THE POSSIBILITY OF USING COPPER CORROSION TESTS FOR LUBRICANTS USED WITH ELECTRIC VEHICLES

Introduction
Usefulness of Copper Corrosion Tests

Copper is an essential component of electric vehicles, commonly found within wiring, batteries, motors, and charging stations, due to its prevailing electrical conductivity, along with its longevity and malleability [1]. Electric vehicles can utilize upwards of 183 pounds of copper, with the majority, in pure electric vehicles, existing as a mile of copper wiring in its stator windings [2]. Copper is a commonly used material in electrical vehicles due to its affordability but comes with the cost of a high susceptibility to lubricant composition and temperature. The lubricant chosen for an electric vehicle must be tested, as a lubricant vulnerable to corrosion will cause the electrical resistance to increase and the eventual failure of the vehicle [1]. Corrosion occurs due to a reduction/oxidation reaction occurring in the metal, causing it to undergo physical changes that can lower the effectiveness of the material. Lubricants often contain sulfur to help protect gearing from wear through chemical reactions with the iron to form a sacrificial layer. A subsequent reaction between the copper components and the sulfur results in the creation of sulfides, which form sludge that inhibits the operation of copper-based electrical components [3]. The rate of corrosion is worse when in the presence of harsh conditions, such as extreme weather conditions.

The batteries found in electric vehicles typically feature copper, either within the cathode or as a solenoid conducting energy between power sources. Solenoids assist in oil flow and pressure by acting as hydraulic switches, controlling gear shifts along with club actuation within the transmission of motors. Solenoid valves have a small window of clearance, causing debris within fuels to be detrimental to the engine and the long-term life of the machine. Batteries that feature copper winding are highly susceptible to sulfur corrosion, as copper sulfide has the potential to connect the bridges between electrical phases which leads to a short circuit. Short circuiting of a battery causes sharp temperature increases which can cause electrical arcing and melting of pieces within the battery and motor it is attached to [4]. The lubricant choice for machinery, especially those with large amounts of copper, is essential to the longevity and functionality of mechanical components. Electric vehicles require copper corrosion testing to characterize and identify the proper lubricant to guarantee the vehicle will not have a drastic failure directly because of corrosion on copper parts.

Historically, ASTM test method D130 has used to assess the relative degree of corrosiveness of a petroleum product via a copper strip corrosion test. ASTM D130 has existed for over a century and continues to be relevant even with the decline of traditional petroleum-based fuels. According to the ASTM D130, the copper strip corrosion test functions by placing a strip of copper inside of a test tube, submerged in a lubricant or fuel of choice, which sits in a water bath kept at a constant temperature for the duration of the test. The specifics of the temperature and test duration depend on the fuel source, with ASTM D130 specifying the conditions for different fuels and lubricants [5]. Results are recorded according to the reading on the ASTM copper strip corrosion standard which allows for assessment of tarnish and corrosion of copper parts. Copper corrosion strip testing is long standing and trusted way to measure the corrosion of certain materials, but the test does have its limitations.

Copper parts are commonly utilized in a wide range of modern motors and machinery, typically requiring some form of lubricant to function properly. Without proper lubrication, copper components are susceptible to corrosion as seen in Figure 1. The copper corrosion test method outlined by the ASTM D130 test method covers most exposed copper parts. The Wire Corrosion Test [6] or the Solenoid Test [7] are specific methods intended for wires and solenoids in electrical vehicles. These parts are typically found in electric engines and batteries.

Figure 1: Corroded Copper Wires [8]

Alternative Test Methods and Their Benefits

Copper corrosion when measured strictly in accordance with the ASTM D130 test method neglects to include the time dependency of the corrosion or a clear application to real world corrosion. Alternative test methods, such as the wire corrosion test or the Solenoid test, allow for a more defined result when combined with the standard test method. A comparison of the three tests is shown in Figure 2.

The Wire Corrosion test involves a thin copper wire suspended in a lubricant and test lubricant vapor, with a direct current of 1 mA applied, while the test is held at a constant temperature [7]. The test measures the corrosion of both the test lubricant vapor and the test lubricant solution, which allows for a greater range of testing and allows for all states of lubricant that appear within a standard motor vehicle to be tested for. Within a motor vehicle,

	Strip Test (D130)	Solenoid Test	Wire Test
Material	Copper strip	Actual hardware	Wire (metal alloy)
Data Collection	Evaluate at end of test	Evaluate at end of test	Real-time data collection
Analysis	Qualitative (color rating)	Qualitative (visual)	Quantitative

Figure 2: Copper Corrosion Test Method Comparison Chart [7]

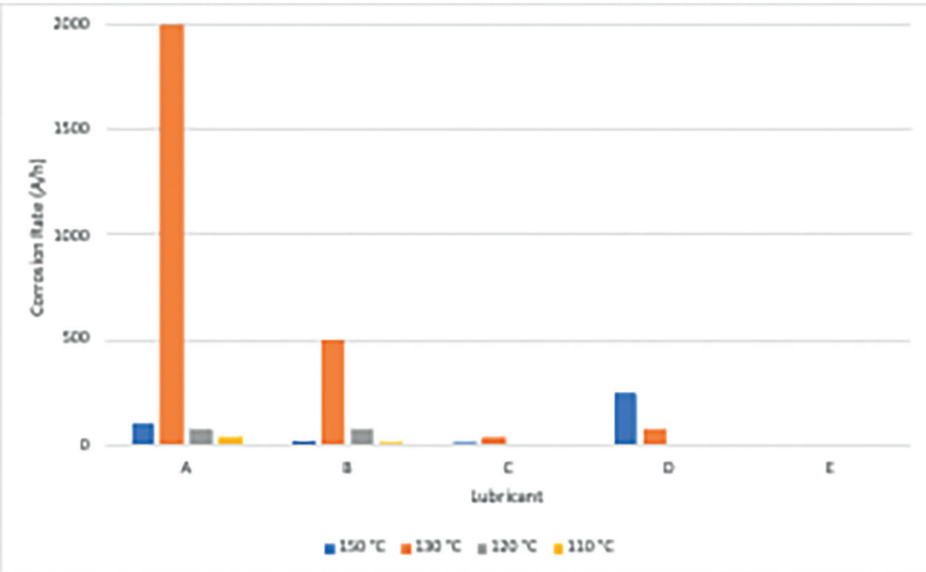

Figure 3: Vapor Phase Corrosion Rates of Select Transmission Lubricants [10]

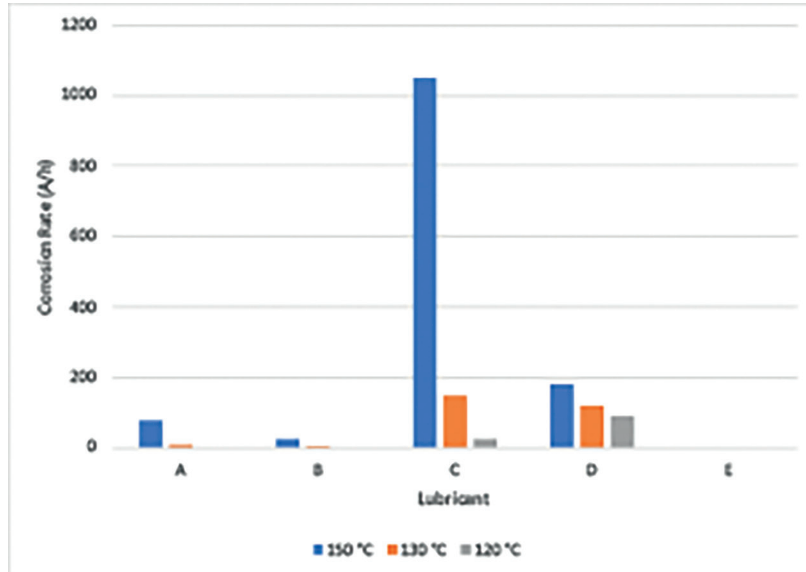

Figure 4: Solution Phase Corrosion Rates of Select Transmission Lubricants [10]

there are parts of the engine in which vapor lubricant will be acting directly upon copper as opposed to solution lubricant. The Wire Corrosion test allows for both options to be considered and tested simultaneously.

In order to factor in resistivity changes, Ohm's Law can be applied to normalize the data allowing for accurate corrosion comparisons for different temperatures. Ohm's Law as found by the equation:

$$R = \frac{\rho l}{\pi r^2} \qquad (1)$$

where R = resistance in Ω, ρ = resistivity of copper in Ωm, l = length of wire in meters, r = radius of the wire in meters.

Along with a modified specific heat equation for copper:

$$\rho_{CuT} = \rho_{Cu20} + \alpha \Delta T \rho_{Cu20} \qquad (2)$$

where ρ_{CuT} = resistivity of copper wire at a specific temperature, ρ_{Cu20} = resistivity of copper at 20℃, α = temperature coefficient per degree for the copper wire, ΔT= difference in temperature between the measured temperature and 20℃ [9]. These equations can be manipulated to calculate the length allowing for $R_{normalized}$ to be calculated based on a standard length of 1.01 meters.

$$l = \frac{R\pi r^2}{\rho_{CuT}} \qquad (3)$$

$$R_{normalized} = \left[\frac{1.01}{l} * R\right] \qquad (4)$$

Equations 3 and 4 show the connection between length and resistance for a standard length. Equation 4 allows for calculations of a normalized resistance through accounting for temperature changes and differences in the length of wire that may occur when collecting samples. The amount of copper that has been corroded can be calculated with alternative derivatives of the previous equations [9]. Equations 5 and 6 allow for the material lost to be found.

$$r_{normalized} = \sqrt{\frac{\rho_{CuT} 1.01}{\pi R_n}} \qquad (5)$$

$$\Delta r = \sqrt{(r_n - r_0)^2} \qquad (6)$$

The Wire Corrosion test typically occurs for an extended period leading into multiple days of consistent testing, which culminates in an extremely small standard deviation in results. The test yields consistent results while also measuring the corrosion resistance of differing lubricants.

In a study by Gregory Hunt and Christopher Prengaman from 2020, five commercially available lubricants used in hybrid and electric vehicles were tested via the Wire Corrosion method at four different temperatures, 110 ℃, 120 ℃, 130 ℃, and 150 ℃. The corrosion measured changed drastically depending on the temperature and whether the wire was submerged or within vapor [10]. As shown in Figure 3, Lubricant A in the vapor phase featured the highest amount of corrosion at 130℃, yet much less corrosion at any other temperature, even higher temperatures When examining the solution phase in Figure 4, however, Lubricant C had the most corrosion at 150℃. These results highlight the importance of performing simultaneous vapor and solution phase corrosion measurements. This alone makes the Wire Corrosion method an integral test to assist in determining corrosion boundaries within specific lubricants.

The Solenoid Test consists of a solenoid mounted to a holder and immersed in a test lubricant kept at a constant temperature for the duration of the test. The test functions in a similar manner to the standard ASTM D130 copper corrosion test, but features a larger amount of test lubricant used, a longer test period of 250 hours, and the solenoids are energized by a current driver at 1 Hz of frequency to circulate fluid through the solenoid. In the test referenced, from a different 2020 study, two copper containing components, a brass spacer and a brass bearing, are shown before and after testing within two lubricants at 120℃ and 150℃ [7]. Figure 5 shows the differences in the brass spacers, while Figure 6 shows the changes to the brass bearings. The test

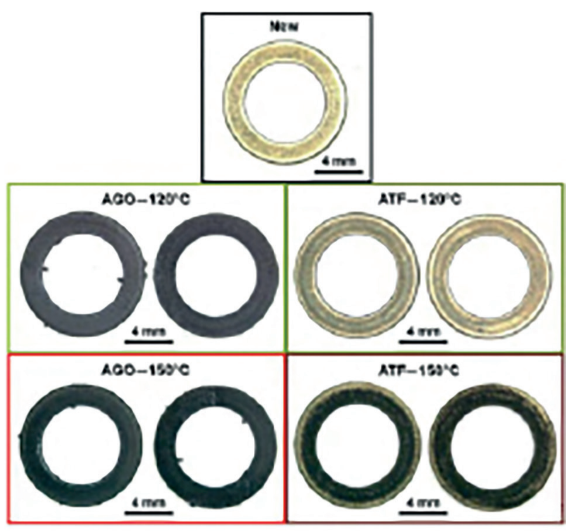

Figure 5: Brass Spacers at the end of the Solenoid test [7]

Figure 6: Brass Bearings at the end of the Solenoid test [7]

lubricants, AGO (automotive gear oil) and ATF (automatic transmission fluid), are commercial driveline lubricants which can be used in a variety of vehicles, including electric vehicles. The results of the solenoid test showed ATF at 120℃ to have the greatest resistance to corrosion, while at 150℃, ATF had much more significant corrosion. AGO had a significant amount of corrosion at both temperatures tested [7]. The Solenoid Test method can be repeated to wield similar and consistent results and allows for a moving part to be tested as if it was inside a motor, therefore allowing more accurate results.

Within all the mentioned test methods, a major factor is heat, as temperature can result in drastic differences within the results. A temperature difference of as little as ten degrees can cause detrimental effects to the copper and change the corrosion results from mild or no corrosion to extreme corrosion, calling for the repair or replacement of affected parts. Electric vehicles must operate within specified temperature range requirements to ensure their longevity and functional integrity. Temperature must be carefully regulated and tested by copper corrosion test methods to accurately predict corrosion due to lubricants.

Conclusion

Copper is a major component of motors, electric and gasoline, and copper corrosion can cause failures throughout the entire system. The copper corrosion test, either through the methods of the ASTM D130 test method, the Solenoid test, or the Wire Corrosion test, all give out successful results for the measurement of corrosion by differing lubricants.

All copper corrosion test methods have their own strengths and are chosen based on how the copper interacts with the vehicle's components. The wire test can have real-time data collection and is ideally used for machines that have copper wiring and circuits, while the Solenoid test is more commonly used to test electric vehicle engines and batteries, and the strip test is primarily used for garnering a general understanding of fuel corrosion over a specified system. A significant finding was that all three of the test methods showed that higher temperatures typically result in more severe cases of corrosion. The correlation of the temperature to copper corrosion indicates that operating temperature is an important variable to consider when selecting the proper lubricant for a specific application. The knowledge of the change of corrosion with varying temperatures of the same lubricant can lead to motors functioning significantly better and requiring much less maintenance. With the addition of a proper lubricant, corrosion is unlikely, allowing these motors to be able to function at full efficiency.

Citations

[1] Ahmed Abdalglil Mustafa, Waleed, et al. "A Review on Potentials and Challenges of Nanolubricants as Promising Lubricants for Electric Vehicles." Lubrication Science, vol. 34, no. 1, 2022, pp. 1–29, https://doi.org/10.1002/ls.1568..

[2] Copper Development Association Inc. (2017). How Copper Drives Electric Vehicles [Infographic]. Copper Alliance https://www.copper.org/publications/pub_list/pdf/A6192_ElectricVehicles-Infographic.pdf

[3] Protecting the electrics in electric vehicle transmissions. Lubrizol360.com. (2021, January 26). Retrieved from https://360.lubrizol.com/2021/Protecting-the-Electrics-in-EV-Transmissions

[4] Nyman, P., Björklund, P., "Importance of Copper Corrosion in

Wet eMotor Systems," Lube Media, June 2021

[5] ASTM D130-12, Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test, ASTM International, West Conshohocken, PA, 2018

[6] Electric vehicle lubricant and fluid testing. (n.d.). Retrieved from https://www.savantlab.com/applications/ev-lubricant-and-fluid-testing/#:~:text=Oxidation%20and%20the%20ensuing%20chemical,copper%20loss%20due%20to%20corrosion.

[7] Bares, J., Hunt, G., Prengaman, C., Wicks, J. et al., "Establishing Long-Term Corrosion Protection of Copper-Based Alloys in Modern Transmissions," SAE Int. J. Fuels Lubr. 13(3):251-264, 2020, doi:10.4271/04-13-03-0016

[8] Dieselfumes. (2017, August 6). How corrosive is Def Fluid, anyway? Sprinter Adventure Van. Retrieved from https://sprintervanusa.com/2017/08/16/how-corrosive-is-def-fluid-anyway/

[9] Hunt, G., "New Perspectives on the Temperature Dependence of Lubricant Additives on copper corrosion," SAE Int. J. Fuels Lubr. 10(2):2017, doi:10.4271/2017-02-0891

[10] Hunt, G. and Prengaman, C., "Understanding Vapor and Solution Phase Corrosion of Lubricants Used in Electrified Transmissions," SAE Technical Paper 2020-01-0561, doi:10.4271/2020-01-0561

About the authors

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, where he has worked for the last 27 years. He is an elected Fellow by his peers at IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at https://bit.ly/3u2e6GY He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology), Auburn Univ (Tribology) and Stony Brook University (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical engineering, Raj also has over 475 publications and has been active in the petroleum industry for over 3 decades

Anthony Schevon is a student of Chemical Engineering at SUNY Stony Brook University, where Dr. Raj Shah is the chair of the external advisory board of directors. Anthony is also part of a thriving internship program at Koehler Instrument Company. Anthony is the founder of the newly established SBU Energy Club at Stony Brook University.

Thoren Giannuzzi is a student of Chemical Engineering at SUNY Stony Brook University, where Dr. Raj Shah is the chair of the external advisory board of directors. Thoren is also part of a thriving internship program at Koehler Instrument Company.

Tom Malinski is a PAO Research Chemist at Chevron Phillips Chemical. Tom received his B.S. in Chemistry from Bloomsburg University in 2014, and his Ph.D in Chemistry from Texas A&M University in 2020. In his current role, Tom oversees R&D and technical support for the Chevron Phillips Chemical PAO business. He has authored eight academic papers, holds multiple patents, and is an active member of STLE and the American Chemical Society.


Anthony Schevon


Thoren Giannuzzi


Tom Malinski

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com

Read, Print, Share or **Comment** on this Article at: **petro-online.com/Article**