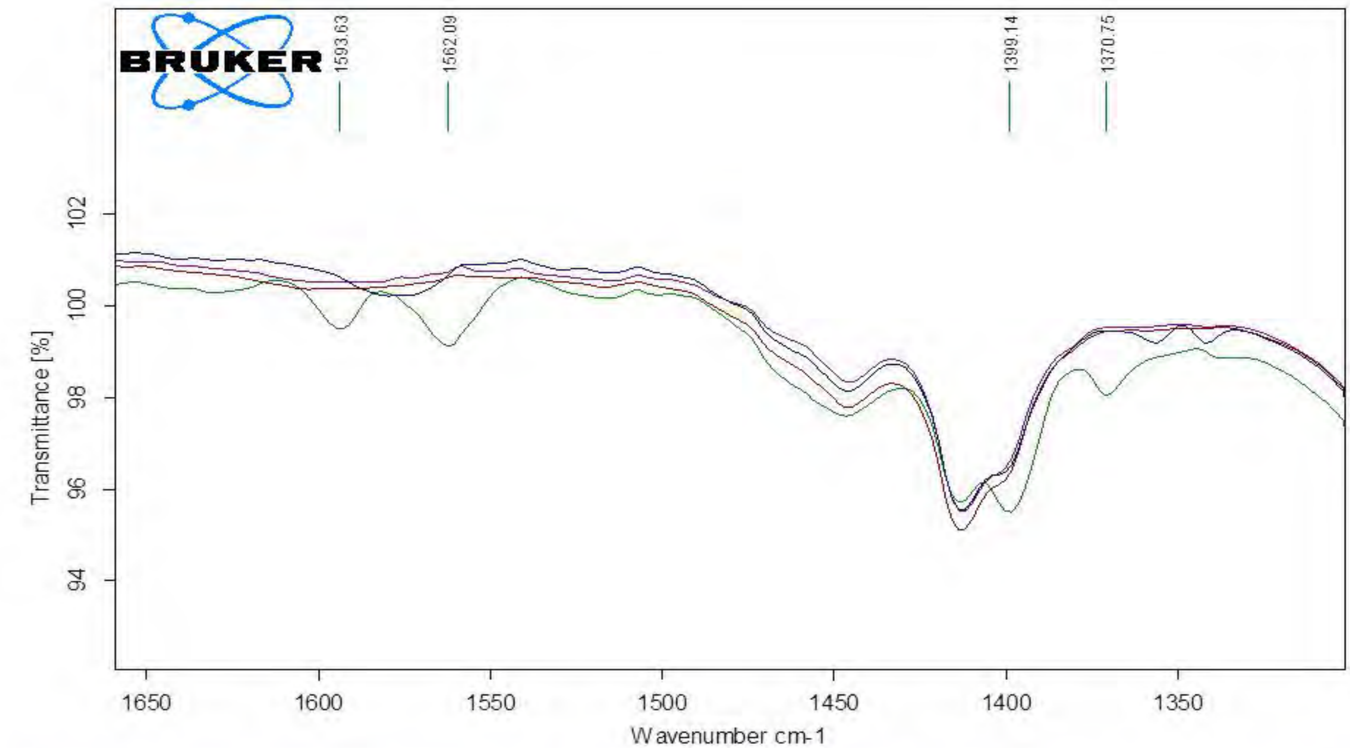

Figure 12. FTIR analysis of new and used SBF, as well as the solid residue from reservoir filter. Used SBF is identified as purple for the bottom layer, brown for the top layer. New SBF is identified as magenta. SBF reservoir residue is identified as green.

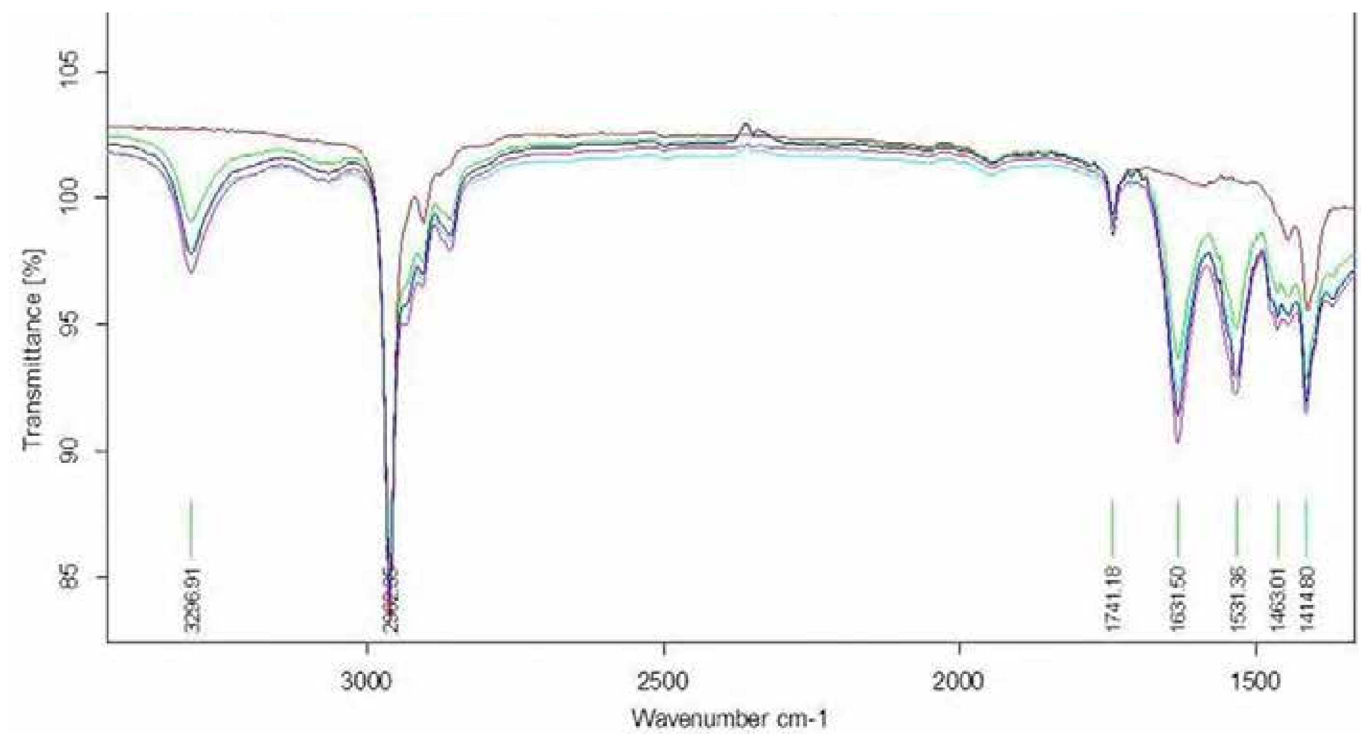

Figure 13. FTIR analysis of servo valve filters (No. 4 - purple, No. 5 - magenta, No. 6 - green, No. 10 - blue), and new SBF (brown).

40°C on Styrene Butadiene Rubber (SBR). Three o-rings (AS-568-O17) were tested for static elastomer compatibility with SBF and DOT III. Two o-rings (AS-568-O12) were tested for dynamic elastomer compatibility with SBF and DOT III. The dynamic seal tester is a reciprocating rig that pushes fluid through pumping element over an elastomer to evaluate fluid-elastomer compatibility under dynamic motion [10]. Because the dynamic seal tester was only designed to accommodate these smaller o-rings, tensile strength could not be determined; however, pre- and post-test weight measurements were made as a way to identify dissolution of elastomer constituents into the fluid. The difference in physical properties, such as, weight, thickness, hardness, volume swell and tensile strength from pre- to post-test conditions were compared.

For static soak tests thickness, SBR elastomers in DOT III were all observed to have reduced thickness over SBF at both ambient and 40 °C temperatures. For static soak test hardness, SBF was observed to reduce the hardness of SBR compared to DOT III at both temperatures. For static soak test volume swell, there was a significant volume swell observed SBR elastomers with SBF fluid and slight volume shrinkage for SBR with DOT III at both temperatures. Lastly, at ambient temperature, the tensile strength returned inconclusive results, as trial results overlapped; however, at 40 °C the tensile strength of SBR decreased.

For the dynamic seal tests thickness, SBR elastomers increased in SBF, while there was negligible thickness change in DOT III. For dynamic seal test hardness, SBF and DOT III was observed to reduce the hardness of SBR; however, SBF resulted in a greater decrease. For dynamic seal test weight change, SBR was observed to have significant weight gain with SBF, while DOT III did not result in any weight change. As well the dynamic seal test volume swell for SBR was much higher with SBF than DOT III.

Used fluids from the static soak and dynamic seal tests were analyzed using GC-MS to determine if any elastomer had leached into the brake fluid. GC-MS analysis revealed that the SBR elastomer had not leached into the brake fluids during the static soak tests.

Collectively the physical and chemical characterization of the components and fluids infers that there was SBR elastomer presence in the used SBF and that there was a fine SBR elastomer layer coated on the surface of the servo valves. As well, it is highly likely that the pump plunger dynamic seal is the location from which the SBR elastomer could have leached into brake fluid due to dynamic motion.

CONCLUSIONS

In conclusion, the SBF ABS test stand unit was able to reach 20,000 cycles before residue and particulates were observed to accumulate on the reservoir filters causing the filters to become too compromised to continue testing. The SBF ABS test stand unit was then dismantled to determine the root cause of residue and particulate on the reservoir filters. It was observed that the pumping elements (front and rear plungers and corresponding barrels) of the SBF ABS test stand unit had wear not only to pumping elements, but to the SBR elastomers associated within. Lubricity tests confirmed that SBF had a lower lubricity than DOT III. As well, static soak tests confirmed via GC-MS that while SBR did not leach into SBF under static conditions, dynamic seal tests confirmed that dynamic motion of SBR elastomer in SBF increased the thickness of SBR elastomer by approximately 6%, the weight by approximately 8%, the volume swell by about 13%, and softened the SBR elastomer by approximately 10%. [14] These increases could subject the SBR elastomer to wear in dynamic motion. Therefore the lower lubricity of SBF combined with the effect of SBF on SBR elastomers lead to increased pump wear, corresponding to increased elastomer wear and subsequent brake residue and particulate build up on the reservoir filters. FTIR tests of the eleven elastomer seals contained within the ABS test stand units revealed that the elastomer seals contained within the pumping elements of the ABS test stand unit likely contain SBR materials and therefore is the likely source of SBR material associated with the solid residue and particulates within the reservoir filters.

FUTURE WORK

Developing a brake fluid that meets US Army requirements in the same way that SBF has historically while also being compatible with ABS poses a difficult task. One potential option is to formulate SBF in a way that enhances its lubricity performance while also ensuring that ABS hardware utilizes silicone-compatible seals that will not be compromised when exposed to SBF under both static and dynamic conditions. Another option is to consider moving from SBF back to a glycol-based brake fluid, as was used prior to the 1980s. Glycol-based brake fluids have improved considerably in the past three decades such that many fluids on the market have wet boiling points and low temperature viscosity performance on-par or exceeding SBF. [11, 12] Reformulating a glycol-based fluid with enhanced corrosion protection is a possible future brake fluid for Army ground vehicles equipped with ABS in lieu of MIL-PRF-46176 fluids.

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