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CONDUCTIVITY AND CAPACITANCE SENSOR FOR MEASURING WATER AND OIL EMULSIONS

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Abstract. *The objective of this work is to perform measurements of water and oil emulsions using cooper plates that will act as a capacitance and resistance sensor. In this way we can measure the fraction between phases and the time of separation.*

Keywords: *oil, water, instrumentation, emulsion, capacitance, conductivity.*

1. INTRODUCTION

General measuring of oil-in-water emulsions is a very important activity in several industrial sectors, such as the oil, chemical and food industry. The characterization of emulsions involves not only the determination of volume fraction of each phase but also the size of droplets of a dispersed phase and the solution's separation time. These three parameters of interest: volume fraction, droplet diameter distribution, and separation time are quantities that required sophisticated measurement techniques so that reliable and accurate results could be achieved. Instruments based on laser diffraction are typically used for this purpose. Despite their high cost, these instruments are generally limited in terms of concentration and possible distribution measurement size.

The objective of this work is to present a system for measuring the separation time between phases (water and oil), and the volume fraction of each phase, by simultaneous measurement of the capacitance and equivalent resistance of the emulsion.

Impedance sensors have been widely used in literature for different purposes, including measurement of liquid level, pressure, humidity, gas and liquid fraction measurement in multi-phase flows. The purpose of the present work is to develop an impedance sensor and an experimental procedure that can provide simultaneous information of volume fraction and separation time.

2. EXPERIMENTAL PROCEDURE

The experimental apparatus consists of a sensing module, a signal conditioning and transduction module, an embedded processing unit (DSP TMS320F28335 from Texas Instruments) and a computer containing real-time data acquisition and monitoring software. In Figure 1 we can see schematically the organization of the measurement method.

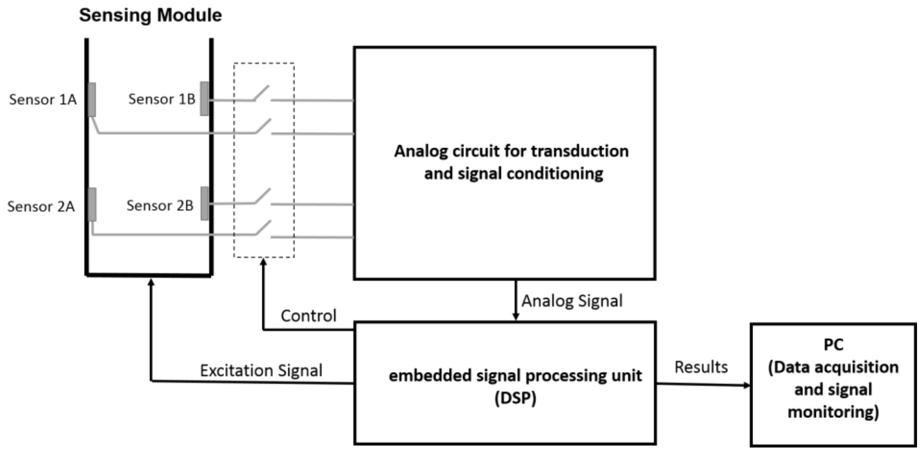

Figure 1. Visual representation of the organization of the measurement method.

As can be seen in Figure 1, the processing unit controls the digital keys coupled to the sensors in the measurement regions. In addition to providing the square wave excitation signal, the unit also processes the analog signal and sends results through serial communication to the computer.

The sensing module consists of two pairs of rectangular and parallel copper plates. These are arranged in a vertical tube of rectangular section. The mentioned arrangement is shown in Figure 2.

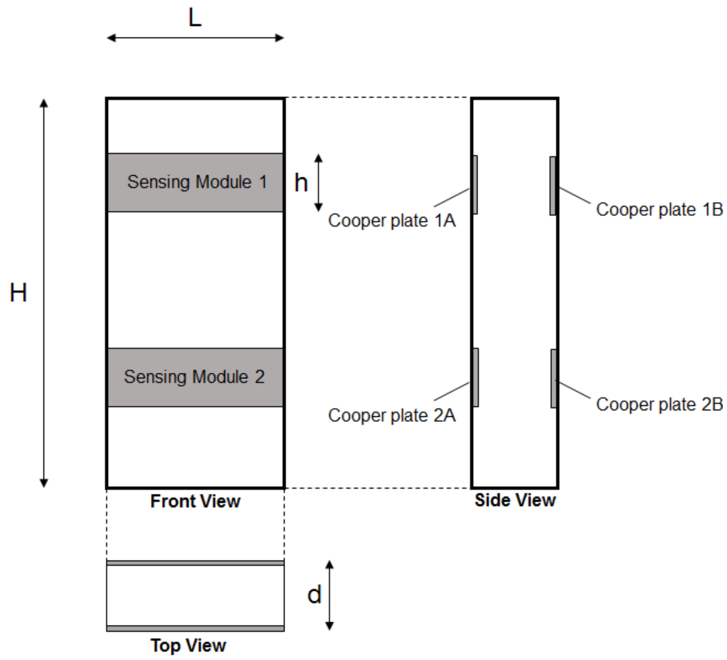

Figure 2. Arrangement of sensors in the vertical tube.

An emulsion formed by oil and water (prepared using a controlled rotation mixer PT 3100 D from POLYTRON) is placed inside the container. Once the recipient is full of the emulsion that will be characterized, the capacitance and resistance in two different levels of the tube (where the two pairs of plates are located) are read.

The impedance model of a generic emulsion consists of a resistance in series with a capacitance parallel to another resistance, as shown in Figure 3.

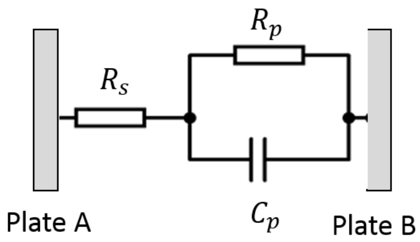

Figure 3. Modeled impedance circuit of an emulsion.

The Measurement System works with the non-simultaneous measurement of each sensor's step response. This step response is obtained through a square wave that is generated by the DSP that must be symmetrical and have a low amplitude so that electrolysis is prevented. The DSP reads the parameters of step response and, through them, calculates the conductivity and permittivity of the emulsion and the oil concentration. In Figure 4 we can see the step response of the system.

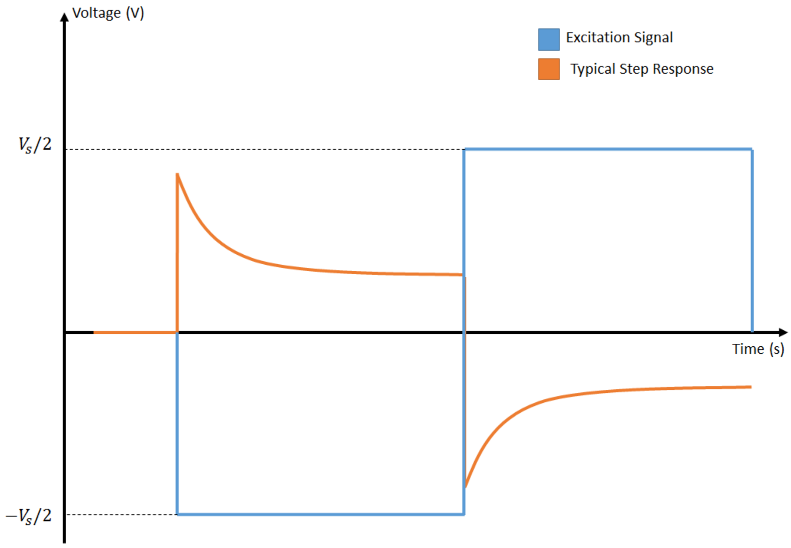

Figure 4: Typical step response expected.

To obtain the parameters of the impedance model shown in Figure 3, we must obtain the steady state voltage, the peak voltage and the time constant of the step response signal (Figure 5).

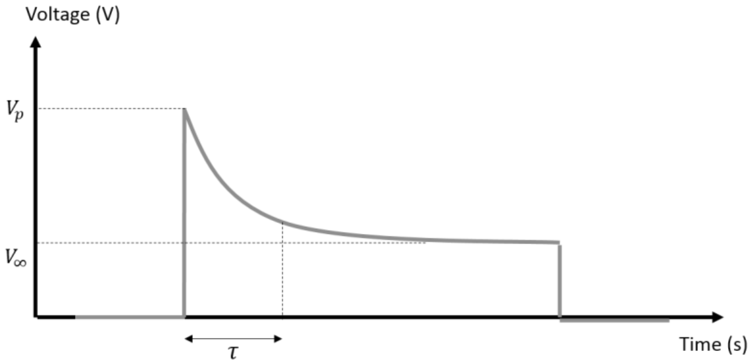

Figure 5. Step response parameters.

Through the step response parameters, shown in Figure 5, the step peak-to-peak voltage (V_s) and the gain resistance (R_g) one can calculate the components of the emulsion impedance model by solving, in the time domain, the electronic circuit. These results are shown in equations 1, 2 and 3.

$$R_s = \frac{V_s}{V_p + V_\infty} R_g \tag{1}$$

$$R_p = \frac{V_p V_s}{(V_p + V_\infty) V_\infty} R_g \tag{2}$$

$$C_p = \frac{(V_p + V_\infty)^2 \tau}{V_p V_s R_g} \tag{3}$$

Through the geometry of the sensors, the previously mentioned calculation of electrical permittivity and emulsion conductivity, can be obtained through equations 4 and 5, respectively.

$$\varepsilon = \frac{C_p . d}{A} \tag{4}$$

$$\sigma = \frac{d}{(R_s + R_p).A} \tag{5}$$

According to Pal (1994) in O/W (oil in water) emulsions, since the conductivity of the oil is very low, the measurement of the ratio between these fluids should be made by the relation between the emulsion's measured electrical conductivity (σ) and the water's conductivity (σ_w). For emulsions with low and mid oil concentration, the oil's fraction (ϕ_{oil}) is given by equations 6 and 7 respectively.

$$\phi_{oil} = \frac{2[\sigma_w - \sigma]}{2\sigma_w + \sigma} \tag{6}$$

$$\phi_{oil} = 1 - \left(\frac{\sigma}{\sigma_w}\right)^{\frac{2}{3}} \tag{7}$$

For W/O (water in oil) emulsions, according to Pal (1994), the concentration of oil can be obtained through the relation between the measured electrical permittivity (ε) and the oil's electrical permittivity (ε_{oil}), as we can see in equation 8.

$$\phi_{oil} = 1 - \frac{\frac{\varepsilon}{\varepsilon_{oil}} - 1}{\frac{\varepsilon}{\varepsilon_{oil}} + 2} \tag{8}$$

Knowing that the sensor has rectangular area "A" and the distance between plates is equal to "d", combining equations 1 to 8, we can explicitly rewrite equations 6, 7 and 8 as a function of the measured parameters (V_∞, V_p and τ), the sensing module geometry (*d* and *A*), the gain resistor (R_g), the peak-to-peak step voltage (V_s), the water conductivity (σ_w) and the oil electric permittivity (ε_{oil}),

$$\phi_{oil} = \frac{2(\sigma_w - \frac{d.V_\infty}{V_s.R_g.A})}{(2.\sigma_w + \frac{d.V_\infty}{V_s.R_g.A})} \tag{9}$$

$$\phi_{oil} = 1-\left(\frac{d.V_{\infty}}{\sigma_w (V_s.R_g.A)}\right)^{\frac{2}{3}} \tag{10}$$

$$\phi_{oil} = 1-\frac{\frac{d.(V_p+V_{\infty})^2 \tau -1}{\varepsilon_{oil}.A.V_p.V_s.R_g}-1}{\frac{d.(V_p+V_{\infty})^2 \tau -1}{\varepsilon_{oil}.A.V_p.V_s.R_g}+2} \tag{11}$$

The DSP performs the signal sampling job at 50 kHz frequency, thus obtaining the parameters of the step response and calculating the emulsion's percentage of oil through the measurement level of each sensor (equations 9, 10 and 11) in real time.

The data acquisition and monitoring software (Figure 6) for the instrument was created using C # language.

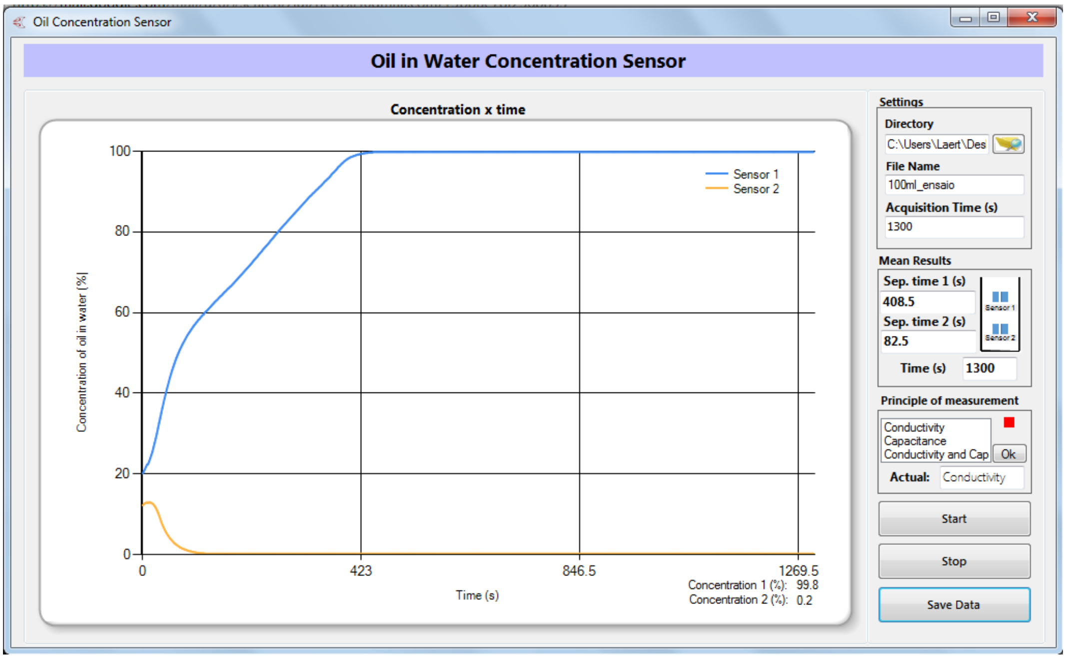

Figure 6. Software Interface

This software plots the concentrations measured by the sensors in real time, allowing the user to choose the conductivity measurement method (O/W emulsions) and/or electrical permittivity measurement (W/O emulsions). At the end of the measurement, the separation time, defined as moment with the concentration as low as 1% below or above to the final value for the first time, is made available. Optionally, the received data can be saved in a spreadsheet in '.csv' format.

3. RESULTS AND DISCUSSION

The measurement trials were performed in a way that the separations could happen quickly, preventing each test from lasting hours (or even days). All emulsions were generated using the same procedure, with the same type of oil (mineral oil), while the water's conductivity constant (σ_w) and the oil's electrical permittivity (ε_{oil}) were previously measured by the system itself.

The typical output signal, before and after the signal conditioning of the analog circuit obtained by Tektronix Scope is shown in Figure 7.

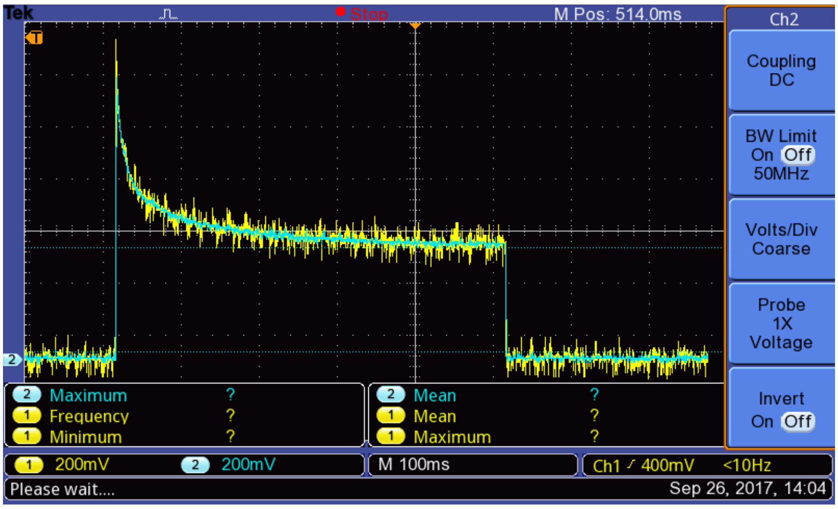

Figure 7. Analogic Signal.

Performing tests with 400 ml emulsion while varying the oil's concentration from 12.5% to 37.5%, the separation curves of the sensing module 2 shown in Figure 8, could be obtained.

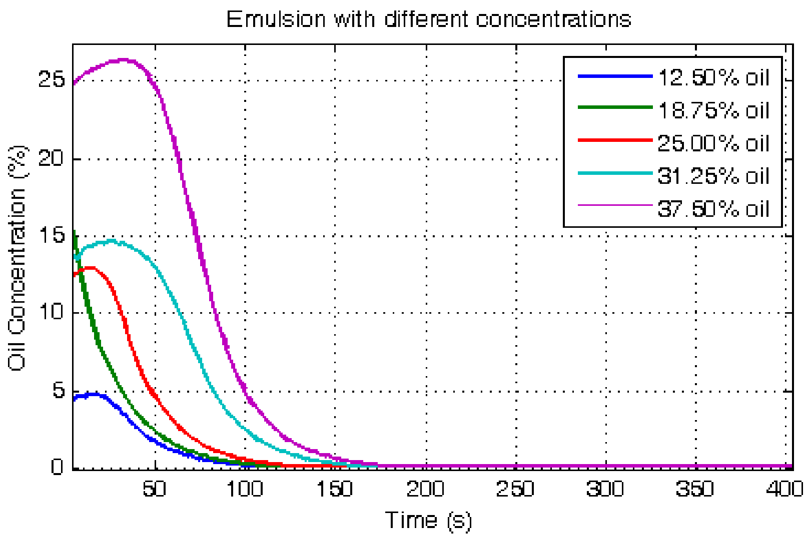

Figure 8. Separation curves associated with sensor 2.

As one can realize from the separation curves, the separation time for sensor 2 tends to be greater as the oil concentration increases. Sensor 2 is located in the lower region of the sensing module. Typically, at the beginning of the tests, there is an increasing concentration of oil in this region due to rising oil droplets located in the region below this sensor. After some time, the concentration tends to decay because these droplets are beyond sensor 2 (they have left the measurement region of this sensor).

The separation curves of the sensing module 1 is shown in Figure 9.

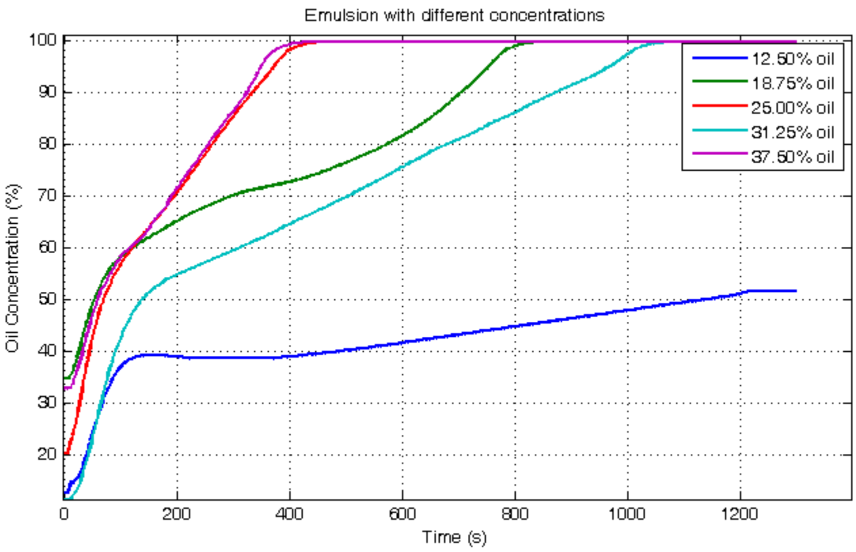

Figure 9. Separation curves associated with sensor 1

From the Sensor 1 separation curves, one can realize that the concentrations measured by this sensing module tend to rise. This happens due to the fact that this sensor is located almost in the top line of the emulsion tested. In this way, the separated oil tends to rise and concentrate in this sensor's region. The only test in which the steady state concentration did not reach values close to 100% was the 12.5% oil test, since the volume of oil used was enough to cover approximately 50% of the area of the plates, as shown in Figure 10.

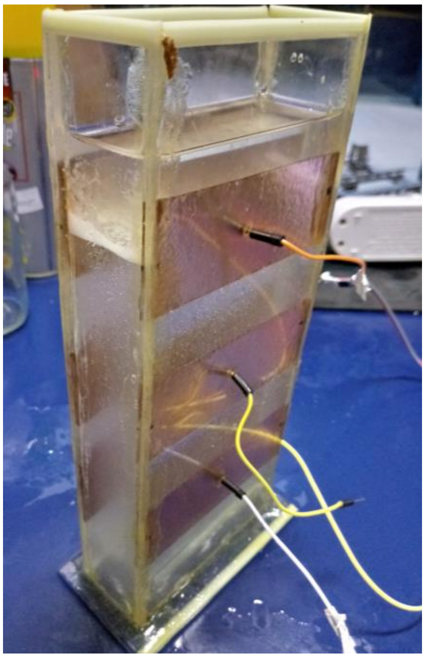

Figure 10. Vessel containing an almost separated oil emulsion.

The separation time for sensor 1 is associated with coalescence between the oil droplets accumulated at the top of the measuring container. From the results obtained with this sensor, one can verify the time that the large droplets take to go up reaching the measurement region of this sensor. This process implies that there will be an accentuated slope at the beginning of the separation curve, indicative of a first characteristic derivative for the system. From this point on, there will be a second derivative that occurs as a function of the droplets' coalescence and pure oil accumulation between the copper plates from the sensing module 1. This second slope can be interpreted as another characteristic derivative for the separation curve. In Figure 11 the region of accumulated large oil droplets can be seen between almost pure water and separated oil.

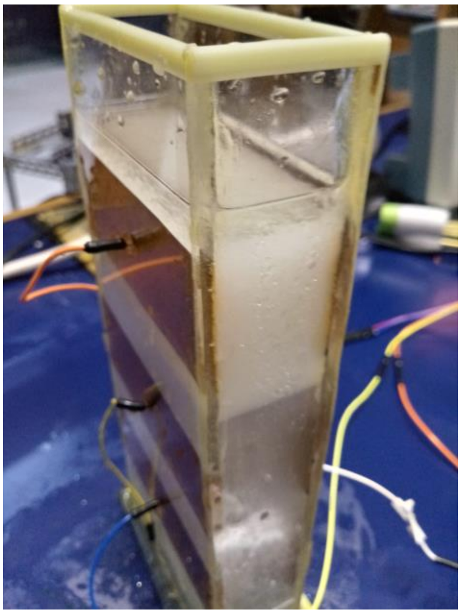

Figure 11. Large oil drops located between almost pure water and separated oil.

The separation times and corresponding steady-state concentrations are shown in Table 1.

Table 1. Separation times and corresponding steady-state concentrations.

Total Volume (ml)	Φ_{oil} (%)	Sep.Time 1 (s)	Sep. Time 2 (s)	$\Phi_{oil,\ final\ 1}$(%)	$\Phi_{oil,\ final\ 2}$(%)
400	12.50	1073	59.5	50.9	0.2
400	18.75	794	70	99.8	0.2
400	25.00	408.5	82.5	99.8	0.2
400	31.25	1020	118.5	99.8	0.2
400	37.50	383	135.5	99.8	0.2

From Table 1, the separation times corresponding to the sensing module 2 had a steady growth according to the oil's concentration, since its measurement at the concentrations tested did not depend so much on the coalescence of the larger oil droplets but of the rise of these drops. It can also be noted that the separation time of sensor 1 in all the tests was much longer than the one associated to sensor 2. This phenomena is explained due to the fact that sensor 1, besides measuring the concentration due to the ascent of the drops, also measures the time taken for the coalescence.

4. CONCLUSIONS

The system has great flexibility in water oil measurements since it is capable of simultaneously measuring resistance and capacitance. The DSP usage provides great robustness and speed in the required calculations. It also allows the storage of the results in the memory of a computer through the serial communication, what represents an important resource for numerous data interpretation.

The use of sensors arranged at two different measurement levels provides very relevant information regarding the separation of the emulsion. For future works it is expected that the derivative of the separation curve, which represents the rising rate or coalescence of the oil droplets, can be mathematically correlated to droplets' average diameters, thus providing another relevant information related to the emulsion.

5. REFERENCES

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6. RESPONSIBILITY NOTICE

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