EVALUATING TAN DELTA AND TE OIL CONDITION SENSORS

1. Introduction

Oil Condition Monitoring (OCM) is a crucial element of any predictive maintenance schedule. OCM includes measuring, monitoring, and analysing changes in lubricant and fuel oils for contamination and chemical content, and tracking degradation in oil quality from new to end-of-life. This data provides insights into issues affecting performance and reliability and can form the basis of an effective maintenance programme.

Senquip has noted the interest in OCM and the potential for the technology to be transformative in the industrial and mining sector. Senquip has also however noted that the claims made by OEM sensor manufacturers have not always matched the end user experience in the field. Senquip, because of the flexibility of its telemetry devices, is in a unique position to be able to test the claims of OCM sensor manufacturers.

Senquip is working with Macquarrie Corporation and Westrac to independently test Tan Delta, TE, Poseidon, and Oil Advantage sensors in lab and field environments. This is the first of a series of Application Notes that details the results of tests performed independently by the team in a laboratory environment with steady state performance verified on a dynamometer.

This first Application Note tests Tan Delta and TE sensor ability to detect water, coolant, diesel, and iron contamination of oil. The results analysis is purposely kept simple because if the results are not obvious in a laboratory setting, then they are unlikely to be reliably useful in-field.

2. References

The following documents were used in compiling this Application Note.

Reference	Document Number	Document Description
A	OQSx-G2-Data-Sheet-Feb-20	Tan Delta OQSXG2-1-AA-02-5 Datasheet
B	Tan D Application-Note-2021-May	Implementing Tan Delta Oil Condition Monitoring
C	Tan D Interface Options 2.6 Gen 2	Interface Options
D	FPS2800 White Paper	Engine Oil Contamination Monitoring with FPS2800 Oil Property Sensor
E	FPC012_N Rev 1	TE FPS2800B12C4 Datasheet
F	FPC013 – FPS2800B12C4	Installation Guideline

3. Sensor Description

The following sensors were used in the tests described in this application-note:

Sensor	Manufacturer	Interface	Protocol	Update Rate	Measurement Type
OQSxG2-1-AA-02-5	Tan Delta	CAN 2.0B RS485 4-20mA	J1939 MODBUS	2 seconds	Tan Delta Number, Temperature

FPS2800B12C4	TE Connectivity	CAN 2.0B	J1939	30 seconds	Viscosity, Density, Dielectric, Temperature

Figure 1 - Tan Delta OQSX-G2

Figure 2 - TE Connectivity FPS2800B12C4

4. Test Setup

For the laboratory tests, the Tan Delta sensor was connected to the RS485 interface on a Senquip ORB and the TE sensor to the CAN interface on the same device. The sensors were suspended in a beaker of oil that was heated and stirred. Notes were taken as to when contaminants were added, and the Senquip ORB measured all of the measurement types available on each sensor.

Figure 3 – Laboratory Test Setup

All tests were performed with 15W40 oil with the specifications shown in Figure 4.

Mobil Special	15W-40
API Service Classification	SM
Specific Gravity	0.875
Pour Point, °C (°F)	-30(-22)
Flash Point, °C (°F), ASTM D 92	237(459)
Viscosity	
cSt at 40°C	108
cSt at 100°C	14.9
CCS, cP	5360@-20
MRV, cP	19800@-25
Viscosity Index	143
Resource Conserving	NO

Figure 4 - Mobil 15W40 Oil Specification

The Tan Delta sensor was configured for Mobil 15W40 oil. The TE sensor had default settings.

The Tan Delta sensor was read at 2 seconds intervals using the MODBUS settings on the Senquip ORB to extract Oil Condition, Tan Delta Number (TDN), and temperature. Viscosity, density, dielectric, and temperature were extracted from the TE sensor with a script running on the Senquip ORB.

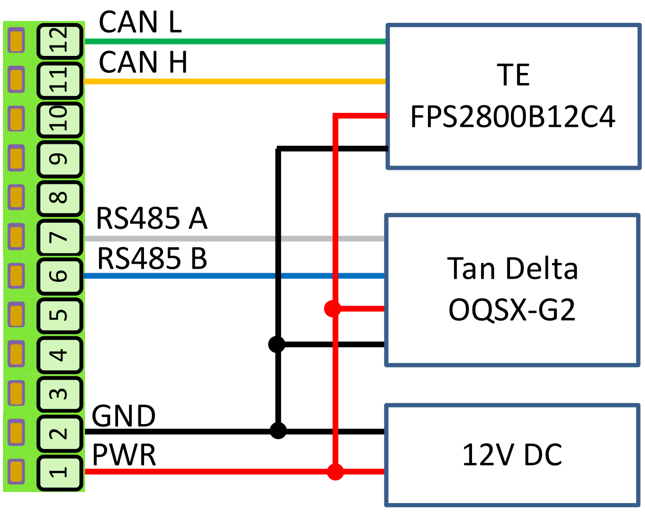

Figure 5 - Senquip ORB Wiring Description

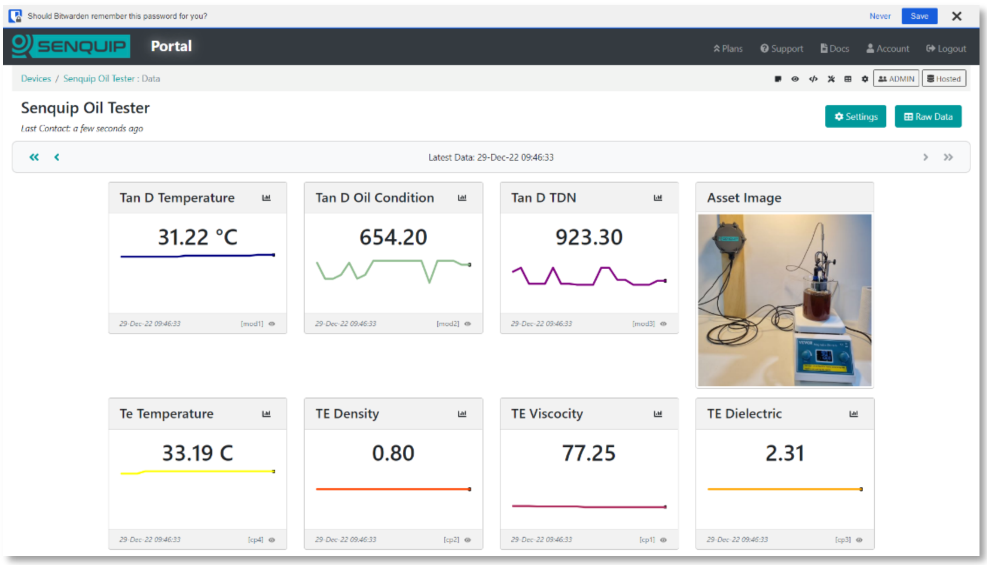

Figure 6 - Data Arriving on the Senquip Portal

For the dynamometer tests, the Tan Delta and TE sensors were mounted in a custom-made manifold through which the engine oil flowed. Additional sensors were mounted in the manifold and will be the subject of a later Application Note.

All tests on the dynamometer were performed with 15W40 oil.

Figure 7 - Sensor Manifold

Figure 8 - Dynamometer

5. Test 1 – Water in Oil Contamination

Water contamination comes from fuel combustion process or from failure of the exterior engine system. It can induce excessive wear for example by cavitation or corrosion. Water also promotes oil oxidation, acid by-products and sludge formation and thus poor engine reliability.

This test was to evaluate whether each sensor could detect water contamination in the oil sample. 700ml of oil was heated in a beaker from room temperature to 90°C and was kept at a stable temperature for the duration of the test. The oil was stirred continuously. The test procedure is shown in Table 1.

Table 1 - Test Procedure

Time	Notes	Water ppm	Water %
16h40	Temp up to 88.5 deg C	0	0.00
16h47	0.35ml water added	500	0.05

16h57	0.35ml water added	1000	0.10
17h03	0.525ml water added	1750	0.18
17h09	0.525ml water added	2500	0.25
17h14	0.875ml water added	3750	0.38
17h19	0.875ml water added	5000	0.50
17h24	1.166ml water added	6666	0.67
17h29	1.166ml water added	8331	0.83
17h34	1.166ml water added	9997	1.00
17h39	3.5ml water added	14997	1.50
17h42	End Test		

During the period where the oil was being heated, the Tan Delta measurements remained largely stable. Although the graphed elements in Figure 9 do show change as the oil heats, the y-axis are magnifying the effect and it should be noted that the Oil Condition will drop to zero and the TDN will reach 130 in later tests and so the effect is small.

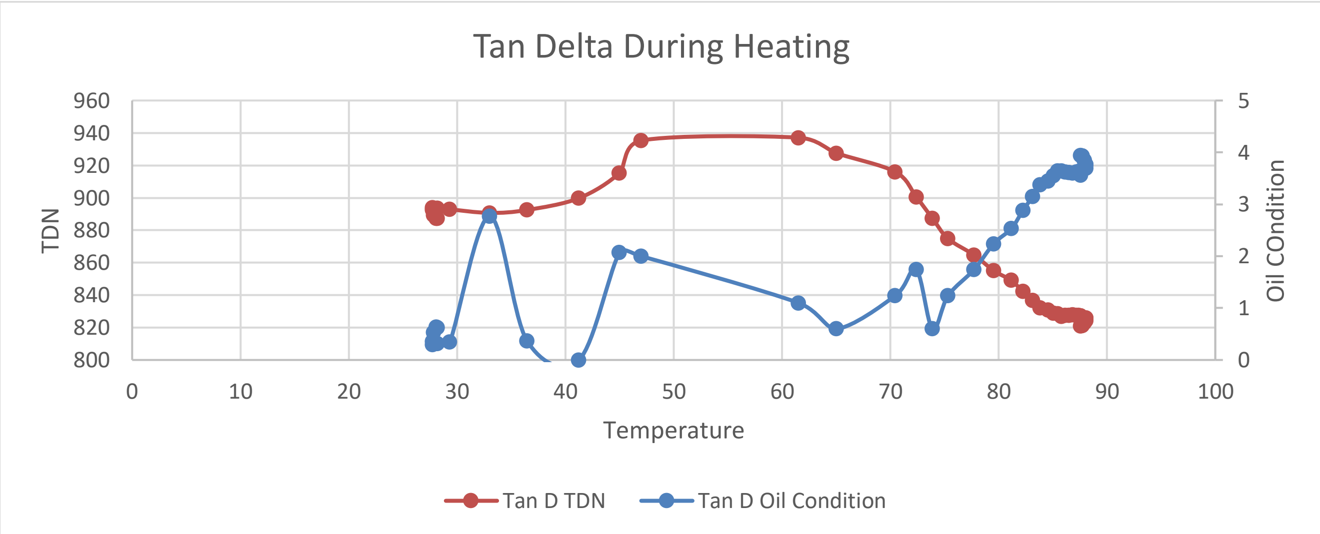

Figure 9 - Tan Delta Measurements During Heating

The dielectric and density measured by the TE sensor remained stable during heating. The viscosity dropped dramatically as one would expect, from 154cp (centipoise)at room temperature to 15cp at 88°C. Centipoise can be converted to centistokes (cSt) by dividing by the specific gravity of the oil (0.875 from the datasheet). The 17cSt measured at 88°C compares favourably with the Mobil datasheet that specifies 14.9cSt at 100°C.

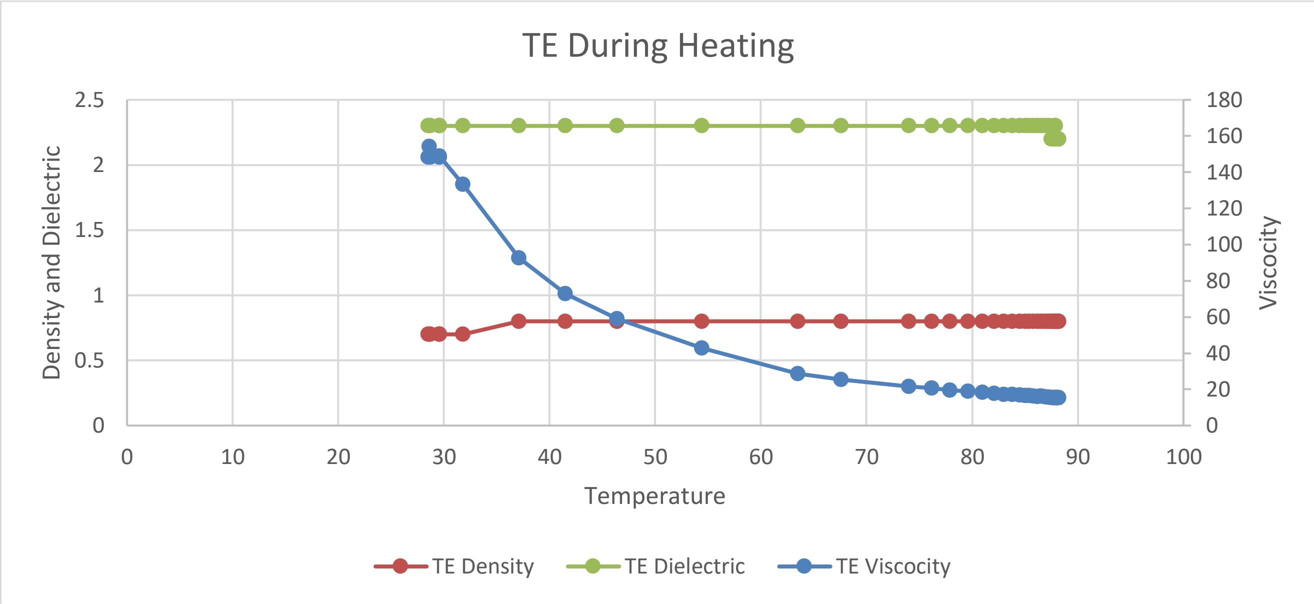

Figure 10 - TE Measurements During Heating

The TE results were validated with readings from the dynamometer. Figure 11 shows the vibration of the dynamometer as measured using the accelerometer internal to the Senquip device. As can be seen in Figure 11, the temperature rises as the dynamometer starts. The temperature reaches a peak of 98.4°C where the viscosity is measured as 13.3cS.

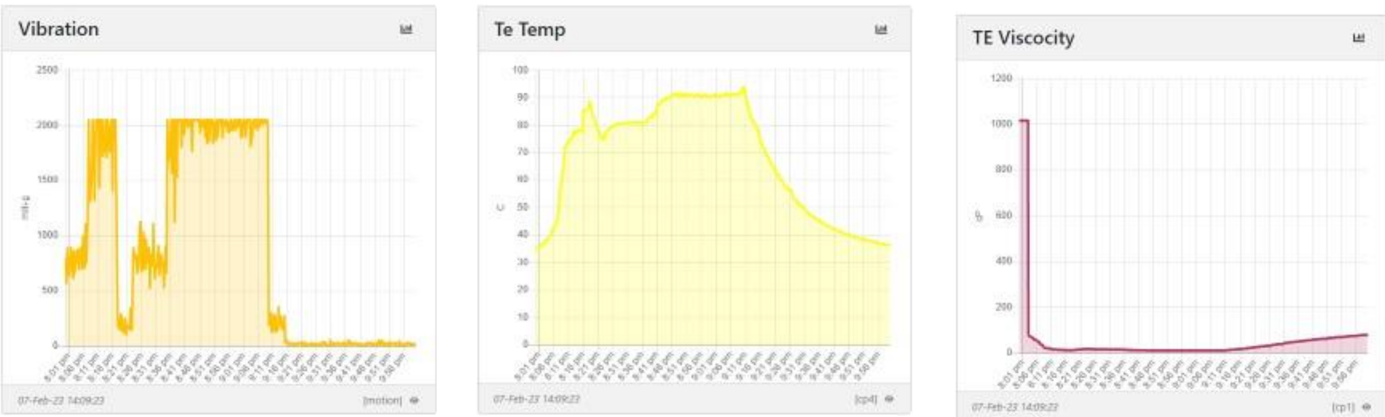

Figure 11 - Dynamometer Vibration Temperature and Vibration

As water was added in accordance with Table 1, the Tan Delta TDN number dropped dramatically from 830 to 0, and the Oil Condition number increased from 3.4 to 137. Both numbers had been stable before the test began.

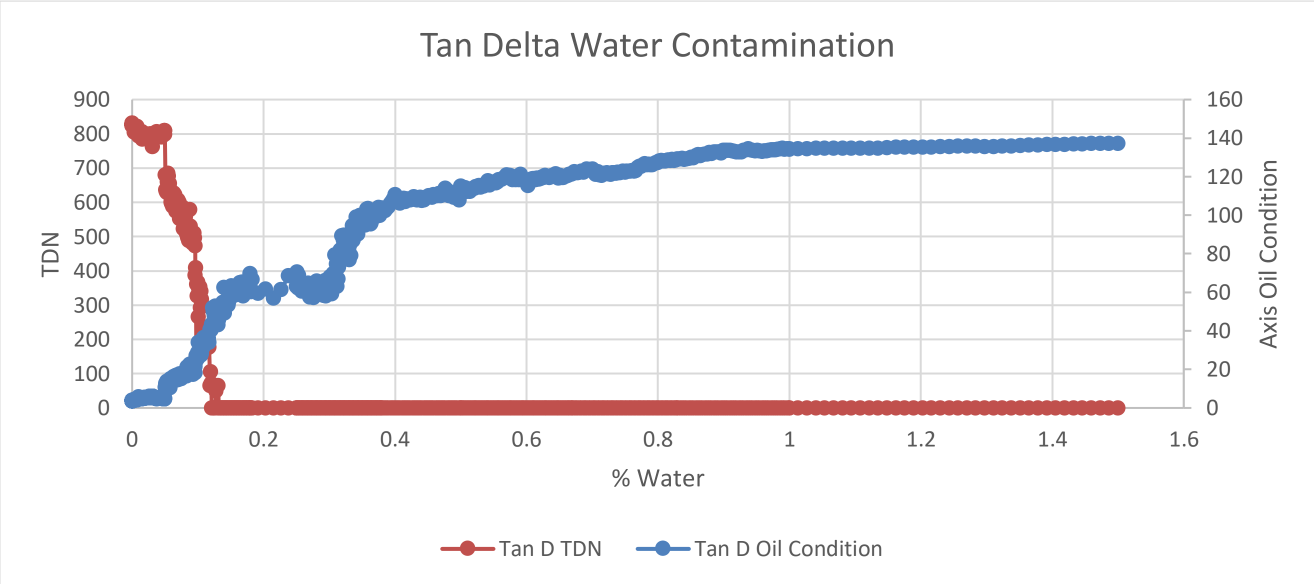

Figure 12 - Tan Delta Water Contamination

The TE Connectivity sensor showed a 20% increase in dielectric from 2.3 to 2.8 over the test. No variation in density was noticed and the change in viscosity was within the measured noise.

Table 2 - TE Water Contamination

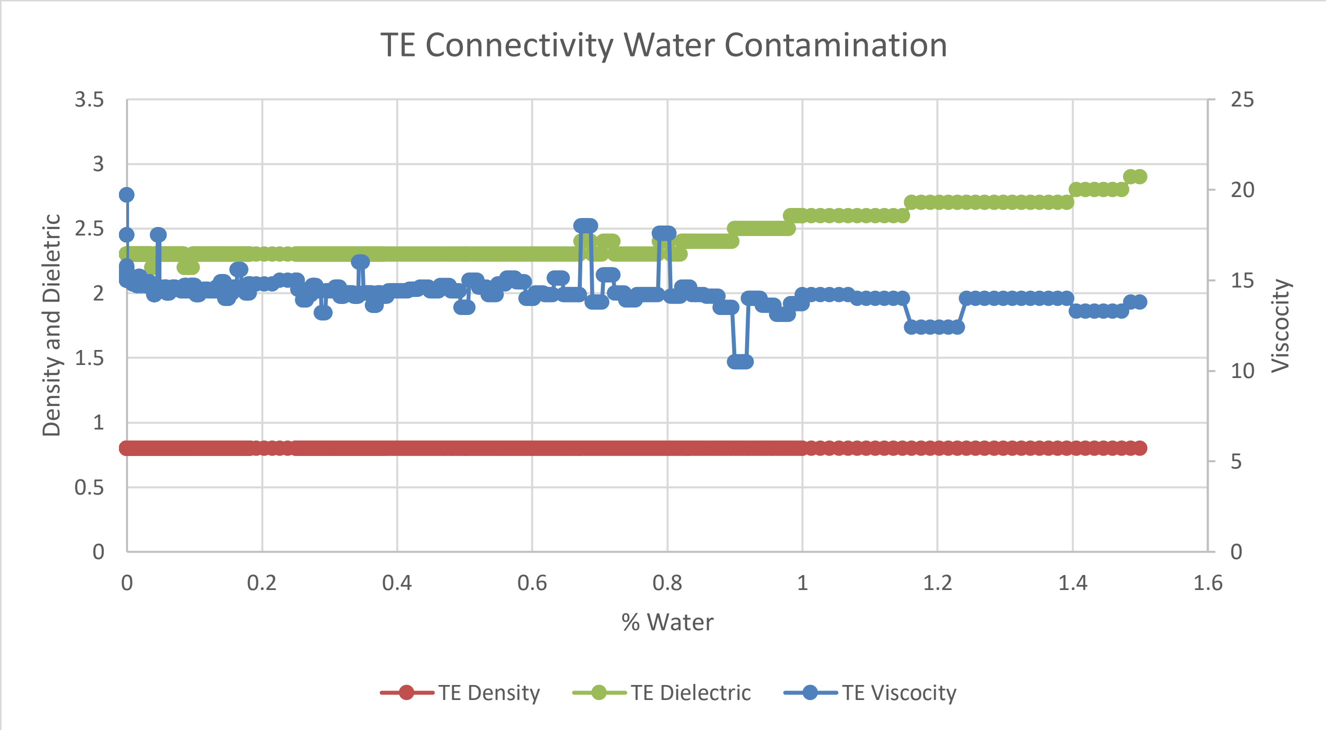

Figure 13 - TE Water Contamination

It was noted that the oil had become cloudy by the end of the test.

Figure 14 - Cloudy Oil

6. Test 2 – Coolant in Oil Contamination

Engine coolant contamination comes from leakage of the engine cooling system. Coolant is composed of ethylene glycol or propylene glycol (40 to 60%), water (60 to 40%) and several additives in relatively low concentrations. Coolant contamination can be dangerous for the engine as is causes heavy sludge deposits and acid compound formation. High coolant contamination can lead to an emulsion or a gel forming that induces build-up on oil passageways, risks filter blockage, causes reduction of oil flow and leads to a serious general decrease of lubrication efficiency.

During this test, a Glycol coolant mix was added to the oil. The Glycol was pre-mixed with two parts water in accordance with the manufacturer recommendation. The oil temperature was kept at a constant 90°C during the test and was stirred continuously.

Table 3 - Test 2 Procedure

Time	**Notes**	**Coolant ppm**	**Coolant %**
10h08	Temp up to 89.6 deg C	0	0.00
10h47	0.35ml coolant added	500	0.05
10h55	0.35ml coolant added	1000	0.10
11h04	0.525ml coolant added	1750	0.18
11h15	0.525ml coolant added	2500	0.25
11h26	0.875ml coolant added	3750	0.38
11h42	0.875ml coolant added	5000	0.50
11h54	1.75ml coolant added	7500	0.75
12h02	1.75ml coolant added	10000	1.00
12h20	End Test		

Again, with the Tan Delta sensor, the Oil Condition number increased dramatically and the TDN number decreased.

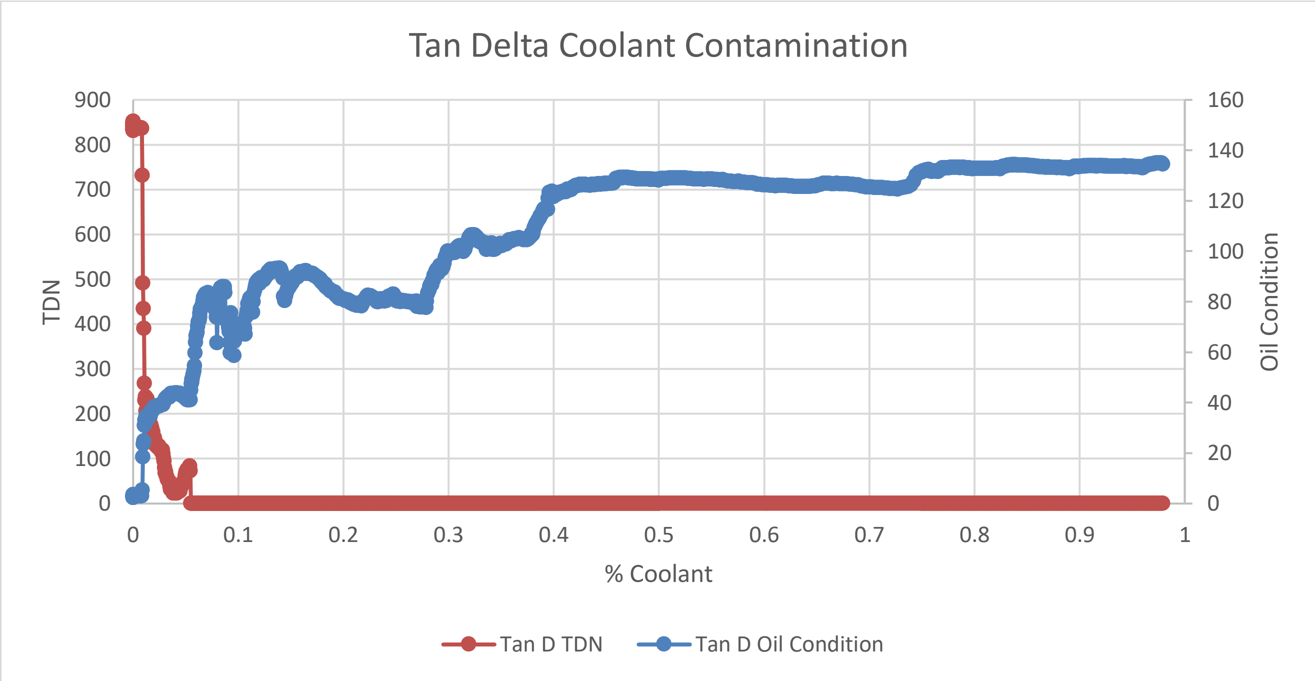

Figure 15 - Tan Delta Coolant Contamination

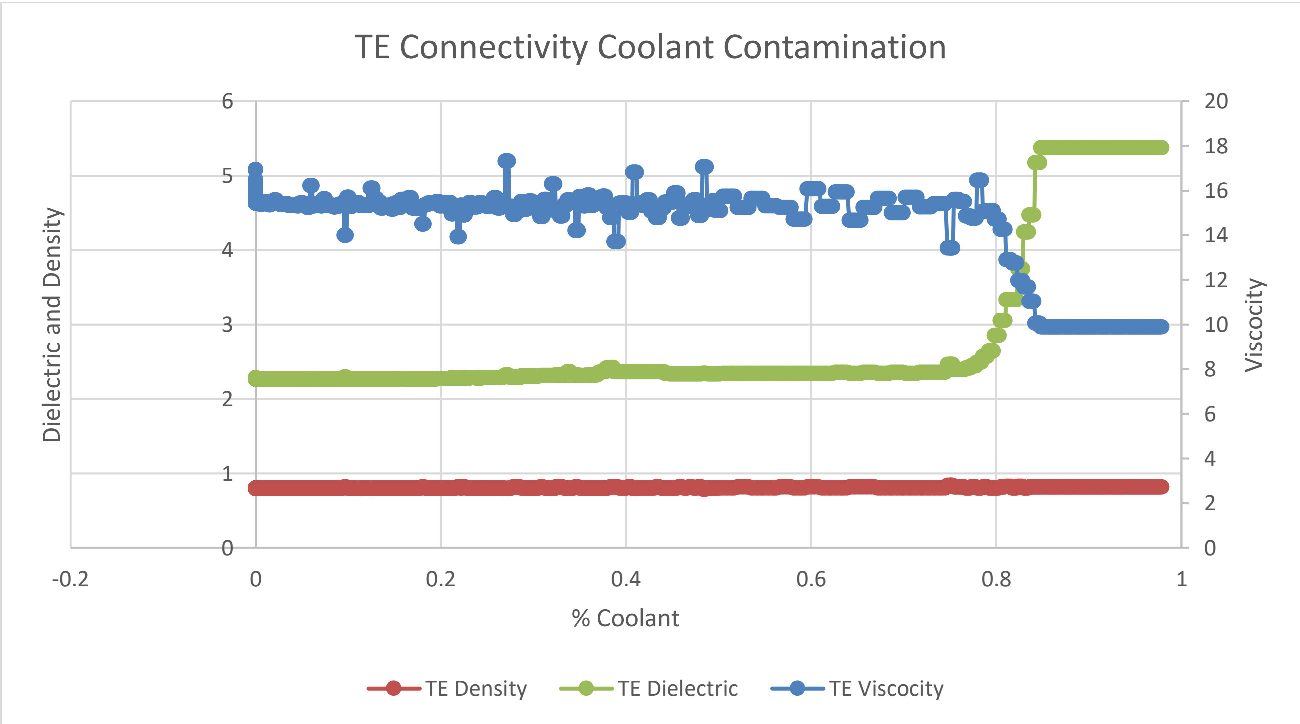

Figure 16 - TE Coolant Contamination

Coolant contamination had a more dramatic effect on the TE sensors with the dielectric more than doubling and the viscosity dropping dramatically as the coolant percentage reached 0.8%. Density was not seen to change.

7. Test 3 – Diesel in Oil Contamination

Fuel contaminations is caused by imperfect fuel combustion and imperfect sealing. Unburned fuel reaches the crankcase through the space between the piston and cylinder and between the piston groove and the ring. Fuel dilution can be enhanced during the DPF regeneration process. Fuel contamination promotes oil oxidation, and acidic compound and soot formation. Fuel dilution will also deteriorate oil lubrication properties and amplify risks of wear.

During this test, diesel was added to the oil. The oil temperature was kept at a constant 90°C during the test and was stirred continuously. At the end of this test, the heating was turned off and the stirring continued in order to see of the reading was stable over temperature.

Table 4 - Test 3 Procedure

Time	Notes	Diesel ppm	Diesel %
12h58	Temperature up to 87.6 deg C	0	0.0
13h07	0.93ml diesel added	1996	0.2
13h23	1.4ml diesel added	5000	0.5
13h32	2.3ml diesel added	9936	1.0
13h42	4.6ml diesel added	19807	2.0
13h50	14ml diesel added	49850	5.0
14h06	23.3ml diesel added	99850	10.0
14h21	Heat off, stirring retained	99850	10.0
20h25	Stirring turned off	99850	10.0

As can be seen in Figure 17 Neither of the Tan Delta measurements changed as diesel was added to the oil.

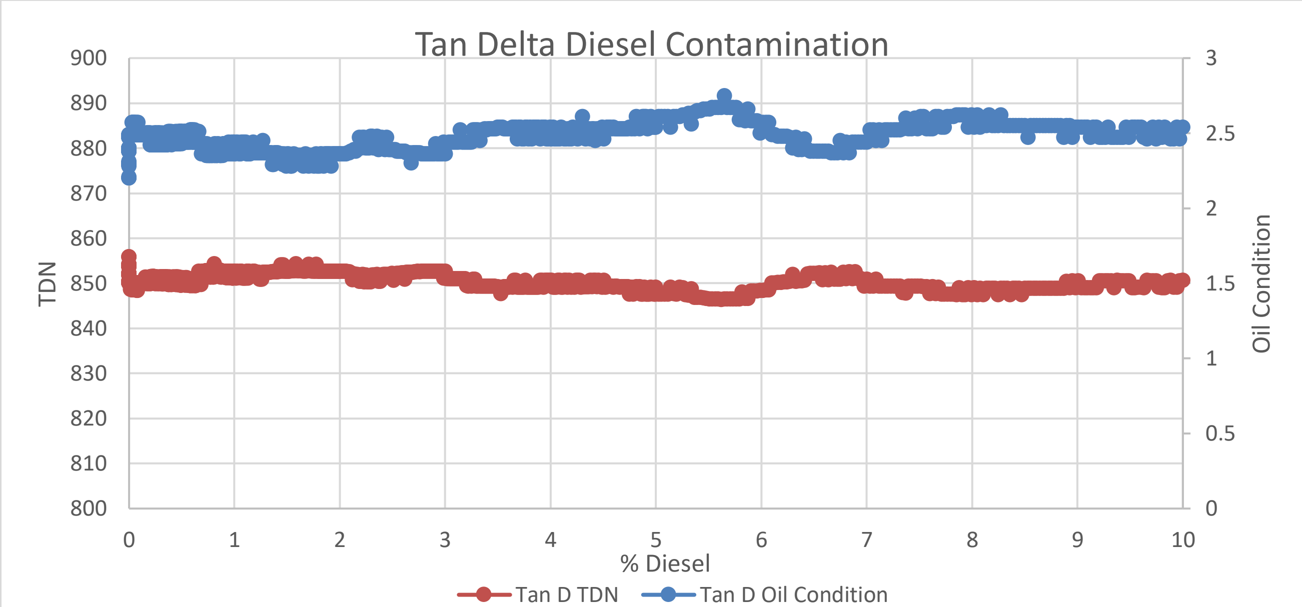

Figure 17 - Tan Delta Diesel Contamination

The viscosity of the oil as measured by the TE sensor dropped from 15 to 11 as the diesel was added to the oil. The density and dielectric were unaffected.

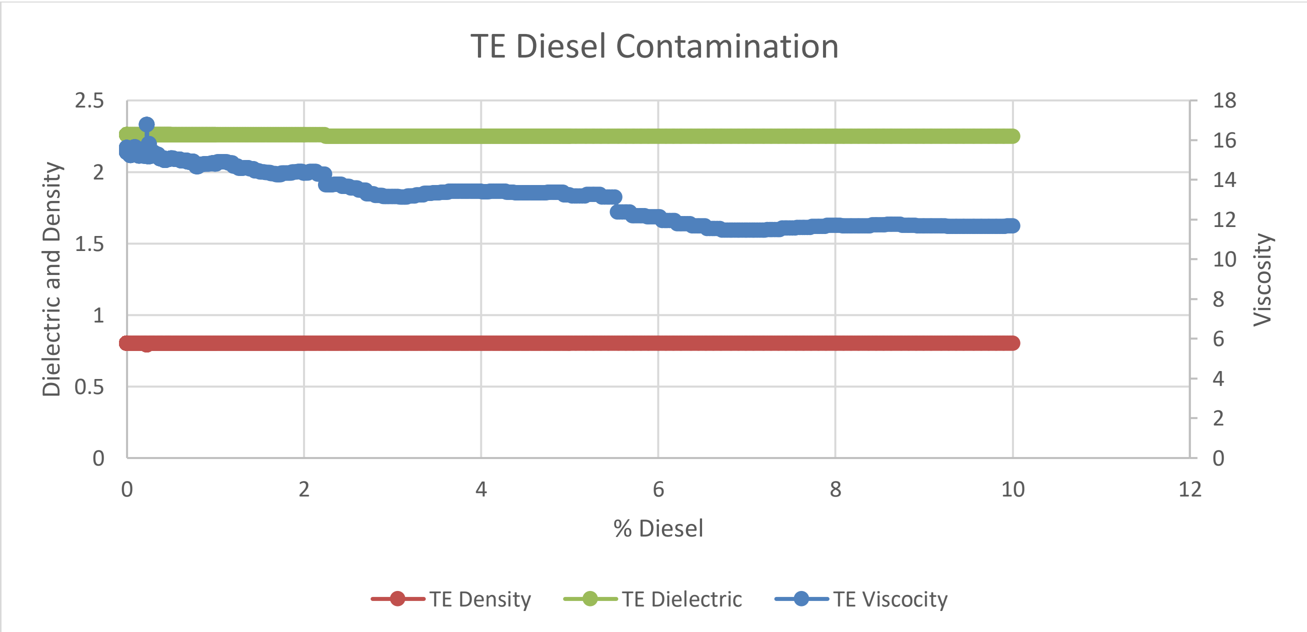

Figure 18 - TE Diesel Contamination

As the oil was allowed to cool, the Tan Delta TDN number increased from around 850 to 940 and the Oil Condition number decreased from 2.6 to 0. Although dramatic in the chart below, the low range on the vertical axis is magnifying the effect. Note that in other tests, the Oil Condition reached 120 and the TDN number dropped to zero.

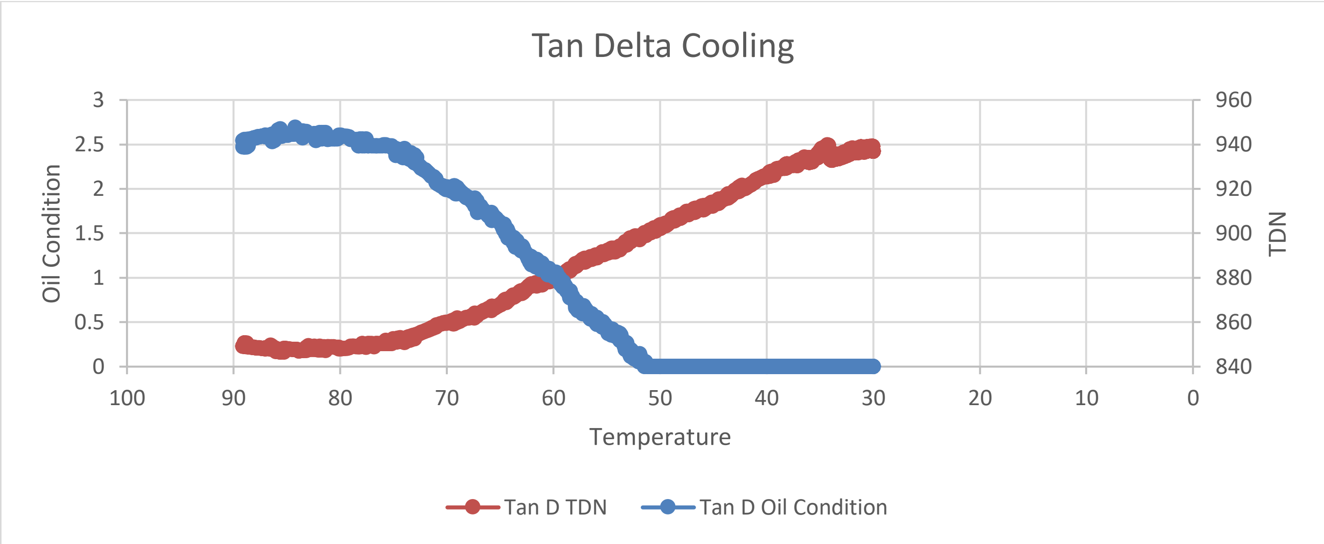

Figure 19 - Tan Delta Cooling

As the oil cooled, the viscosity as measured by the TE sensor increased as expected. The density and dielectric stayed the same.

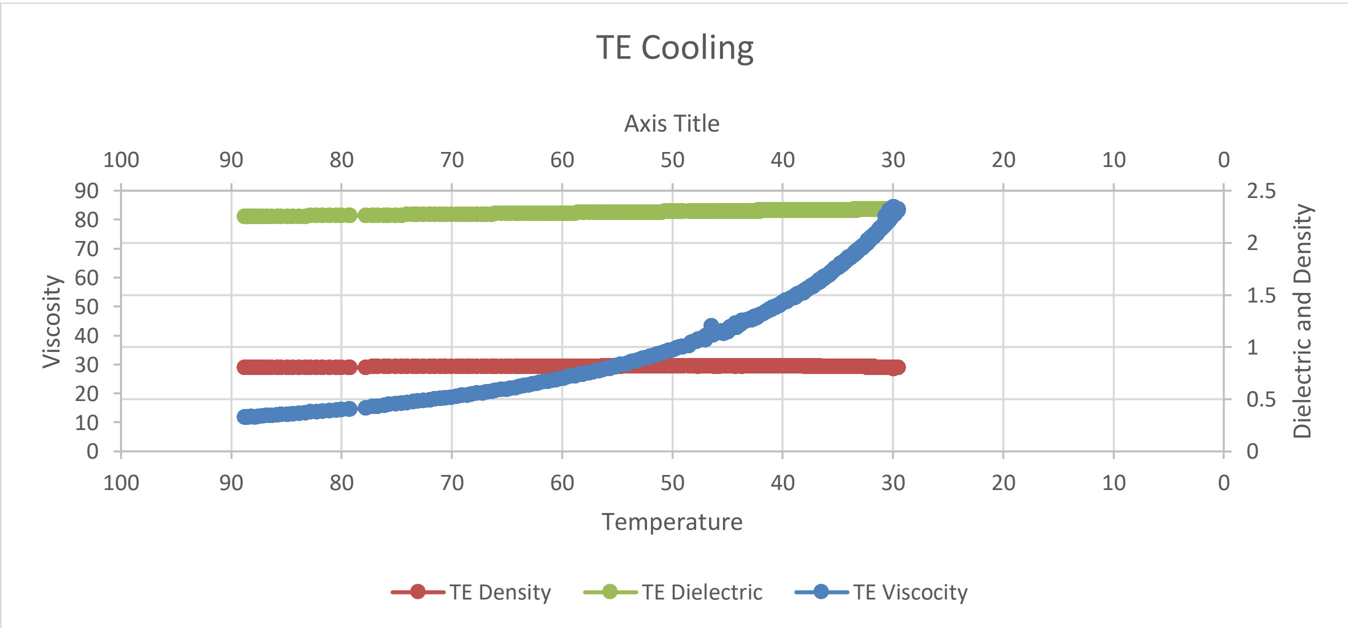

Figure 20 - TE Cooling

8. Test 4 - Iron in Oil Contamination

During this test, iron powder was added to the oil. The oil temperature was kept at a constant 90°C during the test and was stirred continuously.

Table 5 - Test 4 Procedure

Time	Notes	Total ppm	Total %
16h55	Temperature up to 90°C		
16h58	0.055g iron added	10	0.001
17h03	0.055g iron added	20	0.002
17h08	0.055g iron added	30	0.003
17h13	0.055g iron added	40	0.004
17h18	0.055g iron added	50	0.005
17h23	0.1375g iron added	75	0.0075
17h27	0.1375g iron added	100	0.01
17h32	0.55g iron added	200	0.02
17h38	1.1g iron added	400	0.04
17h43	1.1g iron added	600	0.06
17h48	2.2g iron added	1000	0.1
17h53	5.5g iron added	2000	0.2
17h58	Stirring stopped		
18h11	Heating turned off		

The Tan Delta TDN and Oil Condition did not change substantially as the concentration of iron was increased. Tan Delta indicated that the readings were likely to become noisier as metal was added. This can be seen in the data in Figure 22 and would likely be recognisable if the data were compared with a long-term trend.

Figure 21 - Ultra Fine Mesh Pure Iron Powder

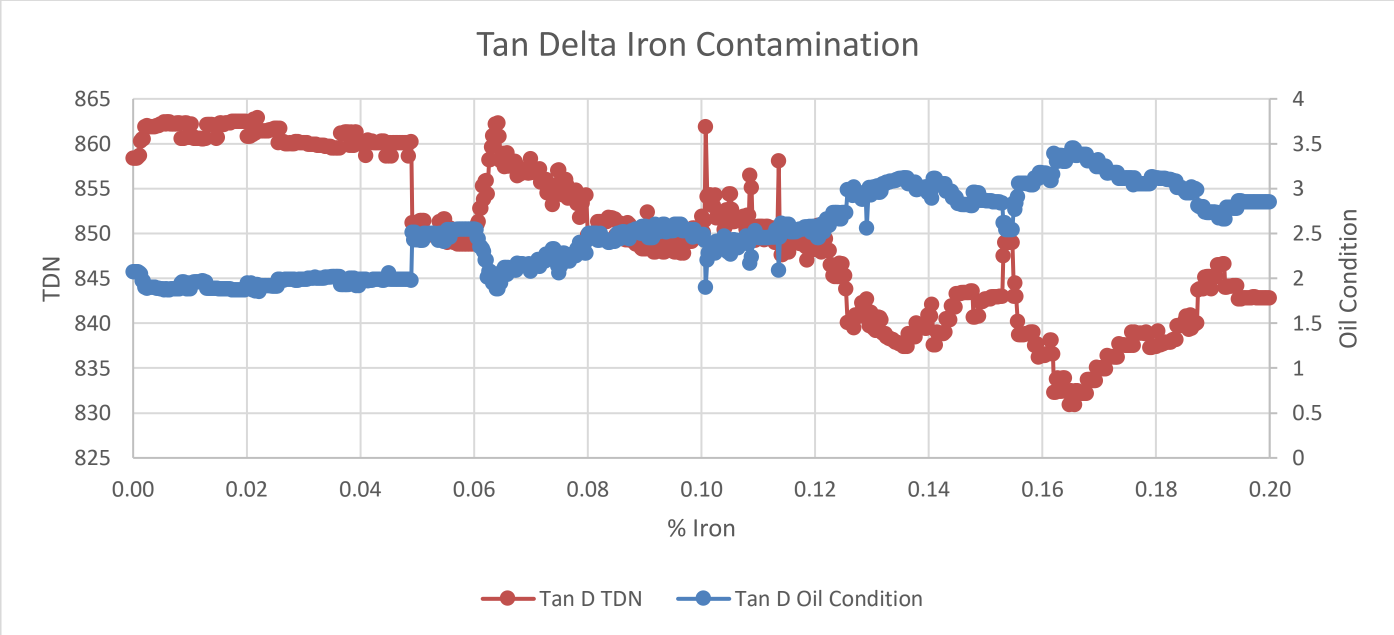

Figure 22 - Tan Delta Iron Contamination

The viscosity, dielectric, and density as measured by the TE sensor did not change substantially as the concentration of iron was increased. The viscosity measurement which is normally extremely stable at a given temperature was significantly noisier.

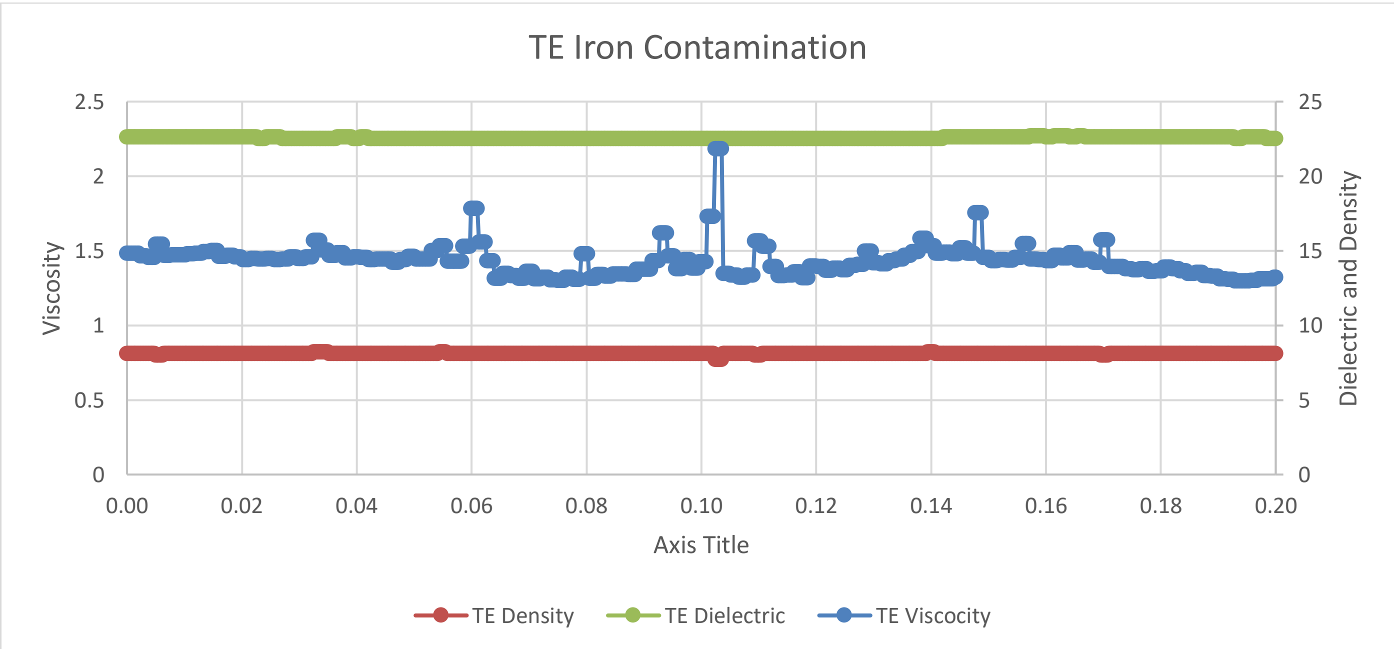

Figure 23 - TE Iron Contamination

9. Oil Life Extension

Both sensors were left in the oil beaker and the temperature was increased to 100°C to promote the oxidation of the oil. After 3 weeks of continuous measurement, very little had changed for either sensor. A laboratory setup is unable to replicate the effect of compression, combustion, soot build-up, and metal contamination.

Previous in-field testing performed with the Tan Delta sensor has shown oil degradation after approximately 500 hours of operation. It has also been noted that after a service, that the oil quality returns to the original state. In this scenario, it is believed that the quality of the oil could be measured and may be suitable for predicting the end of useful life for the oil.

10. Results Analysis

To assist in making sense of the measurements, a summary is presented in Table 6.

Table 6 - Measurements Summary

Test	Description		Tan Delta Oil Condition	Tan Delta TDN	TE Viscosity	TE Density	TE Dielectric
1	Temperature rise	Start	0.6	888	148	0.72	2.3
		End	3.8	824	15	0.80	2.2
		Change	3.2	-64	-133	0.09	-0.1
1	Add 1.5% water	Start	3.4	830	15	0.80	2.3
		End	137	0	14	0.80	2.9
		Change	133.6	-830	-1	0	0.6
2	Add 1% coolant	Start	1.2	875	16	0.80	2.3
		End	134	0	10	0.80	5.4
		Change	132.8	-875	-6	0	3.1
3	Add 10% diesel	Start	2.2	856	16	0.80	2.3
		End	2.5	851	12	0.80	2.3
		Change	0.3	-5	-4	0	0
3	Cool	Start	2.5	851	12	0.80	2.3
		End	0	937	78	0.80	2.3
		Change	-2.5	86	66	0	0
4	Add 0.2% Iron	Start	2.1	858	15	0.81	2.3
		End	2.8	843	13	0.81	2.3
		Change	0.7	-15	2	0	0

As can be seen from Table 6, the Oil Condition, TDN, and as expected, the viscosity are highly temperature dependent. The change in Tan Delta response to water in oil are dramatic and others like the TE dielectric change to water are moderate. No substantial changes are seen from any of the sensors as iron powder is added.

To try and make sense of what should be deemed as a significant change from steady state, the oil parameters were monitored over 5 hours with the temperature cycling between 85°C and 95°C and the average, maximum, minimum and standard deviation were noted. The temperature range was thought to be realistic of a machine operating at a range of loads. The results are presented in Table 7.

Table 7 - Steady State Oil Values

	Tan D Oil Condition	**Tan D TDN**	**TE Viscosity**	**TE Density**	**TE Dielectric**
Average	2.51	849.64	15.07	0.81	2.26
Max	3.39	865.6	18.38	0.81	2.27
Min	1.71	832	13.23	0.75	2.22
Std Dev (σ)	0.45	8.99	1.34	0.00	0.01

Standard deviation is a measure of dispersement in statistics and tells you how much your data is spread out around the average due to noise in the sensor and measurement process. Where the data is very spread out, a small change is insignificant but where the data is tightly packed around the average, a small change is significant.

The graph shown in Figure 24 is of a normal distribution and represents a great deal of data in real life. The average is represented by the Greek letter µ, in the centre. Each segment (coloured in dark blue to light blue) represents one standard deviation away from the average. For example, 2σ means two standard deviations from the average.

For a normal distribution, 68.2% of readings will fall within ±1σ of the average and 95.4% of readings will fall within ±2σ of the average. Phrased differently, a reading outside of ±2σ has a 4.6% chance of being normal (and a false alert) and a 95.4% chance of being an exception which should be alerted.

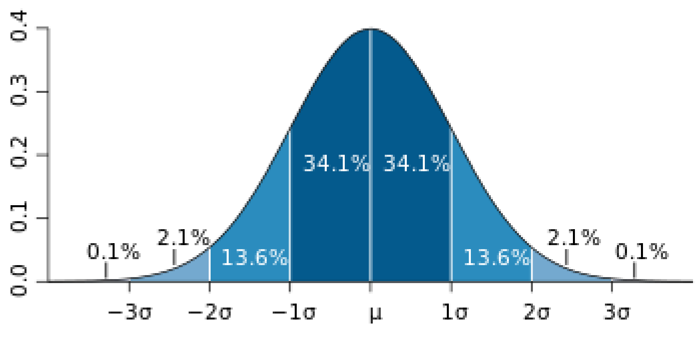

Figure 24 - Normal Distribution

The change in measurements shown in Table 6 for the water, coolant, and diesel tests are now expressed in terms of the number of standard deviations that they represent. The cells are colour coded as follows:

Table 8 - Definition of Significant Change

Number of Standard Deviations	Likelihood of Reading Being an Exception	Colour Code	Comments
±1σ	68.2		A change inside 2σ is unlikely to reliably be differentiated from normal measurement noise.
±2σ	95.4		
±3σ	99.6		A change of 3σ is significant and is unlikely to be noise.
±4σ	99.8		A change of more than 4σ is highly likely to be significant and will easily be differentiated from measurement noise.
>±4σ	~100%		

Given that in a typical machine, oil quality is unlikely to change quickly, averaging of data and other techniques can also be used to increase the likelihood that changes are interpreted as significant and are reported.

Table 9 – Number of Standard Deviations of Change in Each Parameter

Test	Description	Tan Delta Oil Condition	Tan Delta TDN	TE Viscosity	TE Density	TE Dielectric
1	Add 1.5% water	297.2	-92.4	-0.7	0.0	48.7
2	Add 1% coolant	295.4	-97.4	-4.5	0.0	251.6
3	Add 10% diesel	0.7	-0.6	-3.0	0.0	0.0
4	Add 0.2% iron	0.6	-0.6	0.7	0.0	0.0

As can be seen from the data in Table 9, the Tan Delta sensor is able to easily determine the addition of water or coolant but struggles to detect the addition of diesel or iron.

The TE sensor can detect the addition of water and coolant through the change in dielectric and the addition of diesel through the change in viscosity but not the addition of iron.

The readings for the TE sensor are consistent with those presented in Reference D (FPS2800 White Paper). For instance, considering the chart in Figure 25 from the TE White Paper, the dielectric is meant to increase as coolant is added and this is what is seen in the experiment.

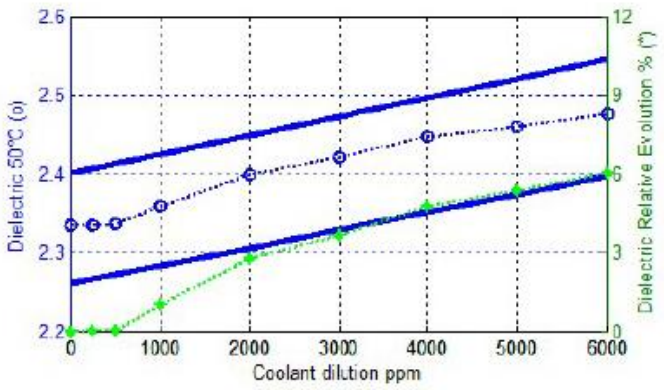

Figure 25 - Coolant Contamination - TE White Paper

It was noted in the TE White Paper (Figure 26) that Iron contamination was measured up to a maximum of $10x10^4$ parts per million. This represents 100,000 parts per 1000,000 or 10%. Senquip did not feel that this was realistic and so limited the test to 0.2%. It is possible that at higher contamination levels that the TE sensor could determine iron in oil.

It should be noted that further work to analyse the noise detected in the measurements when iron is introduced may make it possible to identify iron and other metal contamination.

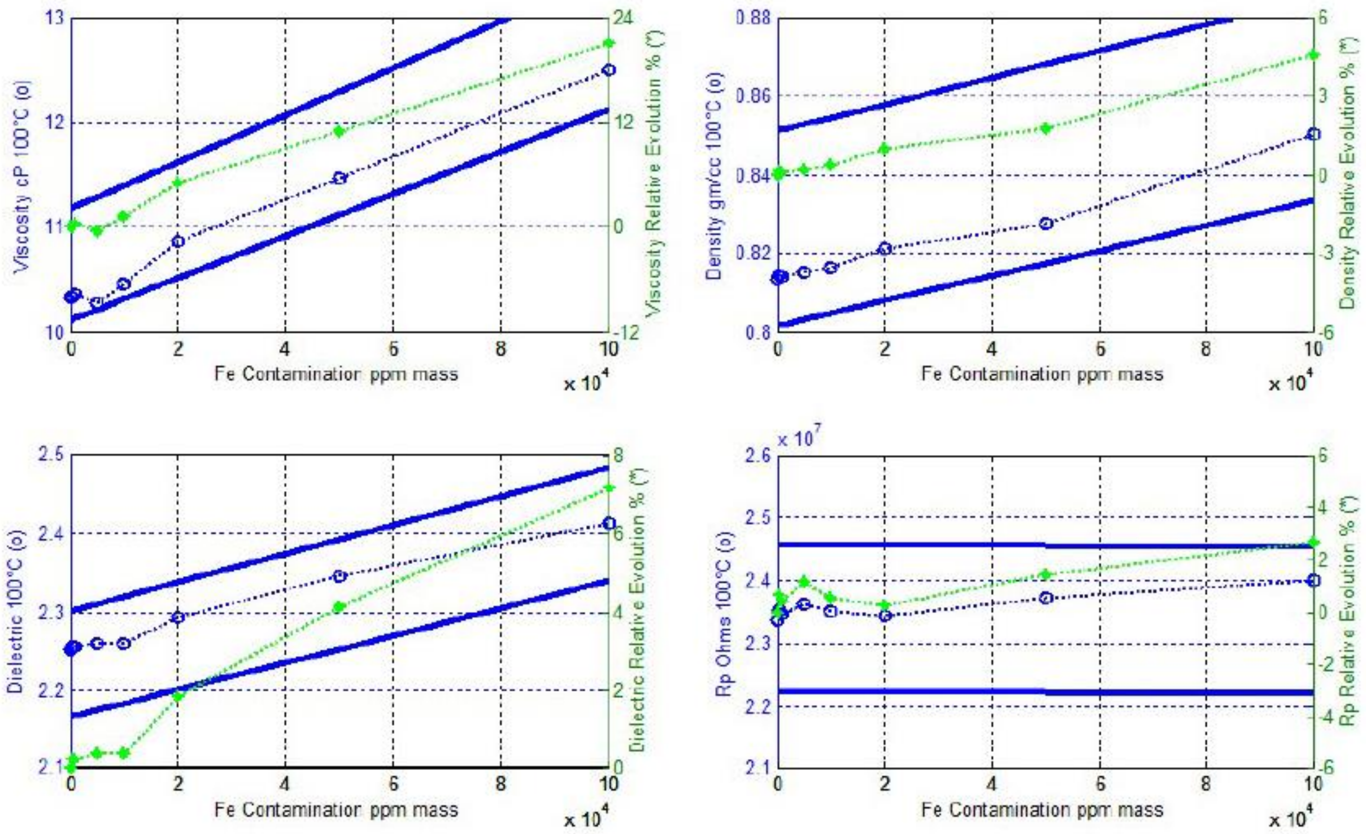

Figure 26 - Iron Contamination - TE White Paper

11.Conclusions

The Tan Delta sensor is easily able to detect water and coolant in oil in a laboratory environment. The Tan Delta sensor is highly sensitive to temperature making the identification of small changes such as those due to diesel and iron contamination difficult to detect.

The TE sensor responds as specified in the White Paper. Water and coolant contamination can be detected by the change in dielectric, and diesel contamination can be detected by a fall in viscosity. Iron contamination is not easily detected by the TE sensor. The TE sensor can differentiate between water and coolant vs diesel contamination in a laboratory environment.

Both sensors became more noisy as iron powder was introduced. This could likely be detected in a machine that operates at stable temperature for a long period of time. In the dynamometer tests, which were generally of short duration and with variable load, the noise due to contamination is unlikely to be noticed.

The sensors are not a “lab in a sensor” and are not a replacement for regular laboratory testing. Both sensors, and the TE one particularly was extremely stable at a given temperature. Oil characteristics should not change quickly due to wear and tear and so any change in output should be viewed as a concern that requires further analysis.

The sensors will offer most value in stationary machines that operate at constant load. In these application, long term trends can be mapped and changes to the trend identified and alerted. It is also likely that in these applications, that oil degradation can be measured and that the life of oil can be extended. For dynamic machines, trend analysis will be more difficult, but the data is still valuable and is likely to be able to detect contamination.

As a next step, algorithms to detect water, coolant, and diesel contamination using the TE sensor will be developed. The algorithms will be written using JavaScript to run locally on Senquip devices. Further analysis will be done on the noise associated with the introduction of metal wear particles and if possible, the script will be enhanced to include wear debris detection.

Senquip would invite interested parties to make contact and to join field-trials in the testing of oil condition algorithms.

Appendix 1: Source Code

```
load('senquip.js');

let DynamicViscosity = 0;
let Density = 0;
let DielectricConstant = 0;
let OilTemp = 0;
let EngineHours = 0;


SQ.set_data_handler(function(data)
{
      let obj = JSON.parse(data);
      if (typeof obj.can1 !== "undefined") {
          for (let i = 0; i < obj.can1.length; i++)
          {

            //OIL SENSOR STUFF -
              if (obj.can1[i].id === 486344767) // PGN 64776 SA: 63
                  {
                    let a = SQ.parse(obj.can1[i].data, 0, 4, -16); //Dynamic
viscosity
                    DynamicViscosity = a*0.015625;

                    let b = SQ.parse(obj.can1[i].data, 4, 4, -16); //Density
                    Density = b*0.00003052;

                    let c = SQ.parse(obj.can1[i].data, 12, 4, -16); //dielectric
constant
                    DielectricConstant = c*0.00012207;

                  }
                if (obj.can1[i].id === 419360319) // PGN 65262 SA: 63
                  {
                    let a = SQ.parse(obj.can1[i].data, 4, 4, -16); //oil temperature
                    OilTemp = (a*0.03125)-273;
                  }
            }
        }
        SQ.dispatch_double(1, DynamicViscosity, 2); //
        SQ.dispatch_double(2, Density, 2); // RESOLUTION
        SQ.dispatch_double(3, DielectricConstant, 2); // RESOLUTION
        SQ.dispatch_double(4, OilTemp, 2); //

}, null);
```