– Technical Report –

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Title: Enhanced Performance Coolants (EPC) Benchtop and Simulated Service Test Report

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Executive Summary

As of 2022, U.S. Army engine coolant is governed by Commercial Item Description (CID) A-A-52624A, which mandates the use of antiquated conventional, supplemental coolant additive (SCA) based technology. SCA based coolant (hereafter "conventional") lacks key advantages of the newer more widely used Organic Acid Technology (OAT) based coolant, also known as Extended-Life Coolant (ELC). ELC has been commercially available and used in passenger cars since 1995, with General Motors being the first OEM to adopt OAT technology in their factory fills, but the U.S. Military has not yet adopted the use of OAT technology [1][2]. One disadvantage of conventional coolant is that it has a short life span of two years on the condition that additives are re-inhibited every six months. In 2015, the Ground Vehicle Systems Center (GVSC) learned from the Combined Arms Support Command (CASCOM) that the re-inhibition process was not occurring at field level maintenance, and instead a full flush and refill was conducted annually. This unnecessarily increases the maintenance burden and quantity of coolant being used.

This report is in support of the Enhanced Performance Coolants (EPC) task of U.S. Army Combat Capabilities Development Command (DEVCOM) GVSC's Ground Systems Fluids and Fuels (GSFF) research project. The objective of the EPC task is to evaluate a series of ELCs for use in military ground vehicles and define military-specific fluid requirements to safeguard Army ground vehicle cooling systems in all operational environments.

The effort detailed in this report identified five (5) commercially-available ELC candidates via market survey, ground vehicle survey, specification research, and communication with industry experts. Candidates identified conformed to several different ELC coolant technologies and were classified as one of four heavy-duty coolant formula types: OAT, Hybrid OAT (HOAT), Nitrited OAT (NOAT), and conventional coolant as a comparison only.

These candidates underwent benchtop testing to baseline chemical properties and determine key performance characteristics. Routine testing was performed in accordance with (IAW) test methods found within ASTM D3306-20 [8]. Additional testing included a compatibility study between the ELC candidates, similar to those done within OEM specifications.

Downselection occurred based on knowledge gathered during the course of the testing. In conversations following these analyses, multiple OEMs concurred with GVSC's recommendation that Heavy-Duty (HD) Nitrite Free OAT ELC was the best technology due to the unique circumstance of military vehicles utilizing both light and heavy duty engines, and the desire for one coolant technology type.

The two (2) OAT candidates (nitrite-free) then underwent additional benchtop and simulated service testing to determine compatibility and acceptable performance. The end goal of the EPC task is to create a military performance specification for one type of ELC for use in all Army ground military equipment.

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Background

As of 2022, U.S. Army engine coolant is governed by Commercial Item Description (CID) A-A-52624A, which mandates the use of antiquated conventional, supplemental coolant additive (SCA) based technology. Conventional coolant lacks advantages of the newer more widely used Organic Acid Technology (OAT) based coolant, also known as Extended-Life Coolant (ELC). ELC has been commercially available and used in passenger cars since 1995, but the U.S. Military has not yet adopted the use of OAT technology [1][2]. One disadvantage of conventional coolant is that it has a short life span of two years on the condition that additives are re-inhibited every six months. Unfortunately, this re-inhibition process is not occurring and instead a full flush and refill is conducted annually. This unnecessarily increases the maintenance burden and quantity of coolant being used by the U.S. Army.

In contrast to conventional SCA technology, ELC generally has an increased lifespan of 150,000 miles or 5+ years of service because the additives do not deplete as quickly over time [1]-[5]. Additionally, conventional coolant technology is often said to offer less protection to aluminum engine components from cavitation corrosion and provide lower heat transfer compared to some ELCs [1][6][7]. These advances in coolant technology over the last 25 years have brought to light the need for the Army to transition from conventional to extended-life coolant.

This report is in support of the EPC task of DEVCOM GVSC's Ground Systems Fluids and Fuels (GSFF) research project. The objective of this development effort is to evaluate commercially available ELCs and define military-specific coolant requirements to ultimately transition Army ground vehicles from conventional coolant to ELC. Stakeholders in this research effort include the program offices under PEO CS&CSS, as well as DLA-Aviation, who procures qualified products for field use.

The benchtop testing effort detailed in this report (hereafter referred to as "Project") identified possible extended-life coolant (ELC) solutions by determining key characteristics of ELCs and down-selecting ELC test candidates.

Project Objectives

1. Baseline test candidate performance in benchtop testing, including chemical, physical, and performance tests
2. Down select test candidates based on performance and technical knowledge gathered from subject matter experts
3. Perform benchtop and simulated service testing on downselected candidates

Project Approach and Outcomes

To accomplish the project objectives related to benchtop testing, GVSC conducted four phases:

I. Market and Ground Vehicle Surveys
II. Laboratory Benchtop Testing
    a. Internal Testing (GVSC)
    b. 3rd Party Testing under WD 002 and WD 006 (Army Lab at Southwest Research Institute)
III. Candidate Performance Analysis and Technical Knowledge Gathering
IV. Candidate Down Selection

Phase I – Market and Ground Vehicle Surveys

GVSC conducted a market survey to identify commercial available ELCs. Beta.Sam.Gov posted the market survey for coolant manufacturers to respond with their information within 34 days, from 29 June 2020 through 31 July 2020. In an effort to gain additional responses to the posted market survey, GVSC also contacted twenty-five companies to encourage them to respond. In total, GVSC received eleven market survey responses during the posting period. A market survey report, titled "Commercial Extended Life Coolants for Military Ground Vehicle Usage – Market Survey Responses", was written and published to the Defense Technical Information Center (DTIC) under accession number AD1112055.

Additionally, GVSC conducted a ground vehicle survey of coolant use between November 2019 and May 2020 to review all engine types of every platform, identify what coolant is currently used or recommended, and narrow down which platforms would be impacted by a switch to ELC. This survey effort consisted of internet searches, expanding on previous work done by the Fuels and Lubricants Branch (F&L), and direct communication with various vehicle platform points of contact. The previous work done by F&L was an inventory of every army platform and their associated engines; this provided a great starting point for the ground vehicle survey since half the work was already done. A total of 112 different ground vehicles and pieces of equipment were reviewed. A report summarizing the approach and results was written and published to the DTIC under accession number AD1114771, titled "Survey of Coolant Use in Military Ground Systems to Select Candidates for Evaluation".

Market and Ground Vehicle Survey Results Guiding Fluid Candidate Selection

Based on results gathered from the industry & ground vehicle market survey, contacts within the industry, and internet research, GVSC selected six (6) fluid candidates to use for Phase II laboratory benchtop testing. A selection of 4 different types of coolants were chosen: 2 OATs, 2 HOATs, 1 NOAT, and 1 Conventional SCA for comparison. This selection covers the main types of coolant available internationally in the commercial market. OAT coolants use either aromatic or aliphatic carboxylic acid additives for corrosion protection. HOAT coolant is a combination of Inorganic Acid Technology (IAT), which is used in conventional coolants, and OAT; HOATs rely heavily on conventional additives (Borates, Phosphates, Silicates, Nitrites, etc.) and formulations vary widely from each manufacturer. NOAT coolant is a subset of the HOATs since it is an OAT with nitrite added.

A total of five different manufacturers are represented in the candidate pool. See Table 1 below for test sample IDs, coolant types, and inorganic additives used. Only inorganic additives are listed for coolant candidates to easily identify differences in their formulations; while all ELCs utilize organic acids, inorganic additives prove to be the greatest differentiator between OATs, HOATs, and NOATs. The difference between OATs and HOATs/NOATs is that OATs only need a small amount of inorganic additives (molybdates and nitrate) for corrosion protection. Unlike OATs, HOATs use a lot of the inorganic additives, especially borates, phosphates & silicates, while NOATs specifically use nitrite.

Coolant candidates were procured between August and September 2020.

Table 1. Coolant Candidates

Sample ID #	Marketed Coolant Formula Type	Date Sample Received	Specification	Inorganic Additives
FL-18023-20	HOAT Coolant	13-Aug-20	OEM Spec*	Borate, Phosphate, Silicate, Nitrate, Nitrite and Molybdate
FL-18024-20	OAT Coolant	20-Aug-20	OEM Spec*	Nitrates, Molybdates
FL-18030-20	Conventional Coolant	21-Aug-20	CID A-A-52624	Nitrate, Nitrite, Borate, Silicate
FL-18031-20	HOAT Coolant	26-Aug-20	OEM Spec*	Borate, Phosphate, Molybdate, Nitrate, and Silicate
FL-18071-20	NOAT Coolant	09-Sep-20	OEM Spec*	Nitrites, Molybdates
FL-18072-20	OAT Coolant	14-Sep-20	OEM Spec*	Nitrates, Molybdates

*OEM Specifications are not identified here to maintain confidentiality

Phase IIa – Laboratory Benchtop Testing: Internal Testing (GVSC)

GVSC performed laboratory benchtop testing on five (5) extended-life coolant candidates and one (1) conventional coolant candidate listed in Table 1 above. Testing was performed in the Fuels and Lubricants Laboratory (FLL) from September 2020 to June 2021. The objective of this testing was to characterize baseline chemical properties of the coolants and take note of any differences. A photo depicting all the candidate coolants in shown below in Figure 1.

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

1. Glycol Content (%) via Refractometer
2. ASTM D1287-11 – Standard Test Method for pH of Engine Coolants and Antirusts [9]
3. ASTM D5931-20 – Standard Test Method for Density and Relative Density of Engine Coolant Concentrates and Aqueous Engine Coolants by Digital Density Meter [10]
4. ASTM D3321-19 – Standard Test Method for Use of the Refractometer for Field Test Determination of the Freezing Point of Aqueous Engine Coolants [11]
5. ASTM D1120-17 – Standard Test Method for Boiling Point of Engine Coolants [12]
6. Thermal Conductivity and Specific Heat using C-Therm TCi Thermal Conductivity Analyzer
7. Additives by Coolant Test Strips
8. Heat-Transfer Coefficient Determination via Heat Exchanger

Figure 1. All coolant candidates

Distilled water (Type IV IAW ASTM D1193 [13]) was used to mix all concentrate candidates to a mixture of 60% glycol and 40% water.

Glycol Content (%) via Refractometer

An Atago PAL-91S glycol pocket refractometer, Figure 2, was used to verify the glycol percentage of each mixture prior to testing. All glycol percentages were acceptable, meaning they were within ± 0.4% of the desired glycol percent, which was the decided limit by GVSC since no ASTM method was used to verify glycol percent. This tolerance was chosen such that any observed result would round to 60%. Results of glycol content can be found in Table 2 below.

Figure 2. Glycol Content Refractometer

ASTM D1287-11 pH

The pH of each coolant candidate at a 60%/40% (glycol/water) by volume mixture was performed IAW ASTM D1287-11. Results are shown in Table 2 below. One HOAT candidate and the conventional candidate had a pH of 10.46 and 10.67 respectively, while all others averaged 8.5. These pH values met the requirements listed in ASTM D3306-20, which is 7.5 to 11 pH values.

ASTM D3321-19 Freeze Refractometer

The freeze point for each coolant candidate at a 60%/40% (glycol/water) by volume mixture was determined and performed IAW ASTM D3321-19. The refractometer (Glyclean Coolant and Battery Tester) used for this test is shown below in Figure 3.

Figure 3. Freeze Point Refractometer

The freeze point for all candidates was confirmed to be < -50°F, as shown below in Table 2. These results are not applicable to ASTM D3306-20 requirements for freeze point because the glycol concentration refractometer is not included in the method. A concentration of 60% glycol by volume was used because of the Army's unique operating environments in arctic conditions. Glycol concentrations at 60% by volume yield the best freeze point protection.

ASTM D5931-20 Relative Density

Testing was performed IAW ASTM D5931-20 using an Anton Paar Digital Density Analyzer DMA 4500 M, as shown in Figure 4 below.

The relative density for all candidates at a 60%/40% (glycol/water) by volume mixture was approximately 1.09 at 15.6°C. Exact results shown in Table 2 below.

Figure 4. Digital Density Analyzer, DMA 4500 M

ASTM D1120-17 Boiling Point

Per ASTM D1120-17, "The equilibrium boiling point indicates the temperature at which the sample will start to boil in a cooling system under equilibrium conditions at atmospheric pressure" [12]. Testing at GVSC was performed IAW ASTM D1120-17 to determine the boiling point of each coolant candidate at a 60/40 (glycol/water) by volume mixture. Boiling point temperatures were corrected for the atmospheric pressure at the time of test.

Boiling point results ranged from 110°C to 112°C as shown below in Table 2. These results are as expected for a new coolant. All boiling point results met repeatability.

Table 2. Baseline Chemical Properties of Candidates

Sample ID #	Glycol Content[†] (%)	pH*	Relative Density* (at 15.6 °C)	Freeze Point* (°F)	Boiling Point[†] (°C)
FL-18023-20 (HOAT)	60.0	10.46	1.0898	< -50	112.4
FL-18024-20 (OAT)	60.0	8.67	1.0856	< -50	110.6
FL-18030-20 (Conventional)	60.4	10.67	1.0853	< -50	112.8
FL-18031-20 (HOAT)	60.4	8.20	1.0884	< -50	111.3
FL-18071-20 (NOAT)	60.0	8.38	1.0830	< -50	111.2
FL-18072-20 (OAT)	60.0	8.81	1.0879	< -50	110.9

*denotes single runs; [†]denotes duplicate runs

After all testing in Table 2 was completed, it was concluded that all candidates passed the initial baseline testing. This meant that all selected candidates showed no initial red flags or reasons to be thrown out of the candidate pool. None of this testing provided any significant differences in the performance of each candidate, or major performance differences between extended-life coolant technology types, which was to be expected for commercial coolants. Even though this data was not a discriminator in the downselection process, it was important to confirm all candidates met the basic property requirements and establish a baseline that could be expanded on with additional testing.

Density at Various Temperatures and Concentrations

In addition to testing the relative density of all coolant candidates at 15.6°C, the density of each coolant candidate at 3 different concentrations (60%, 50%, and 100% by volume) and 3 different temperatures (15.6°C, 20.0°C, and 25.0°C) was determined IAW ASTM D5931-20. The data was then plotted to see how density changes with the varying temperatures. The trend lines produced were then used to calculate the density of each candidate at any temperature within 15.6°C and 25.0°C. The calculated density value was then used to calculate the specific heat of each candidate shown below in Table 6.

Table 3 and Figure 5 below show the results of each candidate at a glycol concentration of 60%, Table 4 and Figure 6 below show the results of each candidate at a glycol concentration of 50%, and Table 5 and Figure 7 below show the results of each candidate at a glycol concentration of 100% (concentrate). All results met repeatability of the method (0.0002 g/mL)

Density values decreased as temperatures increased, which was expected. FL-18071-20 consistently had the lowest density values at all 3 concentrations. FL-18023-20 had the highest density values at 60/40 and 50/50 concentrations. One overarching trend that was seen is that the HOAT and OAT candidates had slightly higher densities than the NOAT and Conventional candidates, but this is not a significant finding in terms of impact on coolant performance.

Table 3. Density of 60/40 Glycol/Water at Various Temperatures (g/mL)

Sample Temp (°C)	FL-18023-20 (HOAT)	FL-18024-20 (OAT)	FL-18030-20 (Conventional)	FL-18031-20 (HOAT)	FL-18071-20 (NOAT)	FL-18072-20 (OAT)
15.6*	1.0887	1.0845	1.0842	1.0873	1.0819	1.0868
20.0	1.0863	1.0821	1.0816	1.0848	1.0793	1.0844
25.0	1.0832	1.0791	1.0786	1.0818	1.0763	1.0813

*density values taken at 15.6°C were single runs; all others (including those in Tables 4 & 5 are duplicate runs)

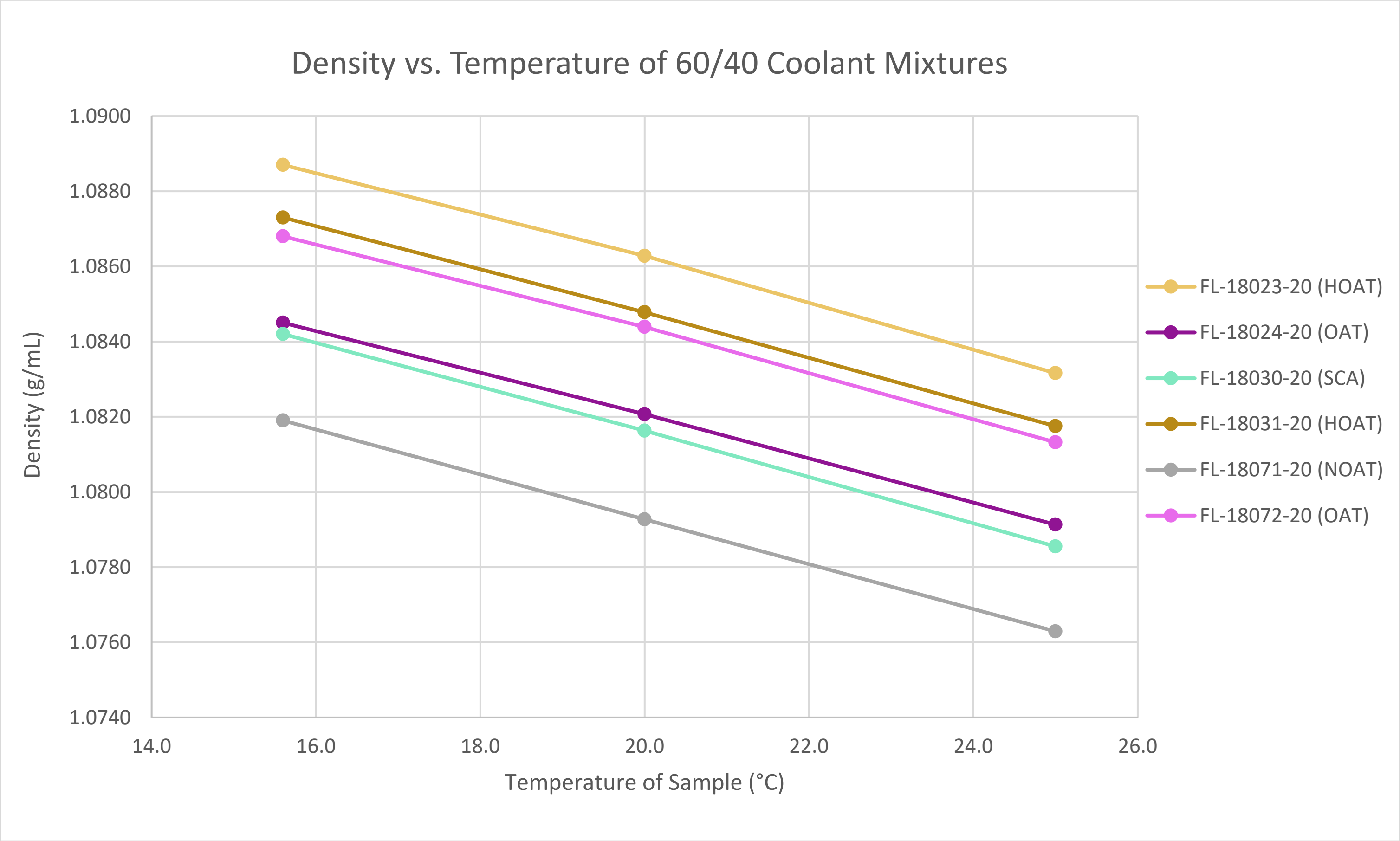

Figure 5. Density vs. Temperature for 60/40 Coolant Mixtures

Table 4. Density of 50/50 Glycol/Water at Various Temperatures (g/mL)						
Sample Temp (°C)	**FL-18023-20 (HOAT)**	**FL-18024-20 (OAT)**	**FL-18030-20 (Conventional)**	**FL-18031-20 (HOAT)**	**FL-18071-20 (NOAT)**	**FL-18072-20 (OAT)**
15.6	1.0752	1.0728	1.07219	1.0741	1.0705	1.0748
20.0	1.0727	1.0705	1.06972	1.0717	1.0680	1.0724
25.0	1.0700	1.0677	1.06689	1.0689	1.0652	1.0696

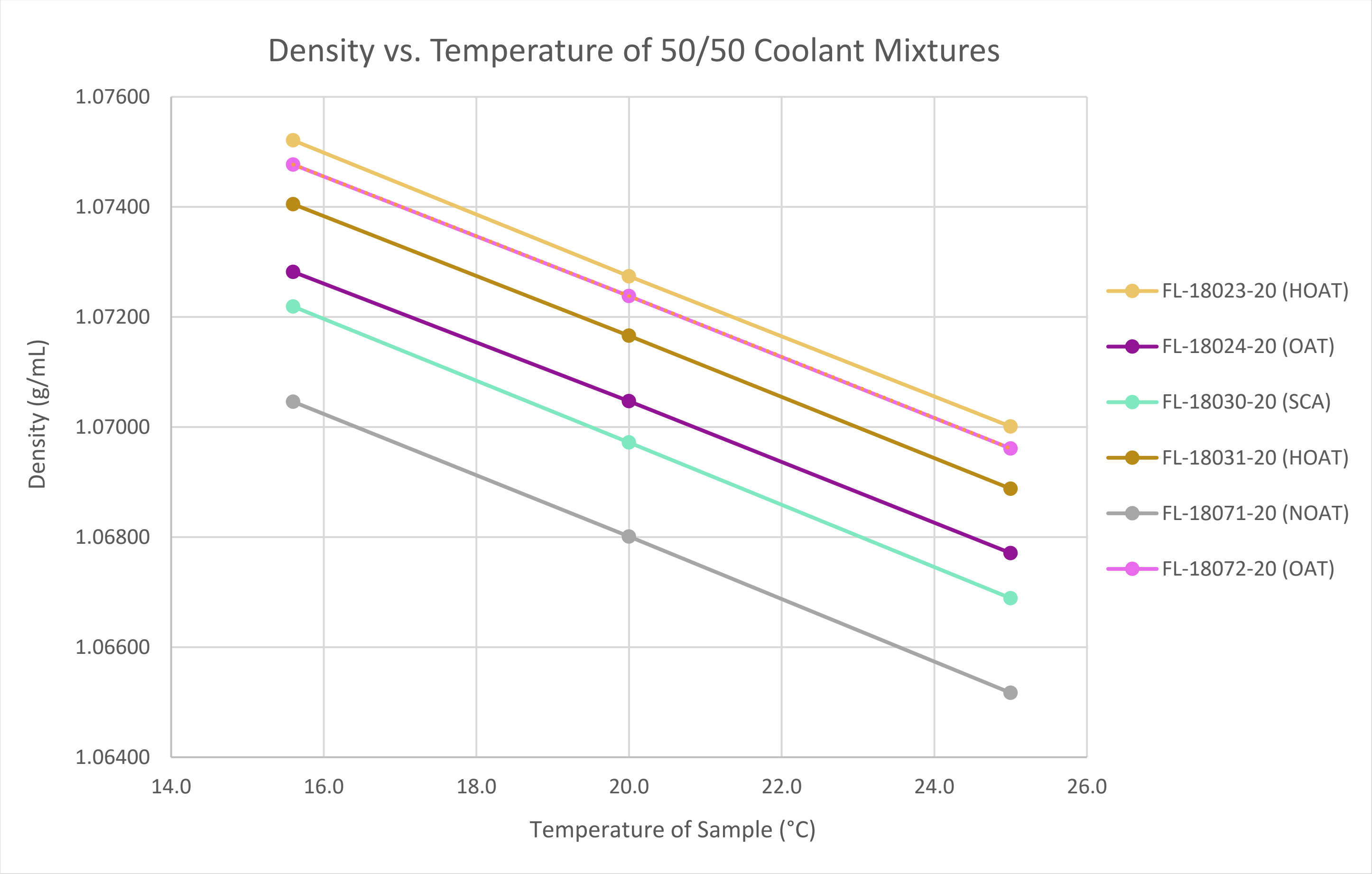

Figure 6. Density vs. Temperature of 50/50 Coolant Mixtures

Table 5. Density of Concentrate Coolant at Various Temperatures (g/mL)

Sample Temp (°C)	FL-18023-20 (HOAT)	FL-18024-20 (OAT)	FL-18030-20 (Conventional)	FL-18031-20 (HOAT)	FL-18071-20 (NOAT)	FL-18072-20 (OAT)
15.6	1.1287	1.1344	1.1205	1.1284	1.1182	1.1330
20.0	1.1256	1.1313	1.1175	1.1254	1.1152	1.1300
25.0	1.1222	1.1279	1.1140	1.1220	1.1118	1.1266

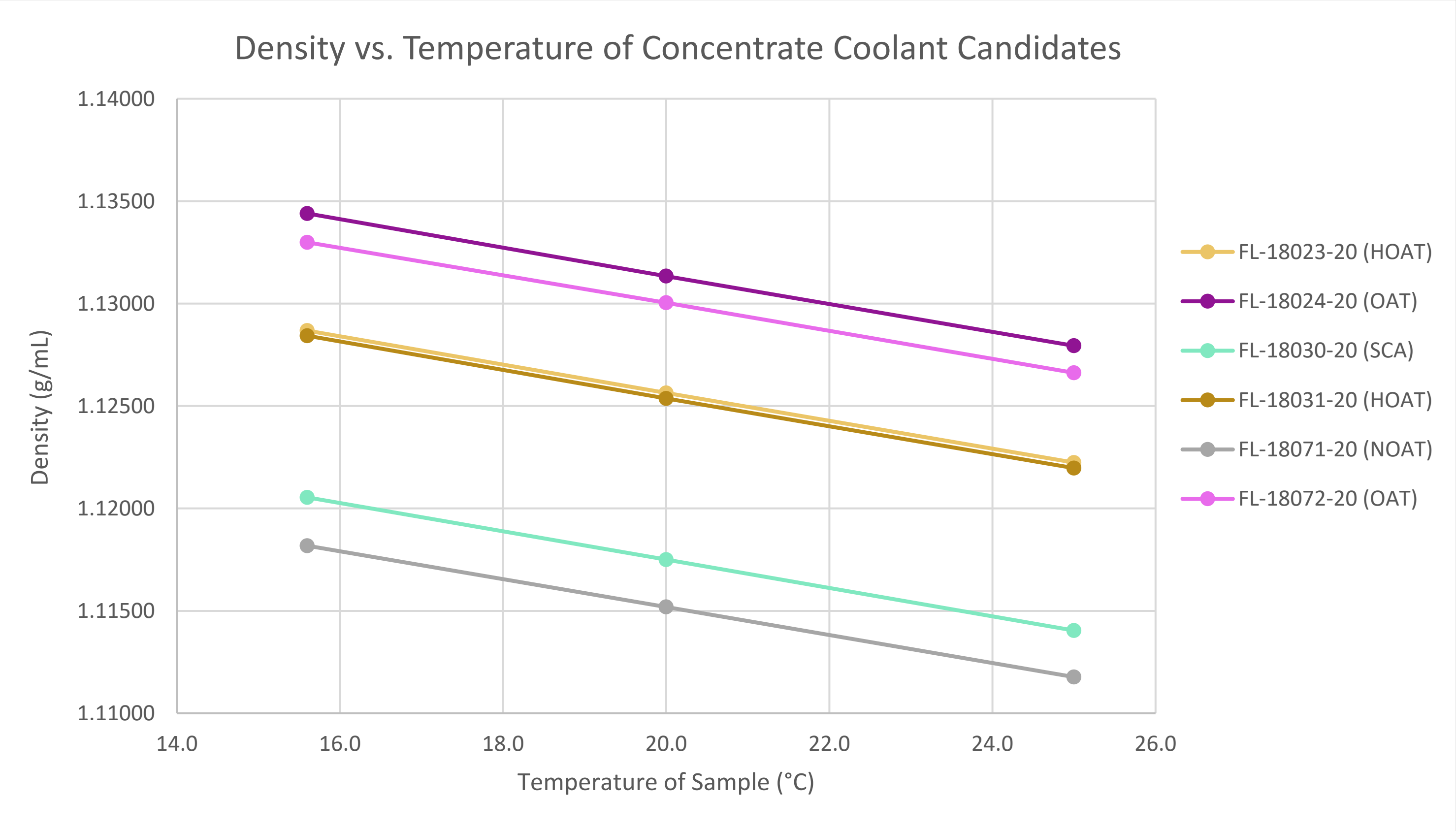

Figure 7. Density vs. Temperature of Concentrate Coolant

Thermal Conductivity and Specific Heat

The thermal conductivity for each candidate was measured at room temperature using a C-Therm TCi Thermal Conductivity Analyzer in the Tribology Laboratory at GVSC. Each candidate was measured in triplicate, with each run consisting of 10 data points taken over ~11 minutes. Averages of each run were calculated and the thermal conductivity values for each candidate at 3 concentrations are shown below in Table 6. A plot showing how the thermal conductivity changes with glycol % can be seen below in Figure 8. The candidates behaved as expected.

Since water has better thermal conductivity (TC) than glycol, the more water present, the higher the TC value. This can be seen when comparing the 50/50 to 60/40 glycol/water TC values. In general, normal TC values for a 50/50 EG coolant are around 0.4 W/mK. Since all candidates are EG based, and the only differences are the additives used, which comprise a small fraction of the overall coolant formulation, it was not expected to see a major difference in TC values between candidates. For coolants, the base fluid drives the TC value more than the additives used, which is in agreement with the data. In summary, there was no significant difference in the thermal conductivity values between candidates, but the two OAT candidates did have the highest (ie. better) TC values at 50/50 and 60/40 when compared against the HOATs, NOAT, and Conventional candidate.

Using the plots shown above in Figures 5-7 to estimate density values, the measured thermal conductivity values (k), and the measured effusivity values (E), the specific heat (c) was able to be calculated for each candidate. The equation used for specific heat was derived from the equation for effusivity:

$$E = \sqrt{k\rho c}$$

$$c = \frac{E^2}{k\rho}$$

Where E = effusivity (Ws½/m²K), ρ = density (kg/m^3), and k = thermal conductivity (W/mK)

Table 6. Thermal Conductivity* and Specific Heat of Candidates						
Sample ID #	**Thermal Conductivity at 50/50 (W/mK)**	**Thermal Conductivity at 60/40 (W/mK)**	**Thermal Conductivity at 100/0 (W/mK)**	**Specific Heat at 100/0 (J/Kg*K)**	**Specific Heat at 50/50 (J/Kg*K)**	**Specific Heat at 60/40 (J/Kg*K)**
FL-18023-20 (HOAT)	0.4130	0.3959	0.2914	1936	2805	2672
FL-18024-20 (OAT)	0.4383	0.4061	0.2792	1844	2960	2742
FL-18030-20 (Conventional)	0.4212	0.3892	0.2861	1915	2862	2642
FL-18031-20 (HOAT)	0.4287	0.3961	0.2862	1900	2899	2676
FL-18071-20 (NOAT)	0.4261	0.3937	0.2848	1910	2895	2674
FL-18072-20 (OAT)	0.4312	0.4031	0.2836	1876	2913	2719

*average of triplicate runs

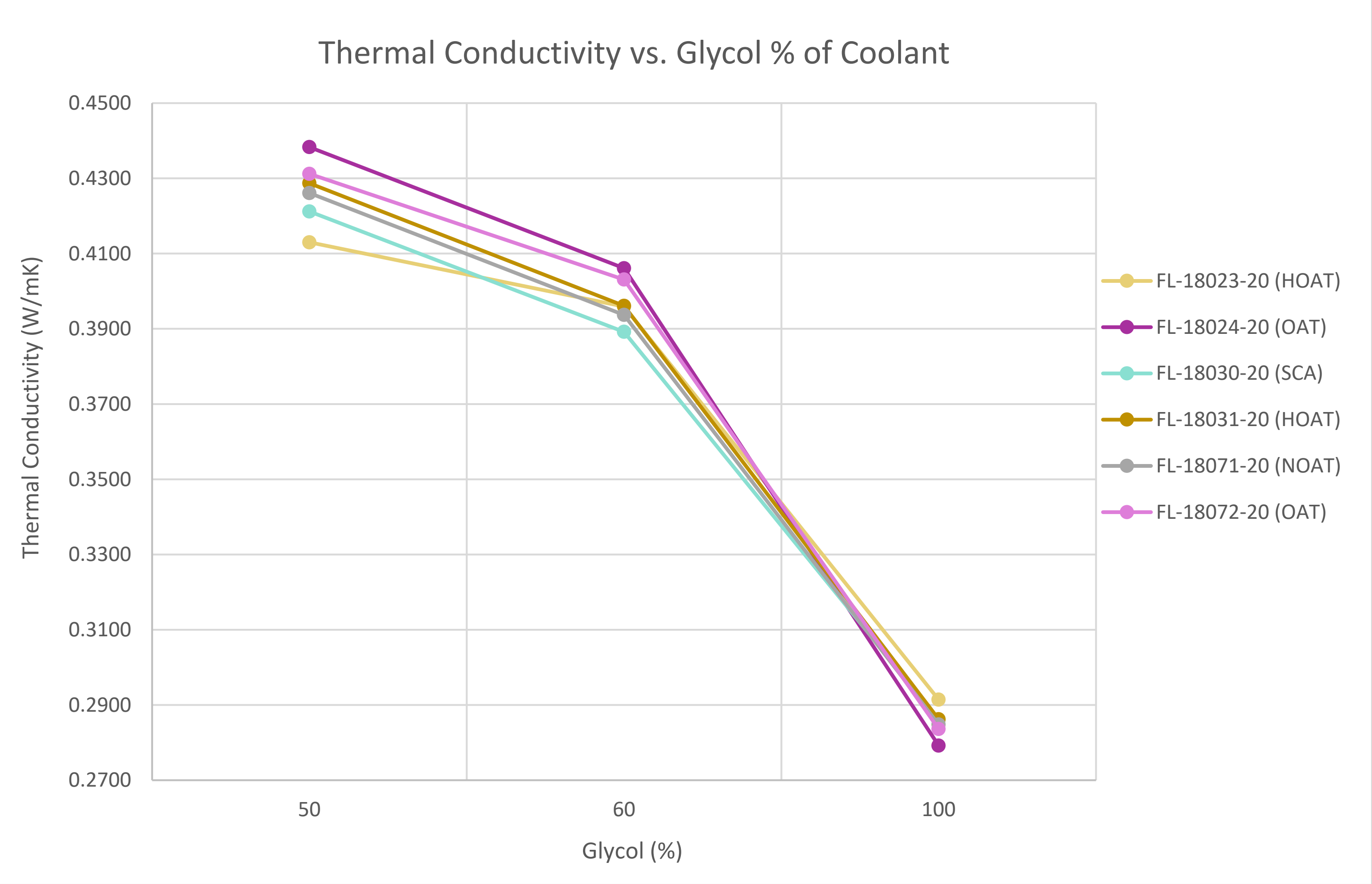

Figure 8. Thermal Conductivity vs. Glycol % for Each Candidate Coolant

Coolant Test Strips

Five different brands of coolant test strips were evaluated on all five (5) ELC candidates and the one (1) conventional candidate in this study. All candidates were tested at 60% glycol concentration and in new condition (ie. not used). The expected results were for the strips to detect passing levels for each property, such as glycol level, pH, and the applicable additives.

There were two goals to this effort: 1) Determine how effective the coolant strips were at detecting what they claim to detect and 2) Ascertain if each brand of test strip could be used on each type of coolant; thereby proving that there was a test strip that could be used “universally” on ELC coolants. A “universal” coolant test strip would be convenient for field maintenance once ELC is part of the Army supply chain.

Unfortunately, while testing was attempted, it was inconclusive. None of the 5 test strip brands were able to be used “universally”. This means that none of the 5 were able to accurately detect the additives and/or glycol concentration on all 6 candidates. In general, when the test strip that matched its coolant counterpart were used together, it could accurately detect what the strip was designed to look for, except in the case of FL-18031-20 and FL-18071-20. This makes sense as the manufacturer designs the strips specifically for their own coolant. But when using a brand of test strip on a differing brand of coolant, which has different additives, the strips tended to fail. The best case was for FL-18024-20, where 3 out of 5 test strips were able to pass. The failures occurred because in many cases, even though a test strip would yield a “passing” value, **due to the unique instructions for each strip, it would actually be analyzed by the user as a failure**. For example, on the test strip designed for FL-18072-20, the instructions state that a pH of 10 is considered failing, but the actual pH on FL-18072-20 should be 10, so even though the coolant is “ok”, the user would believe it to fail and likely initiate an unnecessary flush and fill of the coolant.

There was no candidate were all 5 test strips passed. For full data on the test strip study, see Appendix B.

Due to the military’s unique process of using a qualified products database, which is comprised of many different brands of products, it is not feasible to select just one coolant test strip because there is no guarantee that the matching brand of coolant would be what is procured and could cause false failures in the field.

Heat-Transfer Coefficient Determination via Heat Exchanger

The Fuels and Lubricants Laboratory utilized an Armfield FT74X-G tubular heat exchanger pasteurization unit with the intention of comparing calculated heat transfer coefficients of six (6) candidate coolants when subjected to the same conditions. The attached chiller unit (FT63-G) was repurposed as a reservoir for each candidate coolant at 40/60 coolant/water dilution. Ideally, candidates should have been tested at 60% coolant, but the manufacturer stated that the chiller unit could not handle concentration levels over 40% as the higher viscosity would burn out the motor. The heat exchanger unit was set at 3 temperatures to mimic typical engine operating temperatures: 90°C, 100°C, and 110°C. Results of the calculated heat transfer coefficients at each temperature for each candidate is shown below in Figure 8 and Table 7.

Results were inconclusive. While it was a success to set up this new capability in the FLL, the overall heat-transfer coefficients were not different enough to discriminate between candidates. Additionally, it was not able to be proven that ELC's transfer heat more efficiently than conventional coolant. Under controlled laboratory conditions, the best improvement of heat-transfer coefficients when compared to the conventional coolant was an average of 2% improvement (FL-18072-20 (OAT); while a 2% improvement would be a boon for engine operation, it is unlikely to see that improvement under real vehicle/engine conditions. Additionally, under the testing performed the 2% improvement cannot be deemed statistically significant without further testing.

Further study could be warranted; to improve confidence in the data, the test should be run in duplicate or triplicate and also on a second heat exchanger. At the time of this report's writing, FLL does not have the capability to perform, nor is there enough sufficient justification at this time to pursue due to the relatively small performance improvement on one candidate; all others performed similarly to the conventional coolant. Similarly to the thermal conductivity of coolant, heat-transfer is largely driven by the base fluid, which is ethylene glycol for all candidates.

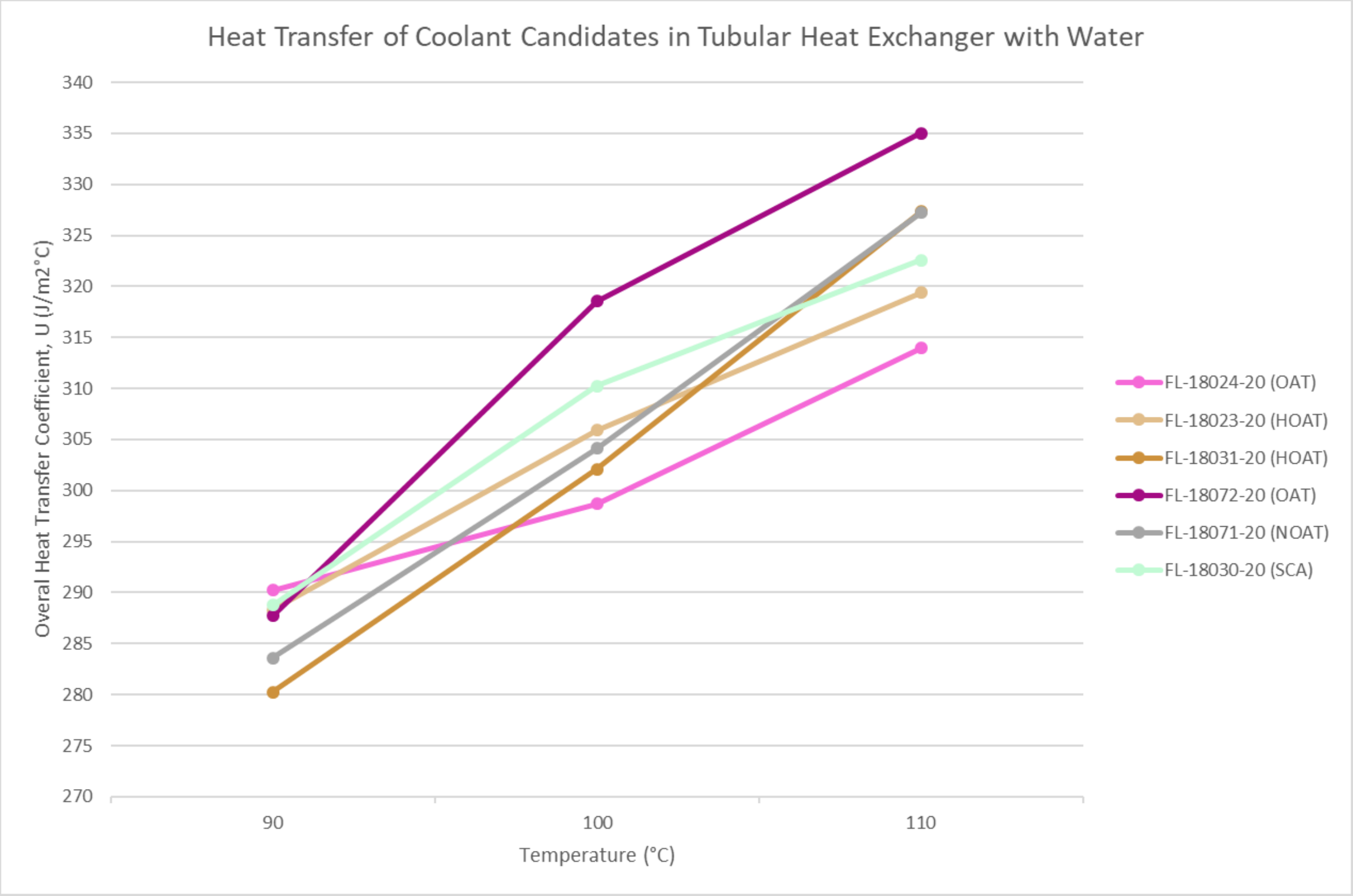

Figure 9. Heat Transfer Coefficients vs. Temperature for ELC and Conventional Candidates

Table 7. Heat Transfer Coefficients (U) of Candidates

Candidates	U (J/m2ºC)			% Improvement over FL-18030-20 (SCA)			
	90°C	100°C	110°C	90°C	100°C	110°C	**Avg**
FL-18030-20 (SCA)	289	310	323	N/A	N/A	N/A	**N/A**
FL-18024-20 (OAT)	290	299	314	0.5	-3.7	-2.7	**-2.0**
FL-18072-20 (OAT)	288	319	335	-0.4	2.7	3.9	**2.1**
FL-18071-20 (NOAT)	284	304	327	-1.8	-2.0	1.5	**-0.8**
FL-18031-20 (HOAT)	280	302	327	-2.9	-2.6	1.5	**-1.4**
FL-18023-20 (HOAT)	288	306	319	-0.2	-1.4	-1.0	**-0.8**

Phase IIb: – Laboratory Benchtop Testing: 3rd Party Testing (Army Lab at Southwest Research Institute)

The GVSC Fuels & Lubricants Research Facility (GFLRF) at Southwest Research Institute (hereafter “SwRI”) is a government-owned contractor-operated (GOCO) 3rd party test laboratory chosen to perform six standard benchtop tests on the same candidates for testing that were unable to be performed in-house by FLL. SwRI procured the commercial candidates themselves under the Work Directives (WDs), which means the candidates are from different lots than those tested in FLL in Phase IIa. However, since all candidates are commercial products, the potential for differences between lots was not a concern. The FLL candidate identification numbers and their corresponding SwRI identification numbers for both WDs are shown below in Table 8.

Additionally, SwRI performed a compatibility study based off of similar tests found in OEM coolant specifications. During compatibility testing, precipitates formed and six of these precipitates were further studied to better understand the results of the incompatibility study. All work was accomplished under Work Directive (WD) 002 of contract W56HZV-21-C-0077 during the period of February 2021 through August 2021. The tests they were asked to perform are found in the light-duty ASTM specification for engine coolant, D3306-20. However, not all tests in D3306-20 were included in WD 002 due to timing and funding restraints. It was not necessary to exhaust all performance testing until the candidate pool was reduced further.

Therefore, after WD 002 was completed and the data reviewed, the downselection process was completed. GVSC F&L Branch contracted for additional work to complete the remaining tests from ASTM D3306-20 not performed under WD 002. WD 006 was under the same contract and performed during August 2021 – December 2021. The performance tests included a simulated service and corrosion test that should prove the OAT formulas are satisfactory for military use.

It should be noted that all ASTM test methods were performed according to the method, with the exception of ASTM D1177-17 Freeze Point, in which the candidates were tested at a concentration of 60% glycol by volume instead of 50% glycol by volume.

Table 8. Candidate Identification Number Correlations Between FLL and SwRI

SwRI ID – WD 002	CL21-5664	CL21-5653	CL21-5655	CL21-5652	CL21-5654	CL21-5651
SwRI ID – WD 006	N/A	CL21-6188	N/A	N/A	N/A	CL21-6187
FLL ID	FL-18023-20	FL-18024-20	FL-18030-20	FL-18031-20	FL-18071-20	FL-18072-20
Type	HOAT	OAT	Conventional	HOAT	NOAT	OAT

The laboratory testing from WD 002 included the following protocols:

1. ASTM D1119-05(2015) – Standard Test Method for Percent Ash Content of Engine Coolants [14]
2. ASTM D1121-11(2020) – Standard Test Method for Reserve Alkalinity of Engine Coolants and Antirusts [15]
3. ASTM D1177-17 – Standard Test Method for Freezing Point of Aqueous Engine Coolants [16]
4. ASTM D1881-17 – Standard Test Method for Foaming Tendencies of Engine Coolants in Glassware Compatibility Study [17]
5. Extended Life Coolant Compatibility Study
    a. ASTM D1384-19 – Standard Test Method for Corrosion Test for Engine Coolants in Glassware [18]
    b. ASTM D4340-19 – Standard Test Method for Corrosion of Cast Aluminum Alloys in Engine Coolants Under Heat-Rejecting Conditions [19]
6. Post Compatibility Test ASTM D4340-19 Precipitate Characterization
    a. Energy Dispersive Spectroscopy (EDS)
    b. Fourier Transform Infrared (FTIR)
    c. Scanning Electron Microscope (SEM)

d. X-Ray Diffraction (XRD)

The laboratory testing from WD 006 included the following protocols:

1. ASTM D5827-09(2015) – Standard Test Method for Analysis of Engine Coolant for Chloride and Other Anions by Ion Chromatography [20]
2. ASTM D1123-99(2015) – Standard Test Methods for Water in Engine Coolant Concentrate by the Karl Fischer Reagent Method [21]
3. ASTM D1882-17(2021) – Standard Test Method for Effect of Cooling System Chemical Solutions on Organic Finishes for Automotive Vehicles [22]
4. ASTM D1384-19 – Standard Test Method for Corrosion Test for Engine Coolants in Glassware
5. ASTM D4340-19 – Standard Test Method for Corrosion of Cast Aluminum Alloys in Engine Coolants Under Heat-Rejecting Conditions
6. ASTM D2570-16 – Standard Test Method for Simulated Service Corrosion Testing of Engine Coolants [23]
7. ASTM D2809-09(2017) – Standard Test Method for Cavitation Corrosion and Erosion-Corrosion Characteristics of Aluminum Pumps with Engine Coolants [24]

WD 002 Results

ASTM D1177-17 Freeze Point

This test method determines the freezing point of engine coolants and was performed with one deviation from ASTM D3306-20 requirements: the candidate coolants were diluted to 60/40 glycol/water by volume mixture as opposed to 50/50. This is because the Army currently recommends using a 60/40 dilution of engine coolant when operating in arctic conditions. This dilution provides better freezing protection and lowers the freezing point of the coolant. Test was performed IAW ASTM D1177 with the exception of the dilution. All candidates had passing results, shown below in Table 9. Although GVSC already performed a freeze point test (Table 1), ASTM D1177-17 is more precise and a true benchtop test, whereas GVSC used a refractometer which provided a field level assessment for freeze point protection. The refractometer provided the same result for all candidates (< -50°F) since the refractometer cannot read below -50°F. All of SwRI's results (Table 9) agree with GVSC's since all values were indeed less than -50°F.

ASTM D1881-17 Foaming Tendencies

This test method is a "glassware test for evaluating the tendency of engine coolants to foam under laboratory-controlled conditions" [17]. This test was performed IAW ASTM D1881-17 with no deviations to the method. All candidates met the requirements of ASTM D3306-20, which are shown below in Table 9.

ASTM D1121-11(2020) Alkalinity

This test method determines the reserve alkalinity of an engine coolant. Measuring reserve alkalinity (RA) was a way to determine how well a coolant could handle acid contamination. However, due to new coolant technologies the method is considered antiquated and not a good indicator of coolant performance. The test was performed IAW ASTM D1121-11(2020). Results need only be reported, per ASTM D3306-20. All reported results are below in Table 9.

ASTM D1119-05(2015) Ash Content

Ash content for each candidate was determined IAW ASTM D1119-05(2015). All results met the ASTM D3306-20 requirements, well below the 5 wt% max. See Table 9 below for results.

Table 9. Third Party Benchtop Chemical Properties of Candidates

Sample ID #	Freeze Point (°C)	Foam (mL/s)	Alkalinity (mL/ 0.1 N HCl)	Ash Content (wt. %)
ASTM D3306 Spec Req	*N/A**	*150 max/5 max*	*Report*	*5 (max)*
CL21-5664 (HOAT)	<-53.8	47/1.16	16.4	2.195
CL21-5653 (OAT)	<-51.1	57/1.46	10.7	2.615
CL21-5655 (Conventional)	<-51.1	38/1.07	6.0	0.400
CL21-5652 (HOAT)	-52.8	37/0.60	16.9	1.565
CL21-5654 (NOAT)	-51.9	48/1.27	4.1	1.040
CL21-5651 (OAT)	<-52.7	40/0.81	9.4	2.485

*ASTM D3306-20 does not use a 60/40 by volume dilution

Extended-Life Coolant Compatibility Study

A compatibility study between all ELC candidates was designed to determine the interactions between different coolant formulations, additives, and metals found in the cooling system including aluminum. All candidates were mixed with each other at 3 ratios (30%/70%, 50%/50%, and 70%/30%), resulting in 30 unique blended coolant samples. The blended samples were then subjected to ASTM D1384 and ASTM D4340 test methods. The test candidate blending ratios and tests chosen to be performed on all blends was inspired by compatibility testing found in existing commercial coolant (OEM) specifications. Key results to look at are the **formation of any solids/precipitates** and the **heat-corrosion rate** on ASTM D4340. Seventeen of the blends produced a large, white precipitate post-test.

Detailed results from the compatibility study are shown in Appendix A, Tables 14-23. Table 13 in Appendix A details the SwRI IDs, the corresponding FLL IDs, and the alphabetical IDs. The alphabetical letters in the tables (shown beneath the percentages) are a way to identify the blends for the purposes of graphing the data in Figure 10. Charted data for the heat-corrosion rates, highlighting the blends that formed precipitates, are shown below in Figure 10.

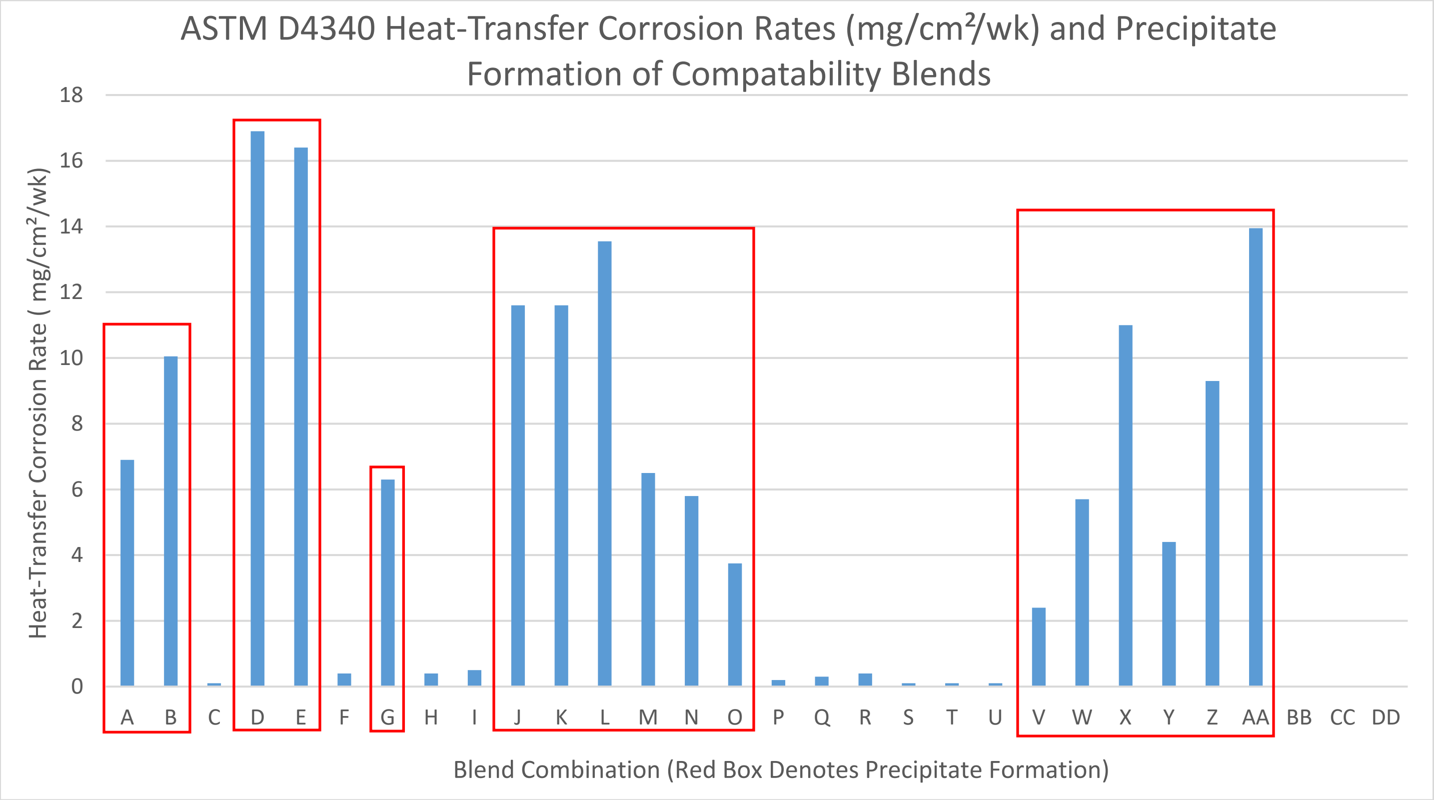

Figure 10. Heat-Transfer Corrosion Rates of D4340-19 Compatibility Blends. Red box indicates that white precipitates were formed post D4340 testing. The corresponding SwRI and FLL codes for the alphabetical letters can be found in Appendix A.

In Figure 10 above, the red boxes indicate which of the blends produced large, white, jelly-fish like precipitates post-test. It is notable to point out that all the blends that produced precipitates also significantly failed the allowed heat-transfer corrosion rate (the specification requirement in ASTM D3306-20 is less than 1 mg/cm^2/week).

Three of the blend combinations produced no precipitates at any of the three ratios. These blend combinations were as follows:

P-Q-R	OAT/OAT
S-T-U	OAT/NOAT
BB-CC-DD	OAT/NOAT

The blend combinations that produced significant precipitates were as follows:

A-B	30%/70% and 50%/50% HOAT/OAT
D-E	30%/70% and 50%/50% HOAT/HOAT
G	30%/70% HOAT/OAT
J-K-L	HOAT/NOAT
M-N-O	OAT/HOAT
V-W-X	HOAT/OAT
Y-Z-AA	HOAT/NOAT

All candidates containing IAT formed precipitates at some level of blend with all other candidates. While it was interesting that the NOAT candidate was able to blend well with both OAT candidates and produce no precipitates, the more important metric used in the down selection process was how the two OAT candidates behaved. Since the OAT/OAT combination across all blend levels (PQR) produced no precipitates and had low levels of heat-transfer corrosion rates, accidental mixing of OATs in the field was determined to pose the least risk to the vehicles. Precipitates are of large concern due to their ability to clog radiator passageways which can lead to engines overheating. GVSC wants to minimize this risk by choosing coolants that do not form precipitates and pass common compatibility tests when blended with each other at all ratios. For this reason, the two OAT candidates were downselected for the next phase of testing, which is elaborated on below in Phase III and IV.

ASTM D1384-19 results for the compatibility study blends met specification requirements and were not note-worthy or able to be used for downselection purposes since there was no differentiating results. This was to be expected as ASTM D1384-19 is largely used as a screening tool to identify poorly performing coolants, not differentiate performance between adequate coolants.

Post Test ASTM D4340-19 Precipitate Characterization

Due to the unusual precipitates that formed under the D4340-19 Compatibility Study, SwRI recommended that the precipitates undergo a characterization panel. This characterization consisted of Energy Dispersive Spectroscopy (EDS), Fourier Transform Infrared (FTIR), Scanning Electron Microscope (SEM), and X-Ray Diffraction (XRD). SwRI also photographed each sample/precipitate solution, four of which are depicted below in Figure 11. See DTIC accession number AD1159599 (Title: FIR 497 - Enhanced Performance Coolants (EPC) Benchtop Testing) for full characterization results, a summary of which will be shown below.

Figure 11. White Precipitates Formed Post- ASTM D4340 on ELC Blends

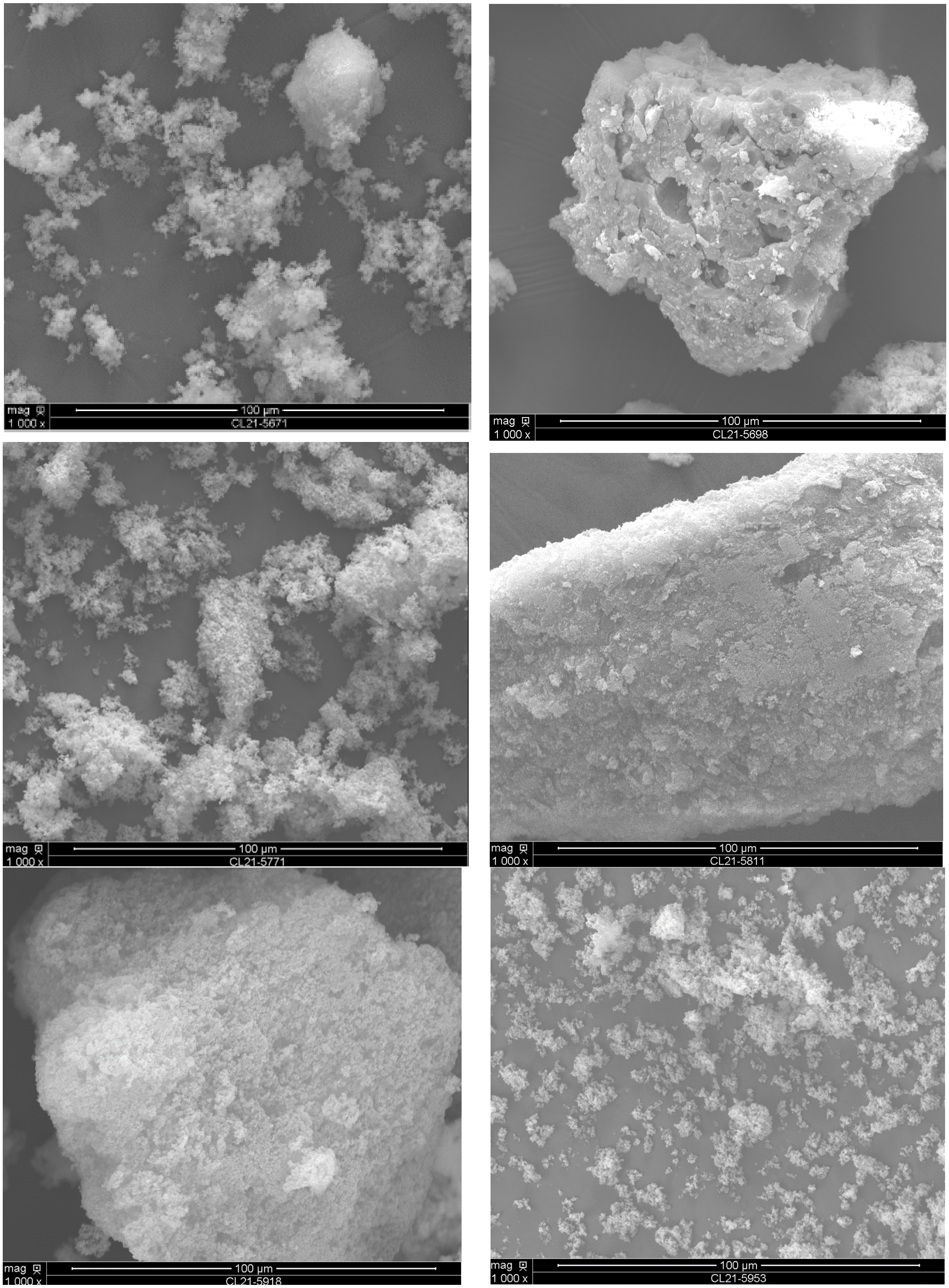

Figure 12. SEM Results at 100µm for each of the 6 precipitates analyzed

From the EDS results, the most notable element found in the precipitates was Aluminum. None of the candidates contained aluminum as an additive. A likely reason for the increased presence of Al is that coolant incompatibility led to corrosion of aluminum components as evidenced by the high heat-transfer corrosion rates. Concentrations ranging between 40-75 wt %, with the two highest wt % concentrations coming from mixtures of HOATs and OATs.

FTIR and XRD results were inconclusive. These tests were not able to identify specific additives that may have dropped out and formed the precipitates.

WD 006 Results – Two Downselected OAT Candidates

ASTM D5827-09(2015) Anions by Ion Chromatography

The following anions were analyzed for in the two OAT candidates IAW ASTM D5827-09(2015): Chloride, Nitrite, Nitrate, Phosphate, and Sulfate. The only anion that has a requirement in ASTM D3306-20 is Chloride, which cannot exceed 25 mg/kg. Both candidates were well under this requirement and had very similar anion results, shown below in Table 10. Results are averages of duplicate runs. As expected, Nitrites, Phosphates, or Sulfates were below detectable limits; these anions would be expected to be present in a NOAT or HOAT coolant.

Table 10. ASTM D5827 Anions via Ion Chromatography (mg/kg)

Sample ID	**Chloride**	**Nitrite**	**Nitrate**	**Phosphate**	**Sulfate**
ASTM D3306 Spec Req	*25 max*	*N/A*	*N/A*	*N/A*	*N/A*
CL21-6187	<1	<1	1618	<1	<1
CL21-6188	10	<1	1801	<1	<1

ASTM D1123-99(2015) Water Content

The water content of each OAT candidate was determined IAW ASTM D1123-99(2015), Karl Fischer Reagent Method. The ASTM D3306-20 specification requirement is a maximum of 5 mass%, or 50,000 ppm. Both candidates were within this requirement.

ASTM D1882-17(2021) Effect on Organic Finishes

The effect of each OAT candidate on automotive paint finishes was determined IAW ASTM D1882-17(2021). There was no change in surface effect for either candidate, and this meets the ASTM D3306 requirement of “No effect”. This test was performed in duplicate with the same results for each run.

ASTM D1384-19 Glassware Corrosion

The effect of the two OAT candidates on metal test specimens was determined IAW ASTM D1384-19, which is a glassware corrosion test using metals typically found in engine cooling systems: copper, brass, solder, steel, cast iron, and aluminum. This test was performed in duplicate. Due to the large amount of data generated in this test, the detailed results and metal coupon photos will not be shown in this report but can be found in the WD 006 report from SwRI, found under DTIC #AD1167229. In summary, all weight changes in the metal coupons met and exceeded the ASTM D3306-20 specification requirements (10 ppm max for Copper, Steel, and Iron; 30 ppm max for Solder and Aluminum).

ASTM D4340-19 Corrosion of Cast Aluminum Alloys

ASTM D4340-19 is a screening test used to evaluate a coolant's ability to prevent corrosion of aluminum. This test method was run under WD 002 on all the ELC blends, but since it had not been run on the pure candidates, which is a requirement of ASTM D3306-20, it was decided to run ASTM D4340-19 on each OAT candidate individually as well. As expected, just like when the two candidates were blended together, each one alone produced passing heat-transfer corrosion rates (the highest result being 0.3 mg/cm^2/week) and no precipitates were formed. See all results in Table 11 below.

Table 11. ASTM D4340-19 Results on Downselected OAT Candidates

D4340-19 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	**Units**	**CL21-6187**	**CL21-6188**
Heat-Transfer Corrosion Rate	mg/cm^2/wk	0.3	0.0
Specimen Color	--	Black	Silver
Specimen Pitting	--	None	None
Used pH Solution	--	8.2	8.1
Used Solution Color	--	Red	Red
Used Solution Clarity	--	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm^2/wk	0.3	0.0
Specimen Color	--	Black	Silver
Specimen Pitting	--	None	None
Used pH Solution	--	8.1	8.1
Used Solution Color	--	Red	Red
Used Solution Clarity	--	Translucent	Translucent

ASTM D2570-16 Simulated Service Corrosion

ASTM D2570-16 Simulated Service Corrosion Testing of Engine Coolants was performed in duplicate on both OAT candidates. ASTM D2570-16 is another screening test, like ASTM D1384-19, but goes one step beyond ASTM D1384-19 by using automotive cooling system components (radiator, coolant pump, and hoses) to circulate the coolant in contact with metal test coupons (copper, brass, solder, steel, iron, and aluminum). It is still a screening test, however, and either an engine or field test should still be conducted to verify performance of the coolant.

Like ASTM D1384-19, the results are extensive, therefore refer to DTIC #AD1167229 for all results for ASTM D2570-16. In summary, both coolant candidates met the requirements of max weight loss on all of the metal coupons. The coolants also had the same visual appearance both before and after test (red in color and translucent). Lastly, no precipitates were formed in this testing.

ASTM D2809-09(2017) Cavitation Corrosion and Erosion-Corrosion

ASTM D2809-09(2017) Cavitation Corrosion and Erosion Corrosion was run in duplicate on both OAT candidates. See Table 12 below for results. The minimum rating for a coolant to pass is 8 on a scale of 0 to 10. This rating is a requirement in ASTM D3306-20.

CL21-6188 (correlating to FL-18024-20) had passing ratings of 9 for both runs. The other candidate, CL21-6187 (FL-18072-20), passed the first run with a rating of 8, but run 2 had a failing result of Rating 5. The failing value was surprising since the candidate is a current commercial fluid and had at some point in the past needed to pass this test in order to be salable. Discussions were had with SwRI, who were equally surprised to see this value for a commercially available coolant. It was unlikely that there was a quality issue with the test pump. Additionally, the candidate coolant sample was all taken from the same bottle, so there is no concern of samples coming from different lots. It remains unknown as to why one of the runs failed. One thing of note is that ASTM D2809-09(2017) is not normally run in duplicate per the method.

A third run was performed and the candidate received a passing rating of 8 in agreement with the first test. The second test was therefore considered an outlier.

Table 12. ASTM D2809-09(2017) Cavitation Corrosion Rating Results

Sample ID	Rating (Run 1)	Rating (Run 2)	Rating (Run 3)
CL21-6188	9	9	N/A
CL21-6187	8	5	8

Project Discussion and Conclusions

Phase III – Candidate Performance Analysis and OEM Knowledge Gathered

Once testing concluded at FLL and WD 002 concluded at SwRI, the data were gathered and analyzed in order to identify which of the candidates would be downselected for WD 006. The key test that had distinguishable results between candidates was ASTM D4340-19 performed during the ELC compatibility study. This test definitively ruled out some candidates that were clearly incompatible with each other due to the formation of large, white precipitates during the test and failing heat-transfer corrosion rates. The results of ASTM D4340-19 with the blends are important because this study was designed using existing coolant compatibility tests performed by OEMs, which can be found in their coolant specifications.

The only mixtures that produced no precipitates were the two OAT candidates when blended together, and the two OAT candidates when each were mixed with the one NOAT candidate. This could mean that OATs and NOATs are able to be mixed with less risk, however, reasons below will elaborate on why a NOAT is not recommended for Military applications.

GVSC contacted multiple OEMs to get their expert advice on what to look for in an extended-life coolant to be used across the Army fleet. The Army has unique considerations in that there are both light and heavy duty engines in the fleet, and the goal is to have one coolant for all vehicle engine types. This means that the chosen ELC type must be compatible with both light and heavy duty engines.

The OEMs that were contacted separately collectively agreed that the chosen coolant should not contain 2-Ethylhexanol (2-EH). 2-EH is used in coolants to give it a long life. However, 2-EH is very harmful to seals and gaskets over time. If the cooling system is not designed for using extended-life coolant, the gaskets could shrink and become brittle causing leaks. GVSC will ensure that 2-EH is not allowed in the future specification for ELC.

In regards to NOATs, majority of OEMs agree that nitrite is not suitable for use in aluminum engine components, which are found in light duty engines. Nitrite can be corrosive to the aluminum and is not recommended in order to avoid adverse reactions resulting in additive interactions, loss of corrosion protection, and precipitate formations. GVSC saw this exact issue of precipitate formations when NOATs were mixed with HOATs in the ASTM D4340 compatibility study.

The OEMs agreed that a Heavy-Duty Nitrite Free OAT extended-life coolant would be the best fit for light and heavy duty vehicles in the Army fleet.

Phase IV – Candidate Down Selection Prior to WD 006

Based on both OEM testimony, as well as the lack of precipitates formed in the ASTM D4340 Compatibility Study from WD 002, it was decided to move forward with the two OAT based coolants in WD 006: CL21-6187 (FL-18024-20) and CL21-6187 (FL-18072-20). Both of these candidates had the least amount of precipitates form when blended with other extended-life coolants, and when blended together they formed none. They also pose the least amount of risk for corroding aluminum engine components due to their lack of nitrites. Lastly, the lack of conventional additives in OAT coolant is another reason for their selection as the Army is trying to move away from conventional corrosion inhibitors which increases risk of incompatibility.

Next Steps

GVSC will look into which Army platforms are willing to utilize one of the OAT candidates in an ongoing field demonstration. This will provide confidence in the use of the chosen ELCs in Army ground equipment, allowing for an easier transition from conventional coolant to ELC, which is the ultimate goal of EPC. Additionally, the field demonstration will be the final piece of the EPC project before development of a draft military performance specification. This draft performance specification is the final deliverable of the EPC project.

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Appendix A. Detailed ASTM D4340 Results from Compatibility Study

Table 13. SwRI IDs and Corresponding FLL IDs for Compatibility Blends

SwRI ID	Corresponding FLL IDs	Type	Chart ID
CL21-5670	30% FL-18023-20 / 70% FL-18072-20	HOAT/OAT	**A**
CL21-5671	50% FL-18023-20 / 50% FL-18072-20		**B**
CL21-5672	70% FL-18023-20 / 30% FL-18072-20		**C**
CL21-5697	30% FL-18023-20 / 70% FL-18031-20	HOAT/HOAT	**D**
CL21-5698	50% FL-18023-20 / 50% FL-18031-20		**E**
CL21-5699	70% FL-18023-20 /30% FL-18031-20		**F**
CL21-5723	30% FL-18023-20 / 70% FL-18024-20	HOAT/OAT	**G**
CL21-5724	50% FL-18023-20 / 50% FL-18024-20		**H**
CL21-5725	70% FL-18023-20 / 30% FL-18024-20		**I**
CL21-5770	30% FL-18023-20 / 70% FL-18071-20	HOAT/NOAT	**J**
CL21-5771	50% FL-18023-20 / 50% FL-18071-20		**K**
CL21-5772	70% FL-18023-20 / 30% FL-18071-20		**L**
CL21-5809	30% FL-18072-20 / 70% FL-18031-20	OAT/HOAT	**M**
CL21-5810	50% FL-18072-20 / 50% FL-18031-20		**N**
CL21-5811	70% FL-18072-20 / 30% FL-18031-20		**O**
CL21-5868	30% FL-18072-20 / 70% FL-18024-20	OAT/OAT	**P**
CL21-5869	50% FL-18072-20 / 50% FL-18024-20		**Q**
CL21-5870	70% FL-18072-20 / 30% FL-18024-20		**R**
CL21-5890	30% FL-18072-20 / 70% FL-18071-20	OAT/NOAT	**S**
CL21-5891	50% FL-18072-20 / 50% FL-18071-20		**T**
CL21-5892	70% FL-18072-20 / 30% FL-18071-20		**U**
CL21-5916	30% FL-18031-20 / 70% FL-18024-20	HOAT/OAT	**V**
CL21-5917	50% FL-18031-20 / 50% FL-18024-20		**W**
CL21-5918	70& FL-18031-20 / 30% FL-18024-20		**X**
CL21-5953	30% FL-18031-20 / 70% FL-18071-20	HOAT/NOAT	**Y**
CL21-5954	50% FL-18031-20 / 50% FL-18071-20		**Z**
CL21-5955	70& FL-18031-20 / 30% FL-18071-20		**AA**
CL21-6024	30% FL-18024-20 / 70% FL-18071-20	OAT/NOAT	**BB**
CL21-6025	50% FL-18024-20 / 50% FL-18071-20		**CC**
CL21-6026	70% FL-18024-20 / 30% FL-18071-20		**DD**

Table 14. D4340 Results of A-B-C

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (A)	50%/50% (B)	70%/30% (C)
Heat-Transfer Corrosion Rate	mg/cm²/wk	6.8	9.8	0.1
Specimen Color	--	Dark grey	Black	Silver
Specimen Pitting	--	Fine	Fine	None
Used pH Solution	--	9.9	10.4	9.0
Used Solution Color	--	Off white	Off white	Purple
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	7.0	10.3	0.1
Specimen Color	--	Dark grey	Off white	Silver
Specimen Pitting	--	Fine	Fine	None
Used pH Solution	--	10.1	10.6	9.0
Used Solution Color	--	Off white	Off white	Purple
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample	--

Table 15. D4340 Results of D-E-F

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (D)	50%/50% (E)	70%/30% (F)
Heat-Transfer Corrosion Rate	mg/cm²/wk	14.1	16.5	0.4
Specimen Color	--	Black	Black	Silver
Specimen Pitting	--	Medium	Medium	None
Used pH Solution	--	10.1	10.2	8.9
Used Solution Color	--	Light green	Light green	Green
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	19.7	16.3	0.4
Specimen Color	--	Black	Blaeck	Silver
Specimen Pitting	--	Medium	Medium	None
Used pH Solution	--	9.8	10.4	9.0
Used Solution Color	--	Light green	Light green	Green
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample	--

Table 16. D4340 Results of G-H-I				
D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	**Units**	**30%/70% (G)**	**50%/50% (H)**	**70%/30% (I)**
Heat-Transfer Corrosion Rate	mg/cm²/wk	6.2	0.4	0.5
Specimen Color	--	Grey	Black	Black
Specimen Pitting	--	Medium	None	None
Used pH Solution	--	9.6	8.9	8.9
Used Solution Color	--	Pink	Dark Purple	Dark Purple
Used Solution Clarity	--	Translucent	Translucent	Opaque
Heat-Transfer Corrosion Rate	mg/cm²/wk	6.4	0.4	0.5
Specimen Color	--	Grey	Black	Grey
Specimen Pitting	--	Medium	None	None
Used pH Solution	--	9.4	8.9	8.9
Used Solution Color	--	Pink	Dark Purple	Dark Purple
Used Solution Clarity	--	Translucent	Translucent	Opaque
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	--	--

Table 17. D4340 Results of J-K-L				
D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	**Units**	**30%/70% (J)**	**50%/50% (K)**	**70%/30% (L)**
Heat-Transfer Corrosion Rate	mg/cm²/wk	10.6	11.5	13.0
Specimen Color	--	Black	Grey	Black
Specimen Pitting	--	Heavy	Heavy	Heavy
Used pH Solution	--	10.0	10.4	10.9
Used Solution Color	--	Pink	Pink	Blue
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	12.6	191.7	14.1
Specimen Color	--	Black	Grey	Black
Specimen Pitting	--	Heavy	Heavy	Heavy
Used pH Solution	--	10.0	10.4	10.8
Used Solution Color	--	Pink	Pink	Blue
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample

Table 18. D4340 Results of M-N-O

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (M)	50%/50% (N)	70%/30% (O)
Heat-Transfer Corrosion Rate	mg/cm²/wk	7.6	6.0	3.6
Specimen Color	--	Dark Grey	Grey	Black
Specimen Pitting	--	Medium	Medium	Medium
Used pH Solution	--	8.8	8.6	8.6
Used Solution Color	--	Yellow	Yellow	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	5.4	5.6	3.9
Specimen Color	--	Black	Grey	Black
Specimen Pitting	--	Medium	Medium	Medium
Used pH Solution	--	8.8	8.7	8.7
Used Solution Color	--	Yellow	Yellow	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample

Table 19. D4340 Results of P-Q-R

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (P)	50%/50% (Q)	70%/30% (R)
Heat-Transfer Corrosion Rate	mg/cm²/wk	0.2	0.3	0.4
Specimen Color	--	Grey	Grey	Grey
Specimen Pitting	--	None	None	None
Used pH Solution	--	8.3	8.4	8.4
Used Solution Color	--	Orange	Orange	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	0.2	0.3	0.4
Specimen Color	--	Grey	Grey	Grey
Specimen Pitting	--	None	None	None
Used pH Solution	--	8.2	8.4	8.4
Used Solution Color	--	Orange	Orange	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	--	--	--

Table 20. D4340 Results of S-T-U

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (S)	50%/50% (T)	70%/30% (U)
Heat-Transfer Corrosion Rate	mg/cm²/wk	0.1	0.1	0.1
Specimen Color	--	Grey	Grey	Grey
Specimen Pitting	--	None	None	None
Used pH Solution	--	8	8.1	8.2
Used Solution Color	--	Red	Red	Red
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	0.1	0.1	0.1
Specimen Color	--	Grey	Grey	Grey
Specimen Pitting	--	None	None	None
Used pH Solution	--	8	8.1	8.2
Used Solution Color	--	Red	Red	Red
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	--	--	--

Table 21. D4340 Results of V-W-X

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (V)	50%/50% (W)	70%/30% (X)
Heat-Transfer Corrosion Rate	mg/cm²/wk	2.3	5.9	11.7
Specimen Color	--	Black	Dark Grey	Grey
Specimen Pitting	--	Medium	Medium	Medium
Used pH Solution	--	8.4	8.4	8.5
Used Solution Color	--	Orange	Orange	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	2.5	5.5	10.3
Specimen Color	--	Black	Dark Grey	Grey
Specimen Pitting	--	Medium	Medium	Medium
Used pH Solution	--	8.5	8.4	8.5
Used Solution Color	--	Orange	Orange	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample

Table 22. D4340 Results of Y-Z-AA

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (Y)	50%/50% (Z)	70%/30% (AA)
Heat-Transfer Corrosion Rate	mg/cm²/wk	4.4	9.8	14.2
Specimen Color	--	Black	Black	Black
Specimen Pitting	--	Medium	Medium	Heavy
Used pH Solution	--	8.4	8.5	8.5
Used Solution Color	--	Orange	Orange	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	4.4	8.8	13.7
Specimen Color	--	Black	Black	Black
Specimen Pitting	--	Medium	Medium	Heavy
Used pH Solution	--	8.5	8.5	8.5
Used Solution Color	--	Orange	Orange	Orange
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample	White precipitates adhered to glassware and observed throughout sample

Table 23. D4340 Results of BB-CC-DD

D4340 Test Parameters (Top Half is Run 1 Bottom Half is Run 2)	Units	30%/70% (BB)	50%/50% (CC)	70%/30% (DD)
Heat-Transfer Corrosion Rate	mg/cm²/wk	0.0	0.0	0.0
Specimen Color	--	Silver	Silver	Silver
Specimen Pitting	--	None	None	None
Used pH Solution	--	7.6	7.9	8.0
Used Solution Color	--	Red	Red	Red
Used Solution Clarity	--	Translucent	Translucent	Translucent
Heat-Transfer Corrosion Rate	mg/cm²/wk	0.0	0.0	0.0
Specimen Color	--	Silver	Silver	Silver
Specimen Pitting	--	None	None	None
Used pH Solution	--	7.6	7.8	8.0
Used Solution Color	--	Red	Red	Red
Used Solution Clarity	--	Translucent	Translucent	Translucent
Test Notes (if applicable)	--	--	--	--

Appendix B. Coolant Test Strip Data

Red boxes denote the strip deemed the result a failure. Green boxes denote the strip deemed the result passing. All coolants were new and should have passed. The phrase “Strip for” below means “The strip intended for use on X candidate coolant”.

Table 24. Test Strip Data for FL-18023-20

	Strip for FL-18030-20 and FL-18023-20	Strip for FL-18072-20	Strip for FL-18071-20	Strip for FL-18024-20	Strip for FL-18031-20
Freeze Point/ Glycol %	60%	50%			50%
Nitrite	1600 ppm	Color change	color was not obviously one or the other		
Molybdate	600 ppm	300 ppm (color was darker than the 300 ppm box)			
Inhibitor Level Pass/Fail				Did not match any color	100
pH		10			10

What the data should have been: glycol: 60%, Nitrite & Moly: present in passing concentrations, pH: 10. Not that the pH value in column 3 generated a value of 10, which is correct, but a value of 10 on that specific strip is deemed a failure. The strip intended for use on this coolant worked as expected.

Table 25. Test Strip Data for FL-18024-20

	Strip for FL-18030-20 and FL-18023-20	Strip for FL-18072-20	Strip for FL-18071-20	Strip for FL-18024-20	Strip for FL-18031-20
Freeze Point/ Glycol %	60%	60%			Did not match any color
Nitrite	0 ppm	0 ppm	0 ppm		
Molybdate	150 ppm	300 ppm			
Inhibitor Level Pass/Fail				Pass	Did not match any color
pH		9			6

What the data should have been: pH: 9, Nitrite: none, Moly: present in passing concentrations, glycol: 60%. The strip intended for use on this coolant worked as expected.

Table 26. Test Strip Data for FL-18030-20

	Strip for FL-18030-20 and FL-18023-20	Strip for FL-18072-20	Strip for FL-18071-20	Strip for FL-18024-20	Strip for FL-18031-20
Freeze Point/ Glycol %	60%	60%			50%
Nitrite	1600 ppm	Color change	2000 ppm		
Molybdate	No color change	No color change			
Inhibitor Level Pass/Fail				Did not match any color	100
pH		10 or 11			8

What data should have been: Glycol: 60%, pH: 10-11, Nitrites present in passing concentrations, no molybdates. Note that in column 3, while no moly was detected, which is correct, that test strip deems it a failure. Additionally, in column 3, the pH value detected is correct, but that strip deemed it a failure. The strip intended for use on this coolant worked as expected.

Table 27. Test Strip Data for FL-18031-20

	Strip for FL-18030-20 and FL-18023-20	Strip for FL-18072-20	Strip for FL-18071-20	Strip for FL-18024-20	Strip for FL-18031-20
Freeze Point/ Glycol %	60%	Did not match any color			50%
Nitrite	0 ppm	0 ppm	0 ppm		
Molybdate	0 ppm	150 ppm			
Inhibitor Level Pass/Fail				Did not match any color	100
pH		8			8

What the data should have been: glycol 60%, inhibitor: pass, pH: 8, No nitrites, Moly present. Note in column 3 that while Moly was detected, it a failure on that strip because anything below 300ppm on that strip is deemed a failure. The strip intended for use on this coolant **did not** work as expected.

Table 28. Test Strip Data for FL-18071-20

	Strip for FL-18030-20 and FL-18023-20	Strip for FL-18072-20	Strip for FL-18071-20	Strip for FL-18024-20	Strip for FL-18031-20
Freeze Point/ Glycol %	60%	60%			50%
Nitrite	800 ppm	Color change	color was not obviously one or the other		
Molybdate	1200 ppm	300 ppm			
Inhibitor Level Pass/Fail				Pass	Did not match any color
pH		8 or 9			6

What data should have been: Glycol: 60%, Nitrites: present at passing concentrations, pH: 8. In column 2, although Nitrite and Moly are shown as present which is good, the values per the strip are deemed too high and therefore failed. Also note, the strip intended for use with this coolant (column 4) failed as well. The strip intended for use on this coolant **did not** work as expected.

Table 29. Test Strip Data for FL-18072-20

	Strip for FL-18030-20 and FL-18023-20	Strip for FL-18072-20	Strip for FL-18071-20	Strip for FL-18024-20	Strip for FL-18031-20
Freeze Point/ Glycol %	60%	60%			Did not match any color
Nitrite	0 ppm	0 ppm	0 ppm		
Molybdate	300 pm	300 ppm			
Inhibitor Level Pass/Fail				Fail	Did not match any color
pH		9			6

What data should have been: Glycol: 60%, Nitrite: none, Moly: present in passing concentrations, pH: 8-9. This particular sample and its test strip counterpart worked well together and passed as it should have, but no other strip worked on it. Note that in column 2, even though 300 ppm of Moly present is correct, that strip deemed it a failure.