# Examination of Contaminant-Induced Faults in Connectors

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**Abstract -** *This paper describes the results of an investigation into the effects of salt water exposure on cable connector impedances. A series of tests were performed to explore the shunting resistance across the pins of wiring harness connectors. The test results show that salt-induced corrosion and moisture may cause intermittent shunting resistances capable of affecting the normal operation of various systems. One important test result is that the induced shunting resistances are a nonlinear function of the applied voltage. This non-linear behavior can be important when evaluating the ESD or radiated RF susceptibility of products that may be exposed to a salt-water environment. An equivalent circuit based on measurements is developed to model the behavior of various salt-water/metal electrode interactions.*

## I. Introduction

It is not uncommon for car owners to experience intermittent problems with their automobiles that can't be reproduced at the repair shop. This can be particularly frustrating when the problem affects an electronic system that prevents the vehicle from being operated. Contaminants that produce an intermittent short are often suspect, but difficult to track down when the short is not present.

Relatively few papers have been published on the effect that typical automotive contaminants can have on electronic systems. Golnabi [1] investigated the electrical conductivities of pure, distilled, municipal, industrial and river water in liquid form. Fernandez [2] introduced a conductivity cell to measure the electrical resistance of various electrolytic solutions. Warburg [3] first proposed that a metal electrode/electrolyte interface could be represented by a polarization resistance in series with a polarization capacitance. Randles [4] proposed a well-known model consisting of an interface capacitance shunted by a reactive impedance, in series with the solution resistance. Franks [5] proposed a measurement technique along with a corresponding equivalent circuit model to quantify the electrode-electrolyte interface impedance using electro-chemical impedance spectroscopy for various electrode materials commonly used in biomedical applications. Troy and Cantrel [6, 7] explored the effects that the electrode-electrolyte interface has on AC potentials in neural science applications. However, there is a lack of published research that describes the effects that contaminants can have on the DC or low-frequency impedances in typical automotive applications.

This paper investigates the effects of contaminant exposure on the shunting impedance of common wiring harness connectors. While normal automotive oil and grease were not found to have a significant impact on typical automotive circuits; exposing a connector to salt water (even briefly) is shown to be capable of generating intermittent shunting impedances that can affect the operation of these circuits significantly both during and long after the exposure occurs.

## II. Measurements of the Shunt Impedance between Pins

In this section, the effects of various salt solutions on the shunt impedance between pins in a cable connector are investigated. The test setup is illustrated in Fig. 1. A voltage supply is connected in series with a known value resistor and a cable connector (3 round pin latching CB/audio cable, from MPJA online, stock no. 17861 CB), which is dipped into the solution being investigated. The distance between the two pins in the connector is about 8 mm. By measuring the voltage across the solution, $V$, the resistance between the connector pins can be calculated as,

$$R_{eq} = R\frac{V}{(V_s - V)} \quad (1)$$

where $R_{eq}$ is the equivalent resistance of the solution between the two pins.

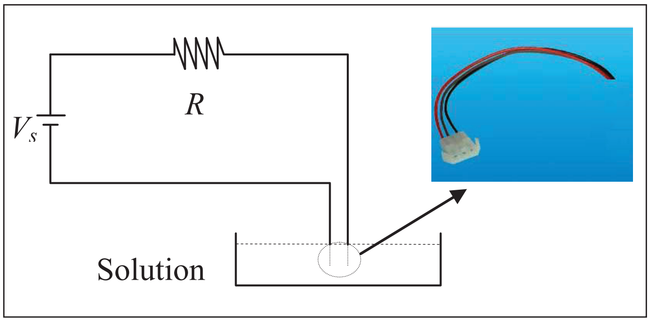


*Fig. 1. Test setup for measuring the resistance of a solution*

### *A. Effect of the stimulus voltage and concentration*

The equivalent resistance was measured for solutions of salt at various salt concentrations and various stimulus voltages. For these tests, the mass ratio of salt to water, r, was varied from 0 to 25%; R was set equal to 100 ohms; and the stimulus voltage, $V$, was varied from 0 to 12 volts by adjusting the supply voltage, $V_s$.

Fig. 2 shows the shunt resistance appearing across adjacent connector pins as a function of the stimulus voltage for various salt concentrations. It is evident that the shunt resistance presented by the salt water depends on the salt concentration. For higher salt concentrations, the resistance is lower. Additionally, the resistance is a nonlinear function of the applied voltage. When the voltage is less than approximately 2 volts, the resistance decreases rapidly as the stimulus potential increases. When the stimulus voltage is well above 2 volts, the resistance levels out. When the mass ratio of salt to water is 0.5%, the resistance levels out at about 400 ohms. The resistance falls below 100 ohms for mass ratios of 10% – 25%.

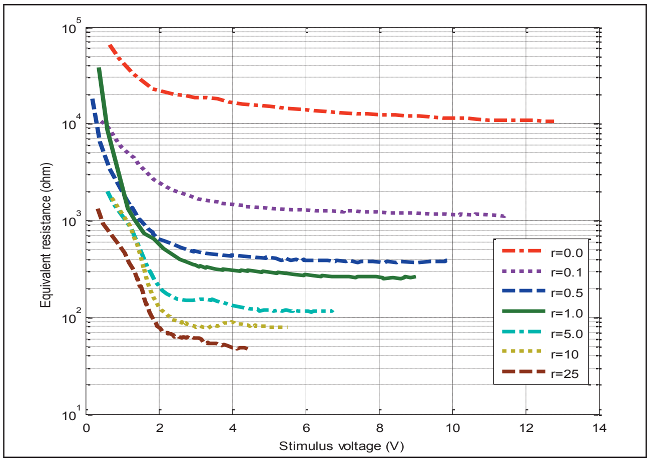


*Fig. 2. Effect of salt on cable connector impedance.*

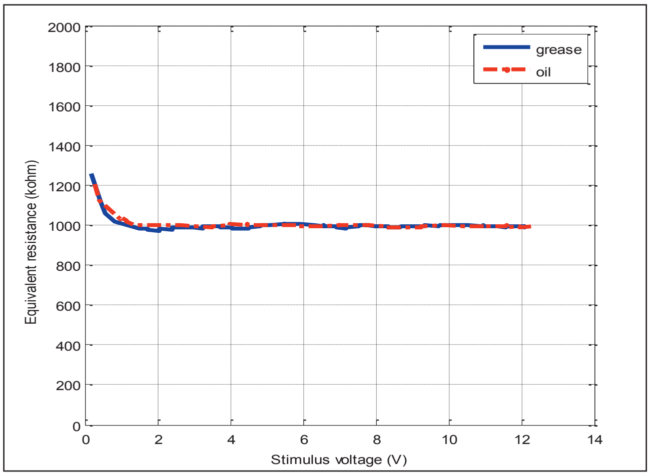


*Fig. 3. Effect of oil and grease on cable connector impedance.*

Similar measurements were performed using pure oil (NAPA Premium SAE 30 Motor Oil) and grease (NAPA Lubriplate No. 105 Motor Assembly Grease) instead of the salt solution. In these measurements, R was equal to 337 kilohms. Fig. 3 shows the results of these measurements. Although there is a slight non-linear behavior below 1 volt, the equivalent resistances of oil and grease level out at around $10^6$ ohms, indicating that these two contaminants have little effect on connector impedance.

### B. Effect of distance and surrounding area

In the salt water tests in the previous section, there was noticeable corrosion deposited on the connector electrodes that grew thicker with time during the course of the test. In order to investigate whether the measured shunt resistance was due to the corrosion or the salt water itself, measurements were made of the resistance between two metal electrodes separated by varying distances. A nickel electrode with a square cross section was used. The mass ratio of the salt solution was 0.1%, $R$ was equal to 50 ohms, and the container dimensions were either 14 cm x 5.5 cm (slim container) or 14 cm x 14 cm (square container). If the corrosion resistance was dominant, one would expect the measurement to be nearly independent of distance. The results in Fig. 4 show that as the distance between the two electrodes increased, the equivalent resistance increased. In the slim container, where most of the current was confined to a uniform cross-section, the resistance was nearly a linear function of distance, indicating that the solution

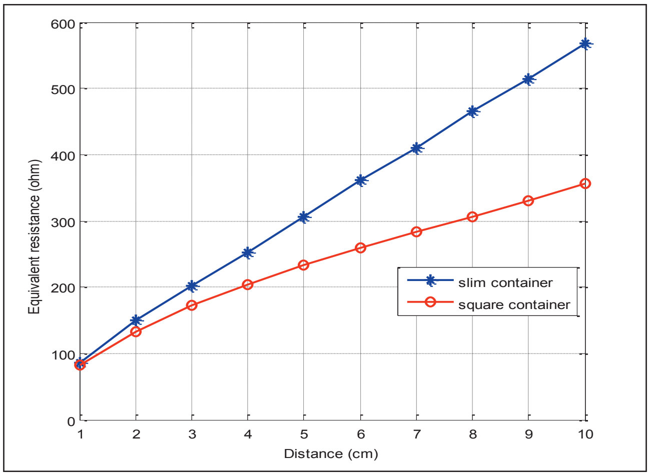


*Fig. 4. Measured resistance as a function of the distance between two electrodes.*

itself was the dominant contributor to the resistance and not the corrosion on the electrode.

### C. Effect of corrosion and moisture

To investigate the effects of corrosion and moisture on resistance, the resistance was measured every minute while:

1. The connector (3 small .110" flat pin CB/audio cable, from MPJA online, stock no. 17856 CB) was soaking in the salt solution;
2. the connector was removed from the solution and hung in the air;
3. the connector was hung in the air again after spending a few hours in a cold environment (refrigerator).

A 100-ohm resistor was utilized for these measurements; the DC voltage, $V_S$, was 6 volts. The equivalent resistance of a sample connector is shown in Fig. 5. It can be seen that equivalent resistance was around 1 kilohm when the connector was first dipped in the salt water. After the salt water was removed and the connector was hung in the air, the measured resistance varied from less than a hundred ohms to hundreds of thousands of ohms randomly. Finally, the system stabilized and a corrosion film deposited on the plastic appeared to form a conductive path between the connector pins with a resistance of only about 20 ohms. After a few hours in the refrigerator, the conductive path was apparently degraded and the resistance resumed a high value; however as moisture condensed on the connector, the resistance again decreased to several kilohms. Fig. 6 shows the results of a similar test on another connector. This time, after the connector was taken out of the salt solution, the resistance steadily increased as the connector dried out. After removing the connector from the refrigerator, the resistance was only a few hundred ohms. The resistance increased rapidly, then dipped again as time elapsed.

Fig. 7 shows the results for another connector after the initial soaking process. The resistance increased as the water evaporated. After the connector was stored in the refrigerator, the resistance remained high for a couple of minutes and then dropped to several hundred ohms and then increased again. It is possible that moisture condensed between two connector pins after it was removed from the refrigerator; then as time went by, the moisture evaporated (possibly

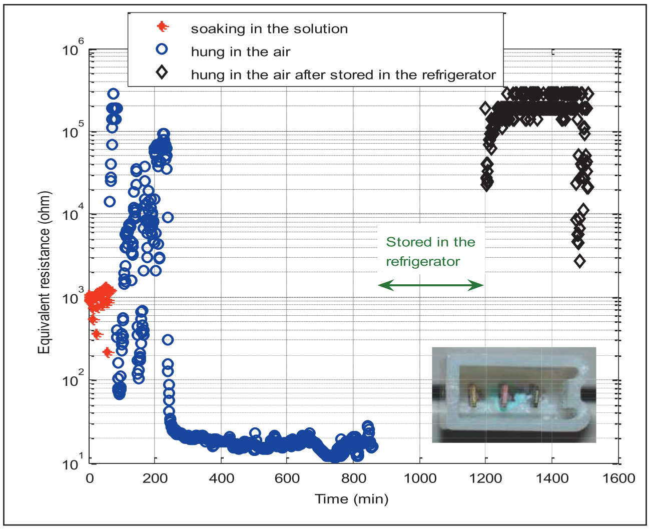


*Fig. 5. Resistance between the pins of a connector, soaked in a salt solution, hung in the air, and hung in the air after being cooled.*

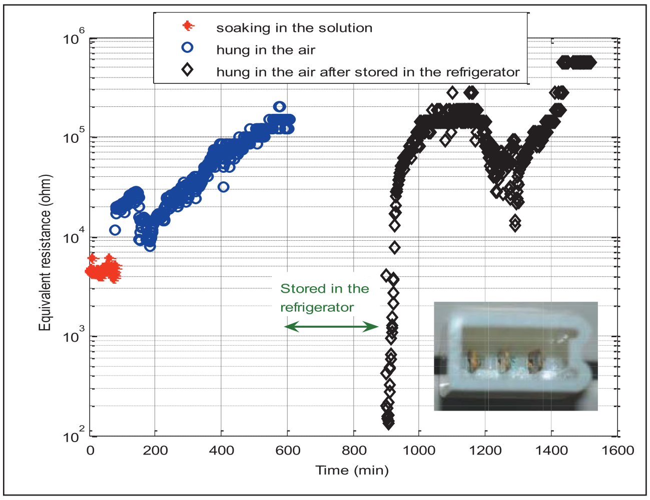


*Fig. 6. Resistance between the pins of another sample connector.*

aided by the current flowing through the fault) and the connector impedance became high again.

Fig. 8 shows the results of another connector impedance measurement. For this measurement, the connector was first soaked in the salt solution, then hung in the air, and then (after the connector dried out) quickly dipped in the solution once again and hung in the air. After the quick dipping, the resistance dropped to 10s of ohms as the connector dried out.

Measurements similar to those shown in Figs. 5 to 8 were repeated with several connectors. The results were different every time; but it is clear that the resistance between connector pins that have been exposed to a salt solution varies unpredictably with time. From these sample test results, it appears that a combination of corrosion and moisture are responsible for the conductive path that forms.

## III. Equivalent Circuit Model

While distilled water is almost an insulator, salts and other contaminants can transform water into a relatively good conductor. With a DC voltage applied to the electrodes, the nonlinear changes in resistance as a function of voltage observed in the previous section make it more likely that a connector fault will exhibit a wide range of impedances. In

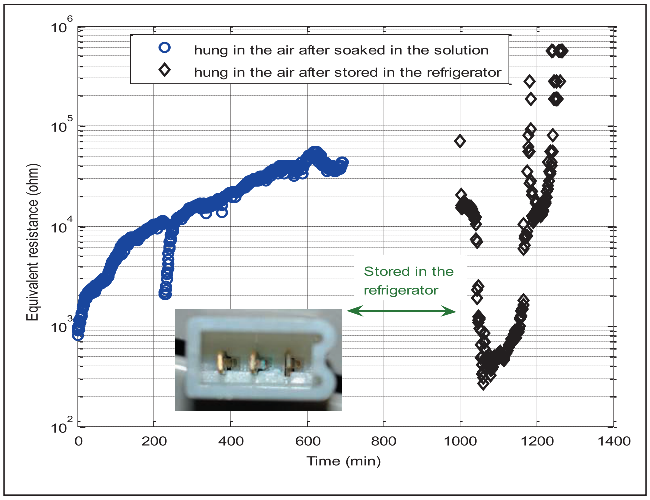


*Fig. 7. Resistance between the pins of another sample connector.*

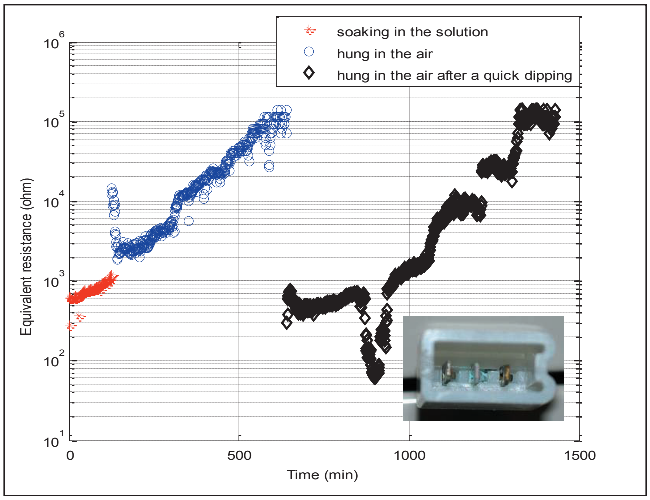


*Fig. 8. Resistance between the pins of a twice-dipped connector.*

this section, an equivalent circuit model is proposed to explain and simulate this nonlinear behavior.

### A. Equivalent circuit model for salt water

The equivalent circuit model proposed in this work is comprised of two diodes, which represent the interfaces between the electrodes and the salt solution, in series with the salt water resistance $R_{salt}$. The model is shown in Fig. 9.

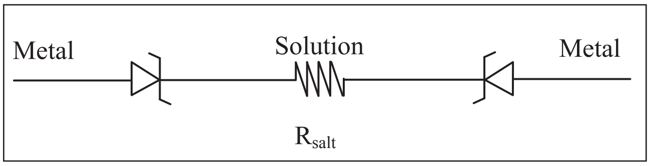


*Fig. 9. Equivalent circuit model including electrode-salt solution interface and salt solution.*

In this model, the interface diode exhibits the following exponential relationship between the diode current $i_D$ and the voltage across the diode ($v_D$),

$$i_D = I_s\left(e^{\frac{v_D}{nV_T}} - 1\right) \quad \text{for} \quad v_D > -V_Z \qquad \text{for} \quad (2)$$

where $V_Z$ is the reverse breakdown voltage, $I_S$ is the saturation current, $n$ is the emission coefficient, and $V_T$ is the thermal voltage. This equation describes diode behavior in the forward and reverse biased region. The thermal voltage is around 25 mV at room temperature.

The resistance of the salt water is proportional to the distance between the electrodes,

$$R_{salt} = R_s \cdot d \quad (3)$$

where Rs is the resistance per unit length of the salt water in the given configuration, and has units of ohms/cm. d is the distance between the two electrodes in centimeters. Therefore the relationship between the total equivalent resistance and the stimulus voltage can be determined by solving the equations,

$$v = \ln\left(\frac{i}{I_S}+1\right)nV_T + iR_S d - \ln\left(1-\frac{i}{I_S}\right)nV_T \quad (4)$$

$$R = \frac{v}{i} \quad (5)$$

where the first and the third terms in (4) are the voltages across the diodes formed in the electrode region and the second term is the voltage across the salt water.

### B. Validation

To validate the proposed circuit model, measurements were performed using various metal electrodes including copper, aluminum, zinc, stainless steel, magnesium, and nickel; and the results were compared to simulation results using the circuit model. The electrodes used for these measurements were rods with square cross-sections of the same size (20-mm width, 1.2-mm thickness, and 12-mm height). Table 1 gives a summary of the fitted parameter values. The salt water resistance for these measurements was determined to be 133 ohms/cm.

Figs. 10 to 15 show both the measured results and the model results for copper, stainless steel, zinc, magnesium, aluminum, and nickel electrodes, respectively. The model results fit very well for each electrode metal. For different electrode materials, the different interface characteristics result in different equivalent resistances.

## IV. Conclusion

The effect of salt, oil, and grease on the shunt resistance of cable connectors was investigated. Oil and grease had little effect on connector impedance; however exposure to salt water had a significant effect on the impedance. The impedance of connectors that had been exposed to salt water was found to be a function of several factors including the stimulus voltage, time since the last exposure, and moisture. The experiment results suggest that corrosion and moisture can form an effective conductive path between connector pins. A nonlinear relationship between the equivalent resistance and the applied DC voltage was observed, and a model was developed to characterize this nonlinear behavior. This equivalent circuit model consists of two interface diodes in series with the salt water resistance. The model was validated for various electrode metals including copper, aluminum, zinc, stainless steel, magnesium, and nickel.

Though this investigation was limited in scope and more work needs to be done to fully characterize the effect of various con-

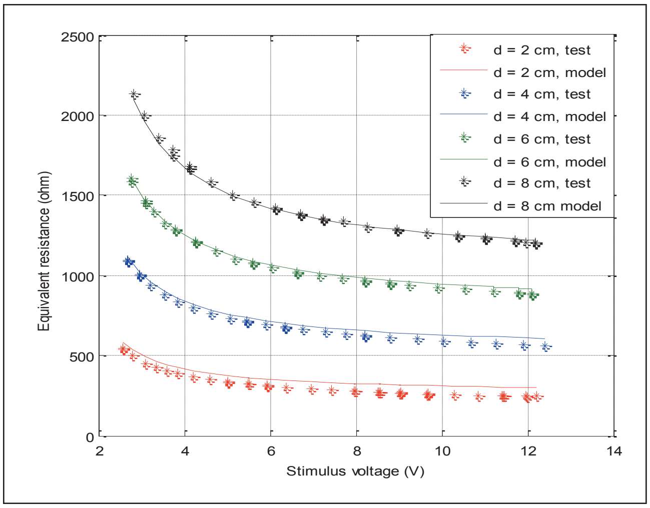


*Fig. 10. Comparison between the measurements and model for copper electrodes.*

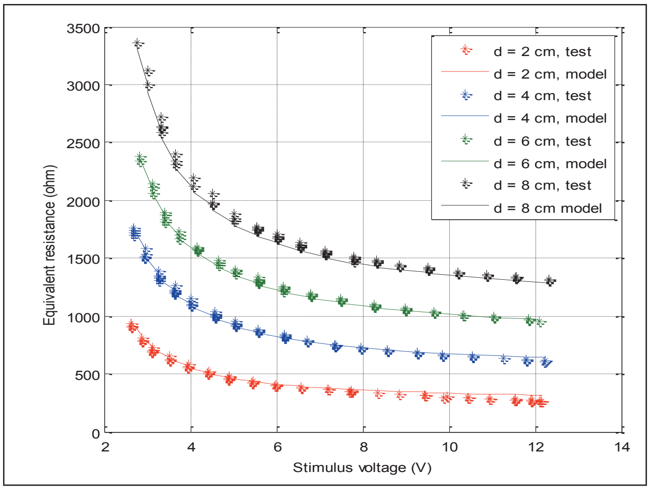


*Fig. 11. Comparison between the measurements and model for stainless steel electrodes.*

*Table 1. Model parameters obtained by fitting the experimental data.*

| | Copper | Stainless steel | Zinc | Magnesium | Aluminum | Nickel |
|---|---|---|---|---|---|---|
| $I_s$ (A) | 1.859e-9 | 1.146e-11 | 6.584e-9 | 6.691e-9 | 6.678e-9 | 3.638e-11 |
| $n$ | 2.0 | 2.0 | 1.34 | 1.0 | 1.89 | 2.0 |
| $V_T$ (V) | 0.025 | 0.025 | 0.025 | 0.025 | 0.025 | 0.025 |
| $R_s$ (ohms/cm) | 133 | 133 | 133 | 133 | 133 | 133 |

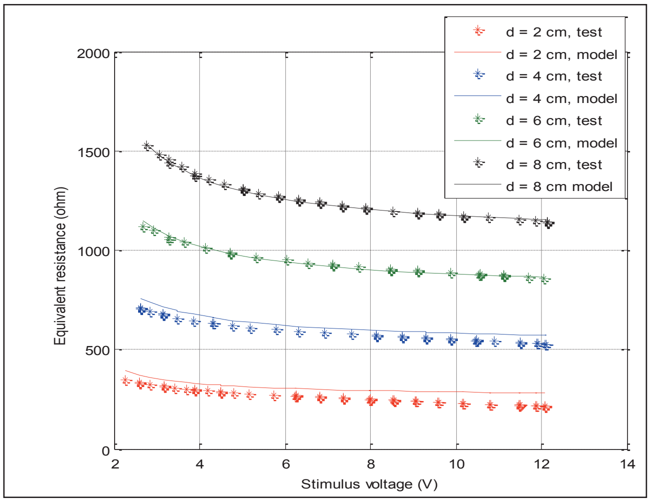


*Fig. 12. Comparison between the measurements and model for zinc electrodes.*

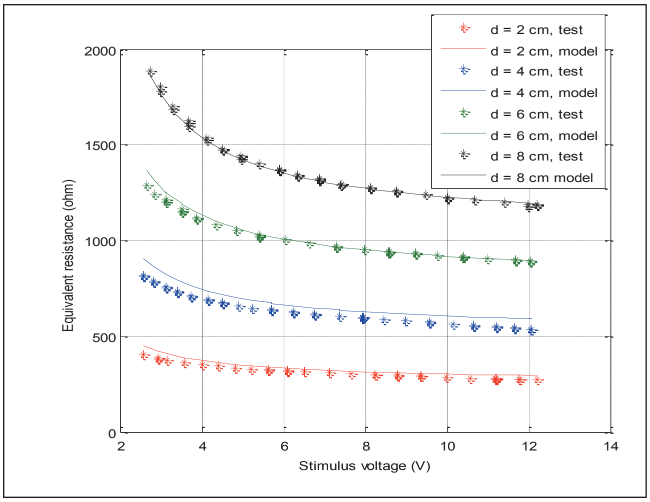


*Fig. 14. Comparison between the measurements and model for aluminum electrodes.*

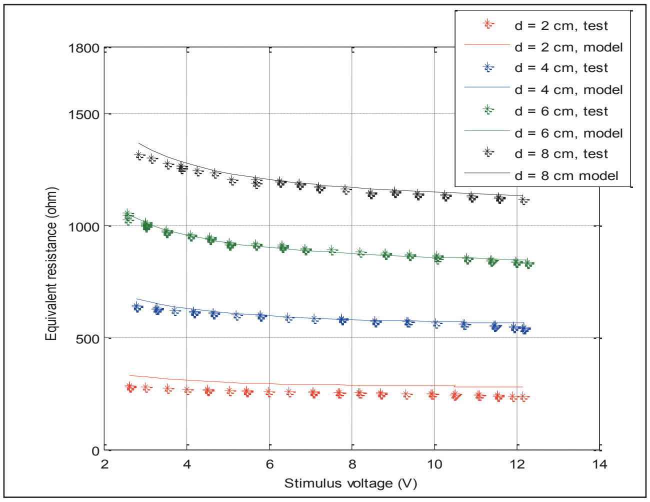


*Fig. 13. Comparison between the measurements and model for magnesium electrodes.*

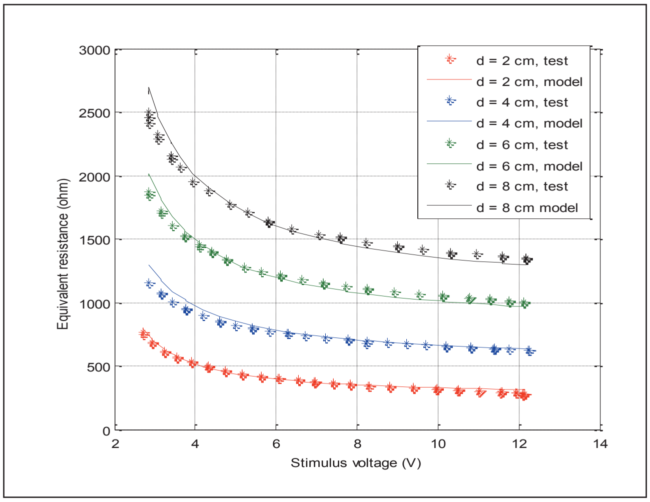


*Fig. 15. Comparison between the measurements and model for nickel electrodes.*

taminants; the results presented here confirm that contaminants containing salt are capable of producing low shunt resistances on the order of 10 ohms to several kilohms. The non-linear nature of these impedances makes them difficult to detect with typical hand-held resistance meters that apply less than 1 volt across the shunt during a measurement. This non-linearity can also rectify or partially rectify applied RF signals in a manner similar to the "rusty bolt" effect that is well known to most EMC engineers. This could effectively demodulate RF signals with an amplitude modulation. Another possible effect of this non-linear behavior is the unwanted rerouting of transient currents (e.g. due to electrostatic discharge or power line spikes).

It probably wouldn't surprise many engineers to learn that salt water in an electrical circuit can have undesirable consequences. However, the non-linear nature of salt water shunting impedances and the fluctuating behavior of these impedances with time and moisture are less well understood. These factors can potentially have a significant impact on EMC and reliability testing of products that have to function in less than ideal environments. **EMC**

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## Biographies

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