

Electrical Conductivity of New and Used Automatic Transmission Fluids

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ABSTRACT

Hybrid drivetrain hardware combines an electric motor and a transmission, gear box, or hydraulic unit. With many hybrid electric vehicle (HEV) hardware designs the transmission fluid is in contact with the electric motor. Some OEMs and tier suppliers have concerns about the electrical properties of automatic transmission fluids (ATFs). Lubrizol has conducted a fundamental research project to better understand the electrical conductivity of ATFs. In this paper, we will present conductivity data as a function of temperature for a range of commercially available ATFs. All fluids had conductivities ranging from 0.9 to 8×10^{-9} S/cm at 100 °C and can be considered insulators with the ability to dissipate static charge. Next we will deconstruct one ATF to show the relative impact of the various classes of lubricant additives. We find that more polar additives have a larger effect on conductivity on a normalized (per weight %) basis. Finally, we will show conductivity data for ATFs taken from field trial vehicles and present data to demonstrate that the increase in conductivity is due to oil oxidation and a reduction in viscosity, not the presence of metallic wear particles or dissolved metals.

CITATION: McFadden, C., Hughes, K., Raser, L., and Newcomb, T., "Electrical Conductivity of New and Used Automatic Transmission Fluids," *SAE Int. J. Fuels Lubr.* 9(3):2016, doi:10.4271/2016-01-2205.

1. INTRODUCTION

Hybrid drivetrain hardware combines an electric motor and a transmission, gear box, or hydraulic unit. With many hybrid electric vehicle (HEV) hardware designs the transmission fluid is in contact with the electric motor.

Representatives of some OEMs and tier suppliers have expressed concerns about the electrical properties of automatic transmission fluids (ATFs) - specifically, that the ATF may be sufficiently conductive to short circuit the electric motor. The implication was that the conductivity of the oil should be as low as possible in order to ensure transmission reliability. This concern was echoed in a recent paper on lubricants for hybrid electric vehicles [1], whose authors recommended an arbitrary upper limit for new oil conductivity.

However, the strategy to pursue the lowest possible conductivity does not consider the potential for oils with insufficient conductivity to allow static buildup and discharge, which can lead to equipment damage and increase the rate of oil degradation [2, 3, 4, 5].

In principle, there are two concerns regarding electrical conductivity of ATFs and other lubricants. The conductivity should be low enough so that the lubricant is a good electrical insulator, but also high enough so that it can dissipate static charge. In practice, the difficult task is to determine the range of acceptable conductivities for a particular application and hardware configuration. How high is too high? How low is too low?

We have also heard concerns about to what extent the accumulation of metal increases ATF conductivity and whether this could also to lead to a short circuit of the motor.

Though concern over ATF conductivity may seem new in light of the introduction of HEVs and EVs into the marketplace, these characteristics have been considered before when electronics were introduced into automatic transmissions [6]. Though the authors stated that the electrical conductivity is important in light of increasing use of electrical components, they did not offer guidelines. The absence of electrical characteristics as part of ATF specifications for the following 25 plus years suggests that while understanding the value is important, in practice this characteristic is not problematic.

These conversations have prompted us to conduct a fundamental research project to better understand the electrical conductivity of ATFs. In this paper, we will present data that address the following questions.

- What is the electrical conductivity of commercial ATFs, and how much variation is there?
- Which ATF components have the largest effect on conductivity?
- How does conductivity change in use?
- What are the effects of oil aging, metallic wear debris and dissolved metals?

Electrical conductivity is proportional to the number density and mobility of charge carriers. The mobility of charge carriers is determined primarily by their charge, size, and the viscosity of the fluid.

In principle, charge carriers can be formed by the separation of ion pairs (i.e., ionic compounds or salts) or by the dissociation of neutral molecules. However, the specific chemical species that form the charge carriers in nonpolar fluids is not so simple. In their comprehensive review, Dukhin and Parlia state “There is no answer yet as to what molecules break-up and create the initial separated charges that are being solvated with non-ionic surfactants. It's not even clear if this question can be answered at all. Very small amounts of impurities, on the scale of ppb (10E-9), either in the solvent or in the surfactant would provide a potential source of ions causing conductivity to be on the scale of 10E-8 S/m” [7].

While the identity of the charge carriers in nonpolar fluids is generally not known, it is generally agreed upon that the number of charge carriers is a very small fraction of the total number of ionic or neutral species from which they originate [8,9]. Thus, even parts per billion (ppb) levels of contamination could account for the experimentally measured conductivities.

The presence of chemical species that are able to form ions is only one requirement. The ions, once generated, must be prevented from immediately recombining due to electrostatic attraction. They must be solvated, i.e., surrounded by solvent molecules with sufficient dipole moments to screen their electrostatic potential.

Solvation efficiency is a key difference between aqueous and non-aqueous fluids. Water molecules have very large dipole moments (water has a very high dielectric constant) and so solvation of ions is easily achieved in aqueous systems. In contrast, hydrocarbons in fuels and base oils have very small dipole moments (hydrocarbons have low dielectric constants) and the limited ability to solvate ions is a key factor limiting the number of charged species, and, therefore, the conductivity of these fluids [7].

In nonpolar fluids, inverse micelles are thought to play an important role in solvating charge carriers [10,11]. It is generally agreed that the charge carriers must be present in inverse micelles, surrounded by other polar molecules. The size of the charge carrier that determines the mobility is, therefore, that of the micelle. Measurements of mobility are not sufficient to determine the identity of the charge carriers.

The addition of additives to a hydrocarbon base oil, therefore, may increase conductivity in two ways. One is by increasing the number of species that can form charge carriers. The other is from the ability of the more polar additives to solvate ions more effectively than the base oil alone. This would increase the number of charge carriers even if none of the additives were able to form ions.

2. EXPERIMENTAL

Resistivity measurements were made using a Tettex Instruments™ 2830/2831 Precision Oil and Solid Dielectric Analyzer with 2903 Test Cell for Liquid Insulants. It offers the ability to analyze liquid samples from room temperature to 150 °C. The test cell is made of stainless steel and is a cylindrical capacitor with a shielded measuring electrode. Sample volume is approximately 40 ml.

Prior to each measurement, the test cell was dismantled, thoroughly cleaned with heptane and allowed to dry under nitrogen. For each sample, conductivity was measured after heating to 30, 100 and 145 °C (± 2 °C). When the sample reached temperature, the test cell was shorted for 60 s and then a potential of +500 V DC was applied for 60 s. The resistivity is calculated by multiplying the resultant current by the cell constant. Conductivity is the reciprocal of resistivity. Conductivities are given here in units of S/cm, which is equivalent to 1/ohm·cm. For a given oil, the series of three measurements takes approximately four hours.

3. RESULTS & DISCUSSION

3.1. Conductivity of New/Unused Fluids

3.1.1. Temperature Dependence

Example conductivity vs temperature data for an unused ATF, labeled as “ATF A” (a commercially available fluid with viscosity of 6 cSt at 100 °C) is presented in [Figure 1](#). Data is shown for four different batches of ATF A.

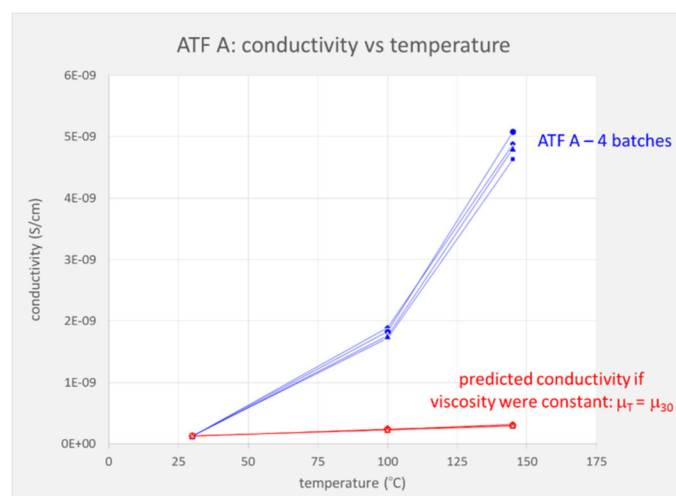


Figure 1. In blue is a plot of conductivity vs temperature for four batches of a commercially available ATF, “ATF A”. In red is the conductivity that would be predicted if viscosity were the same as at 30 °C, at all temperatures.

The four batches of ATF A were blended over a period of several years, and the conductivity measurements were made over a period of several months. The relative error for these measurements ranges from 3.2% at 30 °C to 6.6% at 145 °C.

This good repeatability runs counter to the commonly held idea that the repeatability of conductivity measurements is poor due to trace levels of contamination. It is possible that the reputation for poor repeatability comes from measurements of very lightly additized fluids with very low conductivity, and thus a very low number of charge carriers, such as fuels and transformer oils. One might consider the additives in an ATF (ranging from 5-30%) to be considerably more than trace contamination of the base oil, from the standpoint of conductivity.

The final point to be made about the data in [Figure 1](#) is the strong temperature dependence. The conductivity of ATF A increases approximately 40 times from 30 to 145 °C.

The conductivity of fluids, unlike that of metals, always increases with increasing temperature. In large part this is due to the decrease in viscosity and concomitant increase in the mobility of the charge carriers. In addition, an increase in temperature may also cause an increase in the number of ions in solution if ion formation and/or solvation were temperature dependent.

How much of the temperature dependence can be attributed to viscosity can be estimated by application of Walden's rule. Walden found empirically that the product of conductivity and viscosity is a constant for many fluids [12]. Walden's rule can be recovered by application of the Stokes-Einstein equation, which shows the constant to be related to the charge and size of the solvated ions [13].

[Figure 1](#) shows, in red, the conductivity of ATF A that would be predicted if dynamic viscosity were the same as at 30 °C, at all temperatures - i.e., if viscosity did not decrease with increasing temperature. This was calculated by the following equation, where κ is conductivity and μ is dynamic viscosity.

$$\kappa_{pred,T} = \kappa_T * \frac{\mu_T}{\mu_{30}}$$

It is apparent that most of the temperature dependence is due to viscosity. Using a similar approach, it has been found that the temperature variation of electrical conductivity in turbine oils could be attributed to viscosity changes with temperature, within experimental error [14].

However, even after accounting for the effect of viscosity, the conductivity is not constant with temperature - there is a small residual temperature dependence, increasing with temperature by approximately 2.5 times from 30 to 145 °C. The source of this non-viscosity-related temperature dependence is not known. It may be due to an increase in the number of ions in solution due to its effect on dissociation and ion solvation, as mentioned previously.

The conductivity vs temperature data in [Figure 1](#) can be linearized by making an Arrhenius-type plot of log (conductivity) vs 1/temperature. This is shown in [Figure 2](#). This plot has the practical utility of allowing interpolation to determine the conductivity at temperatures between 30 and 145 °C. Extrapolation should be performed with care, particularly to higher temperatures at which oil oxidation may be significant.

That the Arrhenius plot is linear suggests that the same mechanism of conductivity is in effect at the tested temperatures. All additized fluids tested, new and used, displayed Arrhenius behavior. The only fluid tested for this study that did not was unadditized base oil. This is further discussed with reference to [Figure 3](#).

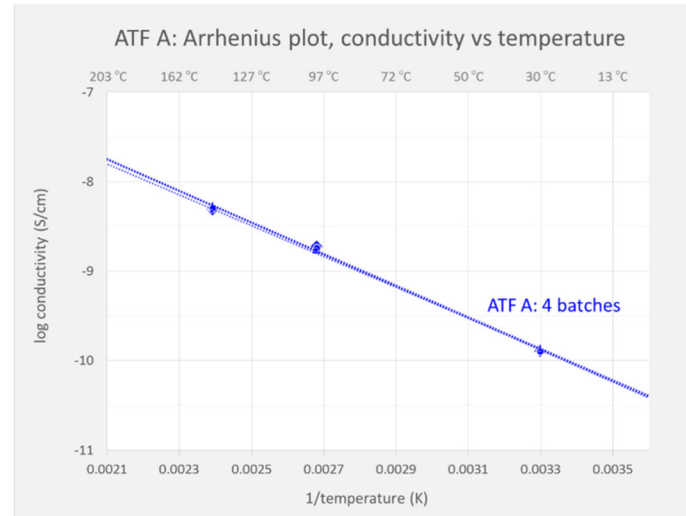


Figure 2. Plot of log conductivity vs 1/temperature for the data in [Figure 1](#). Dashed lines are linear fits to the data.

3.1.2. Effect of Additives

[Figure 3](#) is a plot of conductivity vs temperature for ATF A, the ATF A additive package, and the ATF A base oil. Note that conductivity is plotted on a logarithmic axis, to allow comparison of fluids with conductivities orders of magnitude apart. This data clearly shows the dominant effect of additives on conductivity. The conductivity of the ATF A additive package is 5-6 orders of magnitude greater than that of the base oil alone. This must be due to an increase in the number of charge carriers, because the change in viscosity is less than a factor of two. The effect of additive treat rate, and additive type, on conductivity will be discussed in more detail below.

Although the conductivity of ATF A is much higher than that of the base oil, it is an insulating fluid. The conductivity is 13 orders of magnitude lower than copper, and 7 orders of magnitude lower than sea water near room temperature [15].

One can calculate oil resistance for simple conductor geometries. For example, consider a 1 cm² section of exposed conductor immersed in ATF and separated from ground by 1 cm. The resistance is the oil resistivity (1/conductivity) multiplied by the separation and divided by the area. An oil with conductivity 1x10⁻⁹ S/cm at 100 °C would present a 1 GΩ resistance to ground. If driven by 500 V, this would result in 0.5 μA leakage current.

Low conductivity makes ATF A - and most or all ATFs, as will be shown in [Figure 4](#) - sufficiently insulating that concerns over shorting of electrical motors appear unfounded. However, if the conductivity of ATF A were too low, it would be less effective at dissipating static charge and could pose a risk for damage due to electrostatic discharge.

For example, the conductivity of the ATF A base oil at 30 °C is 4x10⁻¹⁵, more than an order of magnitude lower than the minimum specified for diesel fuels by ASTM D975 (2.5x10⁻¹³ S/cm) or aviation turbine fuels by ASTM D1655 (5x10⁻¹³ S/cm) or MIL-T-5624R (1.5x10⁻¹² S/cm)). These minimum specifications are intended to prevent electrostatic ignition of the fuel during fueling and transfer.