Practical on and off-wing Applications of a Thermal Product Measurement Sensor for Detection of Contamination in Fluids

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ABSTRACT

Lubrication or fuel systems failure due to contamination or degradation can be catastrophic in an aircraft. Preventive maintenance is the key to ensure that these systems do not fail. Contamination in these systems can occur due to particles generated by wear or condensation of water vapour due to bad seals and the oil can degrade over time due to thermal stresses. Currently, on-line oil/fuel condition monitoring systems use sensors that are based on eddy current, optical, capacitive to detect contamination. These sensors have some major drawbacks: prone to surface contamination, non-linearity, insensitive to detect extremely small particulates or false detection such as trapped bubbles.

A new sensor based on platinum thin film heat transfer gauges has been developed at the University of Oxford that works on the principle of measuring the change in thermal product of the material that is in contact with the sensor. The sensor is able to detect metallic, non-metallic, liquid contamination in oil or fuel and can be used for both off-line and on-line condition monitoring. The sensor is found to be quite sensitive and can detect extremely small concentrations of contaminants of the order 0.01% (10PPM) by volume. This paper presents a detailed experimental study carried out to test contamination of oil and fuel in laboratory and on-line.

1.0 NOMENCLATURE

$\dot{q}_{wall}$	Heat transfer rate, $W/(m^2K)$
T_{wall}	Wall temperature, K
T_0	Initial temperature, K
α	Thermal diffusivity, m^2/s
ρ	Density, kg/m^3
c_p	Specific heat capacity, J/kgK
k	Thermal conductivity W/mK
t	Time, s
$\sqrt{\rho c k}$	Thermal Product, $J/m^2Ks^{0.5}$

2.0 INTRODUCTION

Oil and fuel contamination detection in gas turbine engines, automotive engines, manufacturing machines etc is an active area of research. Most of the condition monitoring is carried out in real-time but the monitoring can be performed off-line in a laboratory which is time consuming. Currently, real time sensors used for monitoring are eddy current, capacitance, Hall effect etc. These sensors work well in detecting contamination, however, they are temperature dependent, insensitive to extremely small concentrations of the contaminant or can only detect metallic particles (such as eddy current and Hall effect [1]). Optical based contamination detection techniques are also prone to contamination of optics and can be expensive.

A new sensor based on platinum thin film heat transfer gauges has been developed at the University of Oxford that works on the principle of measuring the change in thermal product of the material that is in contact with the sensor. The sensor can be used in the detection of small concentrations of contaminants (< 10 ppm) in oil, fuel etc. for both on-line and off-line applications. The sensor is robust and can detect small concentrations of contaminants in any liquid. The paper presents some experimental studies carried out using the sensor at both off and on site facilities and shows the evolution of the sensor and electronics to TRL 5/6.

3.0 WORKING PRINCIPLE AND THEORY

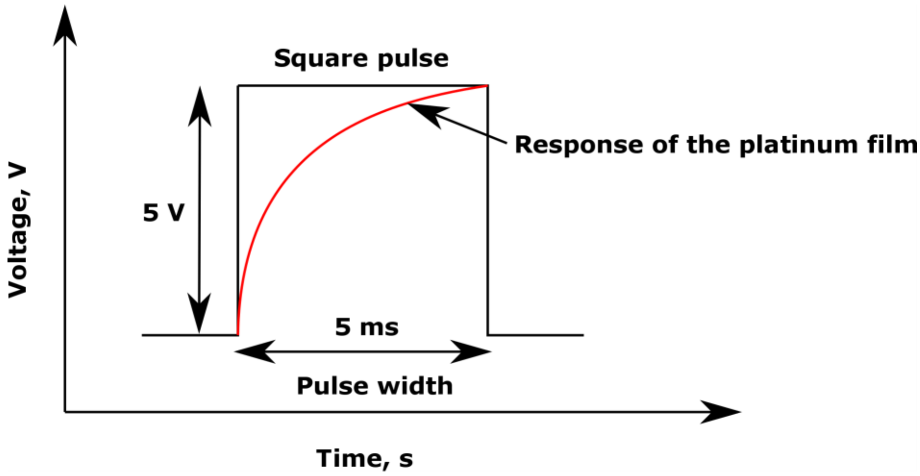


Figure 1: Response of the sensor to a square pulse

As mentioned in the previous section, the sensor can detect the change in thermal product of the material that is in contact with the sensor. An electrical square pulse (Fig. 1) of certain amplitude (generally 5 V) and duration (5 ms) is passed through the sensor and the sensor's temperature increases. Some heat is dissipated in the sensor's substrate and the rest is dissipated in the surrounding material and as a result a certain temperature is recorded by the sensor. As the surrounding material composition changes, the dissipated heat between the sensor substrate and surrounding material changes. The change can be correlated to the change in thermal product of the material. In the case of contamination of oil, the thermal product will be different for the contaminants compared to the oil (typical thermal product for oils is around 500 $J/m^2Ks^{0.5}$, whereas for metals, it is generally in excess of 16,000 $J/m^2Ks^{0.5}$) and hence the heat transfer will be different [2] and [3].

The relation between heat transfer and thermal product is derived as follows:

The one dimensional unsteady heat transfer equation is given as

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha(x)} \frac{\partial T(x,t)}{\partial t} \tag{1}$$

where T is temperature, x is distance in the substrate, t is time and

$$\alpha = \frac{k}{\rho c} \tag{2}$$

The analytical solution for a step function in temperature (see [4]) of this equation is evaluated as:

$$\dot{q}_{wall} = (T_{wall} - T_0) \frac{\sqrt{\pi}}{2} \frac{\sqrt{\rho c k}}{\sqrt{t}} \tag{3}$$

where $\dot{q}_{wall}$ is heat transfer rate, T_{wall} is wall temperature, T_0 initial temperature.

$$q_{wall} \propto \sqrt{\rho c k} \quad (4)$$

This shows that the heat transfer to a material is directly proportional to the thermal product of the material. Since the data from the electronics is measured in volts (V), the equation can be re-written as

$$V \propto \frac{1}{\sqrt{\rho c k}} \quad (5)$$

This shows that as the thermal product increases, the voltage measured by the sensor decreases.

Table 1: Thermal properties of the liquids and metals

Material	Density	Heat capacity	Thermal conductivity	Thermal product ρ cp k
	(kg/m3)	(J/kgK)	(W/mK)	J/m2Ks0.5
Water	998.2	4182	0.6	1582
Acetone	791	2160	0.18	555
Oil	884	1910	0.14	486
Iron	7870	450	79.5	16779

Table 1 gives the thermal properties and thermal product values for water, acetone, oil and iron. We note that the thermal product values are quite different and the sensor is able to detect these changes.

4.0 THERMAL PRODUCT SENSOR

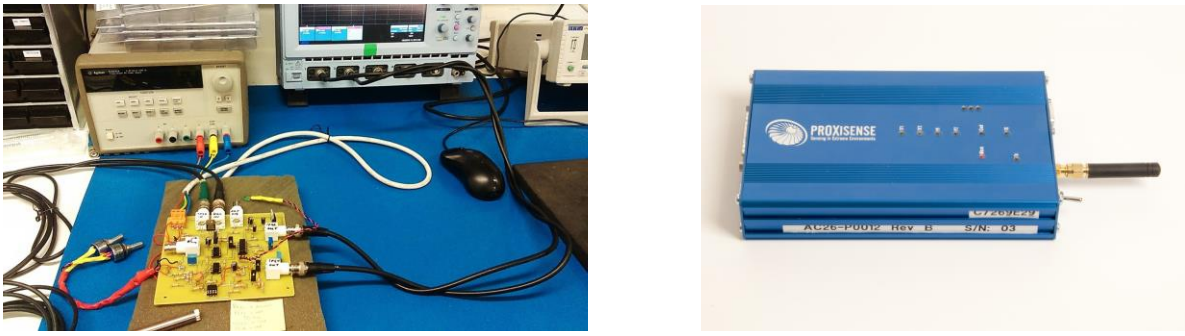
The thermal product sensor is manufactured by painting two platinum thin film tracks which are connected by gold tracks for electrical connectivity. The platinum gauges and conducting tracks were painted on a

(a) Typical thermal product sensor **(b) Thin film gauge sensor for liquid contamination**

Figure 2: Thermal product sensor

MACOR [R] substrate to ensure that an insulating surface is used underneath which can withstand high temperatures. The substrate is then fired in a furnace to form the films and the tracks (Fig. 2). A standard ktype thermocouple is generally placed in the middle of the two gauges to measure the temperature of the liquid and contaminants, however this depends on the application as the temperature can also be derived from the thin films.

5.0 ELECTRONICS



(a) Thermal product electronics (1st gen) **(b) Improved thermal product electronics (2nd gen)**

Figure 3: Thermal product electronics

Figure 3a shows the first generation of electronics that was developed in house and consisted of two channels to drive the sensors. The circuit used a signal generator to provide the pulses and the measurement was taken using a wheat-stone bridge. The measured signal was recorded on a National Instruments 16-bit DAQ and the signal was processed subsequently. These electronics were used to carry out some preliminary tests for detecting metal contamination. Further details of the tests can be found in the paper [2].

The electronics was further optimised and developed into a portable device that can be used for on site testing. Figure 3b shows the thermal product measurement device which is compact and contains all the electronics and signal processing algorithms. The device is capable of driving four thermal product sensors and a thermocouple and has a backup battery and wireless transmission capability.

6.0 WITHOUT CONTAMINATION

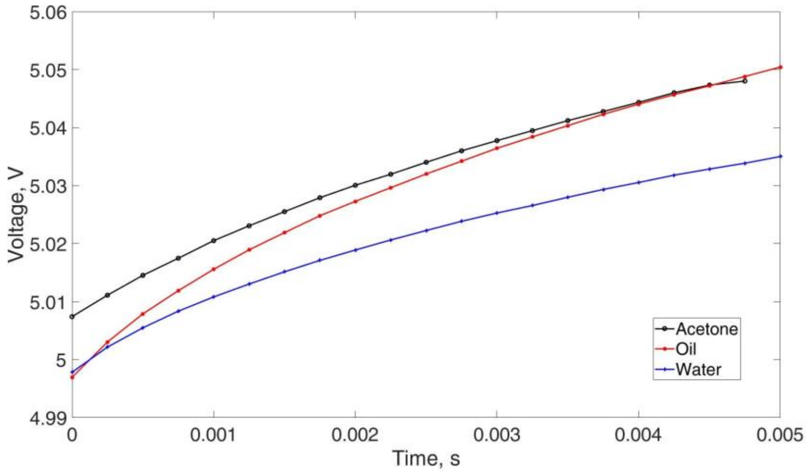


Figure 4: Comparison between various liquids without contamination

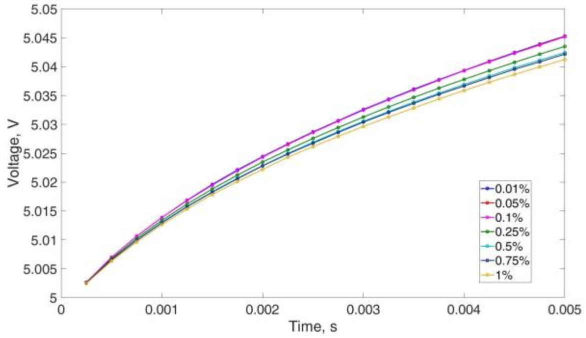
The tests comprised of testing water, acetone and oil individually. From Fig. 4, we see that the numerical results show good agreement with the experimental data. Both numerical simulations and experiments show that, as the thermal product increases (see table 1), the curve shifts downwards, which is expected as the amount of heat absorbed is higher with materials with high thermal products.

7.0 WITH CONTAMINATION

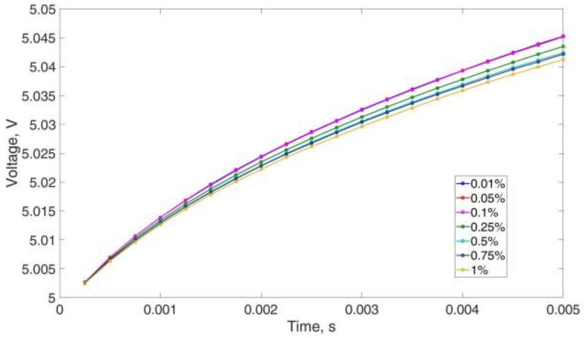
Initially two types of liquid in liquid contamination were investigated: Water in acetone and Water in oil with varying concentrations from 0.01% to 1%. Acetone is used here to simulate fuels as they tend to have thermal products in the same range and the latter case is generally found in gas turbine engines and other machinery where the moisture gets trapped in the oil.

7.1 Water in Acetone and Oil

Figures 5a and 5b shows the comparison of thermal product curves (represented as voltage) with varying concentrations of water in acetone and oil. Notably as the concentration level of the contamination increases, the thermal product curves shifts downwards as water has higher thermal product than acetone and oil. Detailed analysis of this data can be found in [3].



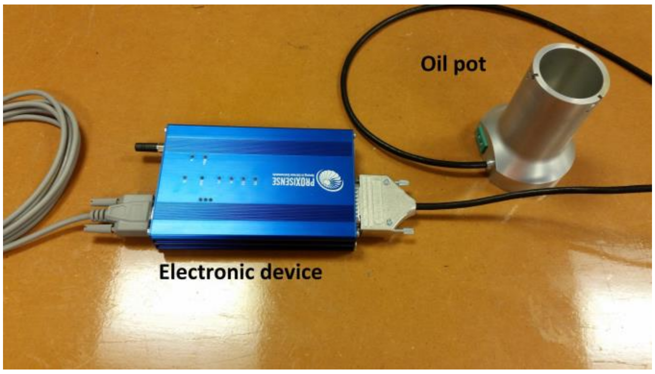
(a) Thermal product curves for water in acetone



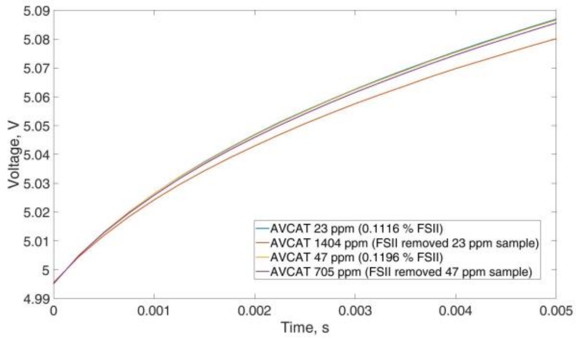
(b) Thermal product curves for water in oil

Figure 5: Thermal product variation with increasing water contamination in fuel and oil

8.0 1710 NAS TESTS FOR WATER IN FUEL



(a) Thermal product setup for 1710NAS

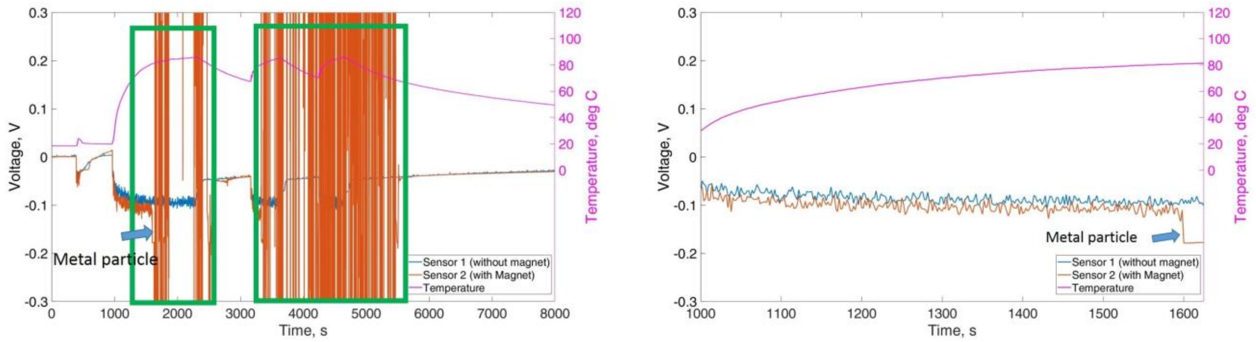


(b) Fuel with different levels of water contamination

Figure 6: Thermal product variation with increasing water contamination in fuel and oil

The work involved testing of fuel and oil samples from various ships and land vehicles belonging to the British armed forces for water contamination. Currently, all the samples are sent back to 1710 Naval Air Squadron (NAS) for testing water contamination in fuel and oil that is kept in storage. 1710 NAS, whilst owned by Navy Command in the UK MOD, it has responsibility for operational and frontline platform and system integrity monitoring across the air, land and maritime domains. The chemistry section within 1710 NAS manages the day-to-day monitoring and integrity of fuels, lubricants and other fluids used with in military platforms. This tends to have a significant lead time as the samples needs to be shipped and tested in the lab. The requirement was to have a system where the testing can be carried out on ships or at the frontline and make a decision in real time. A fluid container instrumented with four thermal product sensors (see fig. 2) was used to carry out the tests on approximately 200 fuel samples that had different levels of water contamination. The setup (Fig. 6a consists of the instrumented fluid container, thermal product electronics driver and a software to process and analyse the data. The results from were compared with that obtained from the currently approved 1710 NAS titration test method. The sensor was able to detect 40 Parts Per Million (PPM) of water contamination in fuel samples (Fig. 6b) which is seen as increase in the thermal product value due to increase in water levels. Software was developed which can give PPM values and traffic light system with user defined thresholds without requiring any post-processing of the data

9.0 ENGINE TEST FOR DETECTING METAL PARTICLES



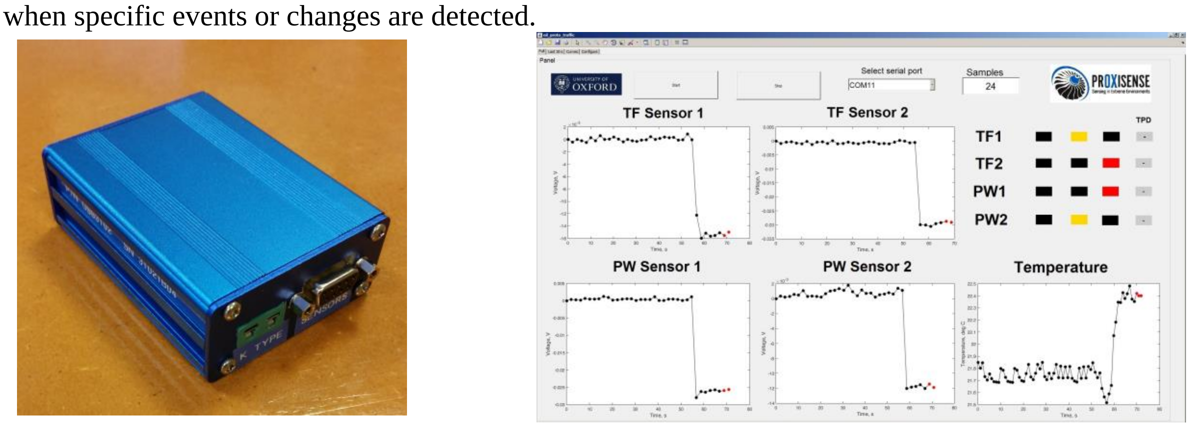
(a) Time series data of thermal product during engine run **(b) Zoomed view of metal particle detection**

Figure 7: Thermal product sensor data from an engine run

The test involved designing a sensor for in-line oil condition monitoring to detect metal contaminants in oil for a gas turbine engine. A new thermal product sensor was built and installed on the engine oil flow line. Several tests with different engine run profiles were carried out. Figure 7 shows the data from the two sensors (blue and red curves) and a thermocouple (pink curve). As the engine runs, the oil heats up and during the run there is sudden drop in the sensor signal on one of the sensing elements (Fig. 7b) whereas the second element does not show this effect. This sudden change indicates that a metal particle has been detected by the sensor and since metal particles have high thermal product the drop in the signal value is higher. The spikes seen in the sensing element is due to the build-up of metal particles (due to a magnet underneath the element) shorting the terminals of the sensor.

10.0 IMPROVED ELECTRONICS AND SOFTWARE

Following all this preliminary testing and analysis, the electronic driver units was redesigned to make it more compact with more customisable capability (see Fig. 8a). The new 4 channel driver unit provides a very low noise signal responses, together with customisable software algorithms to enable the unit to be optimised for the specific application (e.g. fluids and contaminants of interest) in the temperature range of interest. An analytics suite (see Fig. 8b) was also developed which allows real time outputs to be presented which incorporates a programmable traffic lights system to provide actionable indicator warnings to operators when specific events or changes are detected.



(a) Thermal product electronics (3rd generation) **(b) Software with traffic light system**

Figure 8: Thermal product software

11.0 EXPLOITATION MATURITY METRICS

Table 2 shows the exploitation maturity metrics or exploitation maturity level (EML) proposed by the UK MOD. The levels start from zero where there is no end user identified to level 6 where an end user is identified and is actively using the technology in relevant area. When this EML is used against the standard technology readiness level, we get a matrix as shown in table 3 showing where the current technology lies. For example, a technology can be at a high TRL but has not been exploited with an end user for use in-service.

Table 2: Exploitation maturity metrics

EML	EML Description - For Use in UK MOD Health and Usage technology maturation	Summary
0	No end user/operator or industry OEM exploiter has been identified	Low
1	The proposer has aspirations for the results of the offering to be exploited by an identified end user/operator or industry OEM exploiter has been identified	
2	The proposer has involved an identified end user/operator or industry OEM in preliminary discussions about the offering and its applicability	
3	The proposer has liaised withan identified end user/operator or industry OEM and they have produced and agreed an exploitation plan	Medium
4	An identified end user/operator or industry OEM is actively supporting or is involved in the successful exploitation of the offering	
5	An identified end user/operator or industry OEM has a formal commitment to use the results of the offering subject to meeting agreed TRL level	High
6	An identified end user/operator or industry OEM is actively using the results of the research in a relevant area	

Table 4 shows the TRL v/s EML matrix for the oil/fuel condition and contamination monitoring. Notably, the technology is at a TRL 5/6 as there has been significant testing carried out on the sensor in-house, OEM and other research laboratories. The technology is being exploited through a licensing agreement with Proxisense [R] which is an Oxford university spin-out. The development of the product is already being carried out in collaboration with industries such as BP, Rolls Royce, Pratt and Whitney. The technology is expected to reach TRL 7/8 and EML 6 by end of 2023 where the technology will be used routinely for industrial and aerospace applications.

Table 3: TRL v/s EML matrix

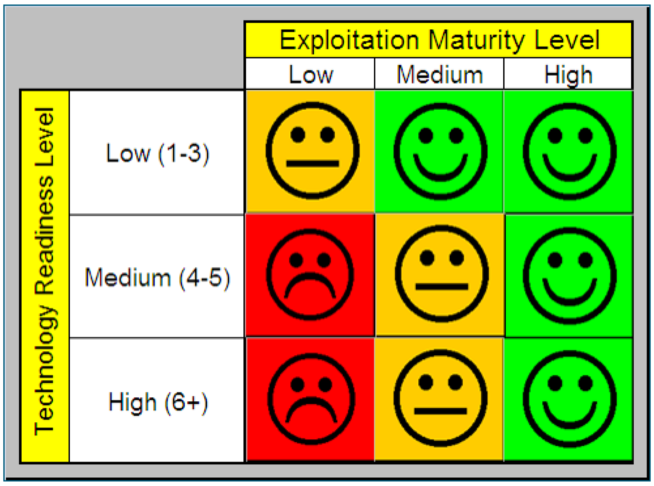


Table 4: TRL v/s EML for oil condition and contamination monitoring

	Lab based tests and ID of potential development partners	Proof of concept on real engines	Sensor performance validation and optimisation	Accelerated Life Testing/ Certification Issues	In-Flight Demonstration on real engine	
Sensor concept developer	Issues with existing approaches Dev sensor & signal conditioning units Lab based performance tests	Proof of concept engine tests Particle counting and sizing Real time analysis suite	Performance assessment/ optimisation Actionable Condition Indicators (ACI)	Widening the scope E.g. fluid in fluid contaminates, ceramic bearing wear detection	Future Developments E.g. Improved sensitivity, Particle composition	EML Low
Sensor Tier 1 Supplier	Technical discussions Commercial, IP and legal arrangements	Manufacture prototype sensor Design and Manufacture DSP	Software for ACI logging/analysis Concept of employment Bearing spallation tests	ECM/ECI tests Vibration and thermal tests Manufacture & Sensor Certification	Supply In-flight sensor, signal conditioning unit and DSP to OEM	EML Medium
Engine OEM	Engine test opportunity offered by OEM Sump plug and in-line designs for target test engines	Test platform sensor system and engine integration Ground tests on target test engines	Identify target engine for sensor system Final sensor engine ICD	Provide target engine platform for engine test	Target engine tests Flight tests	EML High
	TRL1-2	TRL3-4	TRL 5-6	TRL 7	TRL 7-8	
	2014				2023	

12.0 CONCLUSIONS

A new sensor to detect oil contamination and condition has been developed and tested for various cases of liquid and metallic contamination. The sensor is found to detect small quantities of liquid contamination down to 10 PPM. The sensor and electronics have shown to work well both off and on site and real test environments. Work is still being carried on to improve the algorithms to classify the contaminants. The sensors, electronics and software are constantly being improved to suit for in-flight applications and the technology is currently at TRL 5.

13.0 ACKNOWLEDGEMENT

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