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Design Guidelines for Automotive Fuel Level Sensors

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Abstract

Most current automotive and light truck fuel level sensors are essentially rotary potentiometers that have been designed to survive the chemically harsh environments found in the fuel tank. This paper will chronicle the design improvements made from the early wire wound versions to today's more robust thick film ink systems. The paper will highlight potential failure modes and discuss techniques to reduce noise and increase wear life. Data will be provided regarding changes in the circuit layout, ink compositions, and contact materials. Special consideration will be given to the adverse effects associated with the reactive sulfur prevalent in today's fuels.

Introduction

Electromechanical liquid level sensors are often designed with a float arm pinned to the center of a rotary potentiometer. This design concept is used in most automotive fuel level senders because it offers the potential for both long life and low cost. The float arm is mounted vertically, and liquid level changes produce a rotary motion for the potentiometer contacts. This change of position alters the resistive value of the sensor. The influence of the contact position is schematically illustrated in figure 1.

However, over the years, performance requirements have dramatically changed. Initially, the sensors were used to directly drive the analog fuel gauges mounted in the dashboard. This required higher drive voltages and currents than are used today. Additionally, contact noise was not a significant worry since the analog display acted to average the input signal, and in essence, filter out the noise. Today's systems tend to be digital, and signal noise is now interpreted as a change of position or a loss of linearity. In an effort to develop a set of design guidelines, this paper will review the evolution of the potentiometric fuel level sensor. It will attempt to identify most of the known failure modes and offer potential solutions.

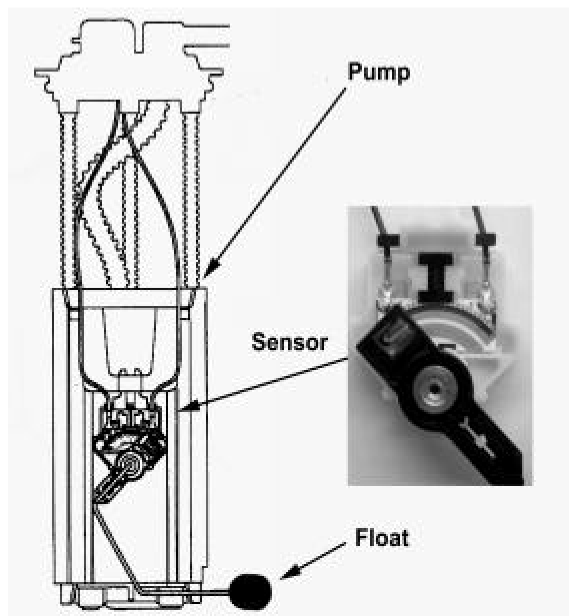
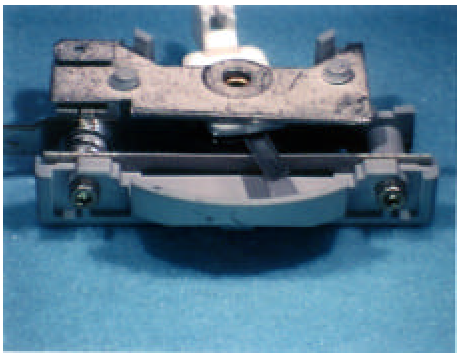


Figure 1. *Schematic diagram illustrating the fuel sender module and position of the level sensor.*

Historical Review

Wirewound Potentiometers

The very early sensor designs often used a wire wound potentiometer, typically using a Ni-Cr wire as the resistive element. As shown in figure 2b, the wire is wound around a non-conductive substrate. Ceramic substrates were often used to prevent environmental distortion. The combination of the wire diameter and the overall wire length controlled the output resistance. The smaller the wire to wire gap, the better the resolution. Linearity was controlled by the uniformity of the wire gaps and consistency of the wire diameter. Once the wire is wound, the system was not easily trimmed to correct for linearity variations.



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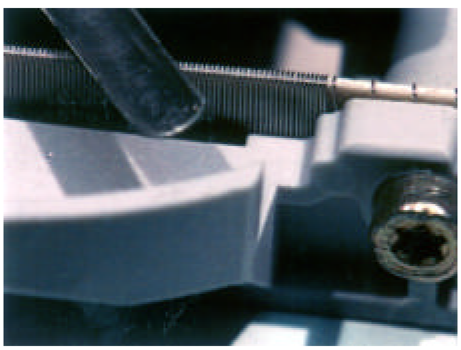
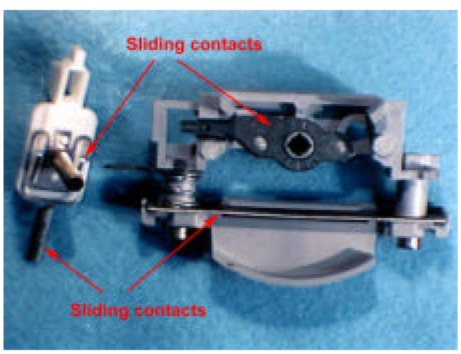


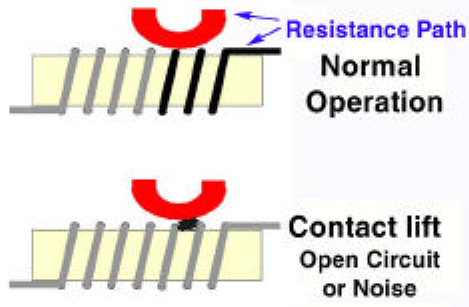
2b



2c

Figure 2: Low magnification views of a wirewound fuel level sensor a) front view, b) enlargement of wire wraps, c) disassembled

Unfortunately, these early designs had a wide range of possible problems. As shown in figure 2c, the sensors had many distinct parts that often required hand assembly. Therefore, the assembly techniques were critical to overall performance and cost. The electrical path was arduous and often included two sets of sliding contacts. In addition to the inaccuracies associated with variations in the wire spacing, the Ni-Cr wire was susceptible to lacquer formation when exposed to a fuel tank environment. The wirewound elements were also susceptible to trapping solid particulate between the wraps, leading to localized open circuits as the particle lifted the contact above the wires. This is schematically illustrated in figure 3.



3a

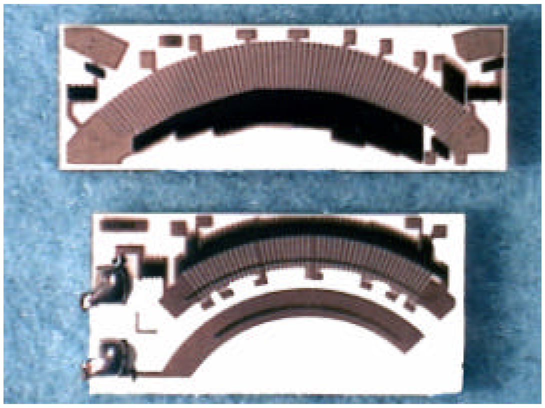
3b

Figure 3: Schematic drawings of wirewound sensor showing
(a) normal contact position and
(b) effect of trapped particle.

The design also required two sliding interfaces, one between the moveable contact and the resistive wire, and a second between the contact and the exit termination. Often the contacts and terminations were nickel electroplated over a copper base alloy (such as CDA 260 brass). Wear of the nickel plate could lead to either local noise spikes or exposure and subsequent corrosion of the underlying brass. Nickel is also susceptible to sulfide tarnish films when exposed to gasoline. These films can cause signal noise, or in the extreme, can add a significant resistance offset to the overall sensor output.

Because of these problems, the industry gradually shifted to a thick film resistive ink technology. The thick film inks are based on a glass carrier and are silk screened and then fired onto an alumina substrate. Firing temperatures are generally in the range of 800 C. Because of the chemical stability of the thick film products, they are superior to the thin film based systems. Gasoline interaction with the resin carriers in the thin film inks can result in degradation and loss of signal integrity.

Thick film products generally fall into two design schools, based on the number of circuit paths found on the alumina substrate. Figure 4 contains the card layout for a typical single and dual trace designed sensor. In both cases, the card has segmented conductor spokes radially attached to the resistor track. The mating contacts slide across the segments and not directly on the resistive ink.

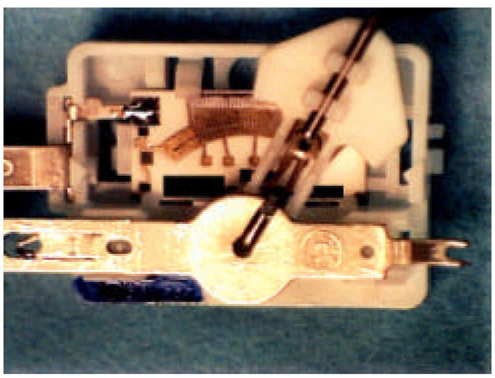


4a

4b

Figure 4: *Thick film inks fired on alumina cards. Layouts are typical for a) Single trace design b) Dual trace design*

The so-called single track designs basically substitute the thick film ink directly for the resistance track. Although they overcome some of the problems of the earlier wire wound approaches, these still suffer from the similar complex assembly / interface issues as their wirewound predecessors. An example of this design is shown in figure 5.



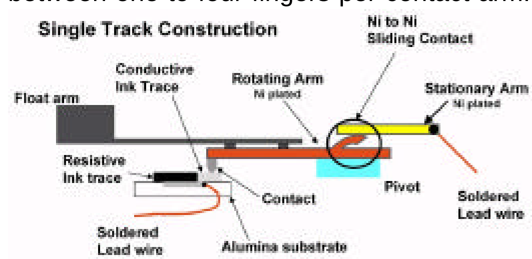
5a

5b

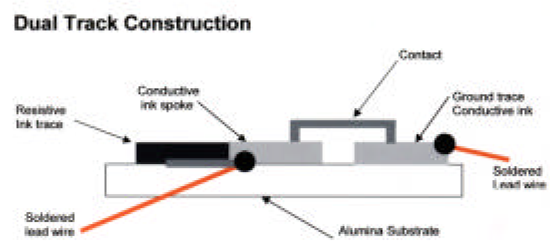
Figure 5: *View of early generation single trace thick film sensor a) top view b) contact assemblies*

This example uses a rivet style contact for mating to the thick film ink and a radiused nickel plated contact for mating to the I/O terminal. The Ni to Ni interface requires high mechanical forces to clean away the tarnish films.

In the dual track design, however, the card circuitry also contains a parallel ground trace. The sliding contact acts as a short between the two tracks and the I/O terminations are made at the end of both traces. With this approach, the metal composition of the sliding contacts are generally the same for both tracks and are often a precious metal. This approach eliminates the Ni to Ni sliding contact and replaces it with a contact that slides against the conductive ink trace. The relative complexity of both designs is shown schematically in figure 6. Figure 7 shows a typical dual trace sensor using a three-finger, bifurcated contact design. Commercial designs can be found with contacts using between one to four fingers per contact arm.

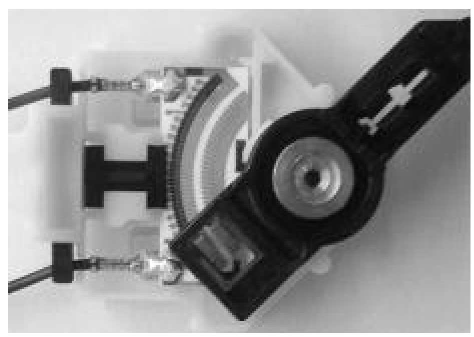


6a



6b

Figure 6: Schematic diagrams illustrating the typical current path and assembly complexity for both the single and dual trace, thick film designs.



7a

7b

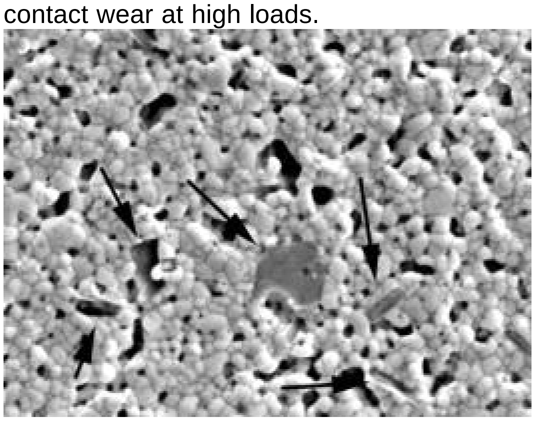
Figure 7: *View of recent design, dual trace thick film sensor a) top view b) contact assembly*

It should be noted that the thick film resistive ink is an abrasive mixture of refractory oxides and glass. For that reason, the thick film designs use a shunt approach, and provide a series of conductive radial arms that are equally spaced along the resistive trace. Figure 5 showed the typical tile layouts. The conductive arms are generally based on either a Ag / glass or Ag-Pd / glass thick film ink. These conductive inks are far less abrasive than the resistive trace. However, since these inks contain high levels of silver, they tend to form sulfide tarnish films when exposed to gasoline. The designer is then faced with finding an appropriate way to clean off the noise forming films without creating excess wear on either the contacts or the conductive ink traces. The remainder of this paper will outline a series of design guidelines to help the designer successfully complete this balancing act. These recommendations can be applied to both the single and dual track approaches.

Ink Characteristics

The inks are normally formulated by physical blending metal and glass powders, called frit. The glass provides the bonding agent to the ceramic and the metal provides the conduction path. The powders are mixed with a polymeric binder to allow patterned silk screening onto the substrate. The binder is driven off during a low temperature exposure at the early stages of the firing profile, and higher temperature exposures are then used to sinter the powders. Firing is generally done in air to prevent reduction of the glass and to aid in complete removal of the binder through a combined volatilization /combustion process. Historically, firing schedules were developed to promote solderability by minimizing both surface glass exposure and oxidation of the ink components.

The most common conductive inks contain mixtures of Pd and Ag as the metal powders. Pd levels from 0 to 30% have been tried in these applications. Pd improves the mechanical strength of the ink and reduces Ag migration. At the firing temperatures used to ensure proper adhesion to the ceramic substrates, the metal powders will sinter and therefore anneal; as such, the metal portion of the ink is expected to be extremely soft. However, as shown in the previous papers,[1,2] the wear characteristics of the inks do not always follow what would be expected for a soft, ductile precious metal surface. The sensors studied previously failed by either excessive signal noise at low contact gram loads or by abrasive contact wear at high loads.



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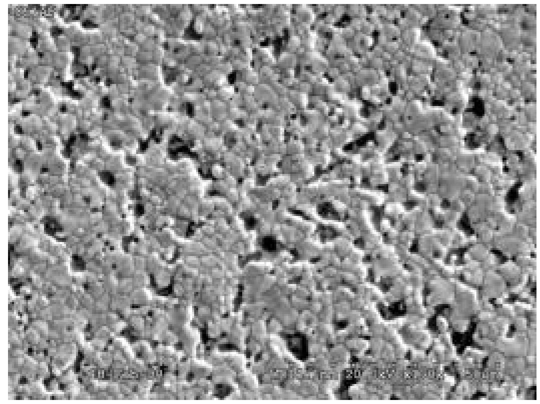

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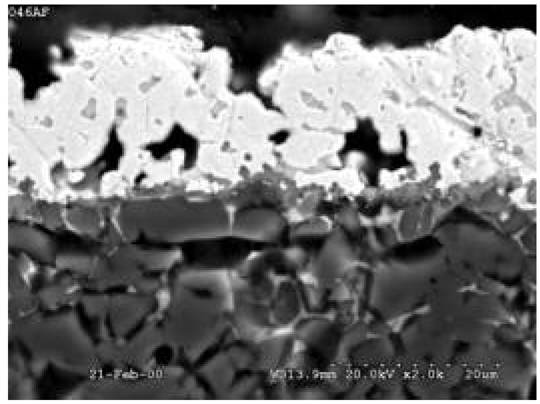


8c

Figure 8. *Examples of surface and cross-sectional structure of typical Ag-Pd conductive inks. a) surface with excessive glass particles, b) acceptable low glass surface, c) cross section of acceptable ink.*

Figure 8 shows cross sectional and surface views of a typical conductive Ag-Pd ink. The two surface views show an example of the variation in surface glass for two different formulations. The higher surface glass content (see arrows figure 8a) produces much higher contact wear. Figure 8c shows a typical distribution of the subsurface glass and porosity.

In addition to the abrasive nature of the glass, the Ag to Pd ratio also effects other important wear characteristics of the inks. At low Pd levels, the ink has a low shear strength. This can lead to either ink smear or excessive adhesive transfer to the mating contact.

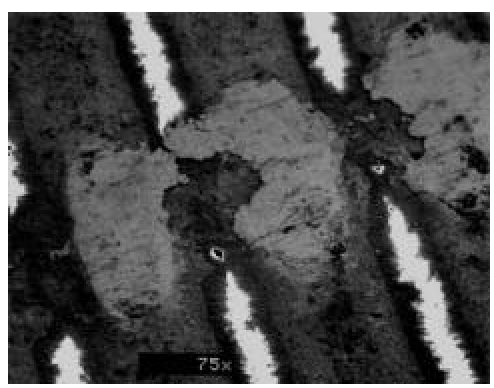
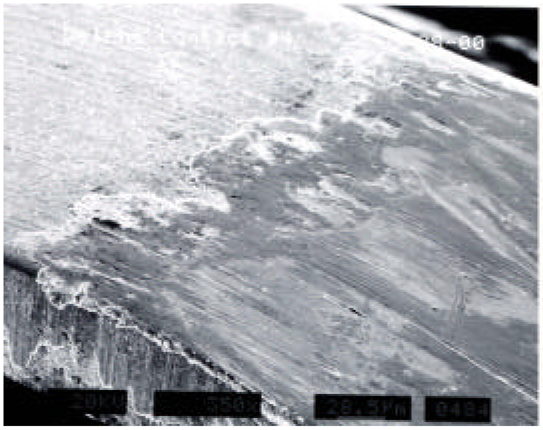


Figure 9. *An example of a low 6Ag -1Pd ink showing signs of smearing between adjacent ink segments*

Figure 9 shows an example of smearing. In this figure, the smeared ink is just about to cause bridging across two adjacent segments. This acts to electrically short the two segments and results in a loss of resolution. Figure 10 shows an example of adhesive transfer from the ink to the sliding contact. The contact was a Pd- Ag-Cu alloy, and SEM X-ray analysis (10b) shows a Ag rich transferred layer, that has reacted with sulfur from the gasoline. The resulting tarnish film created the high noise signal shown in figure 10c. Field experience suggests that Pd levels above 25% tend to reduce or eliminate the smearing and transfer issues.



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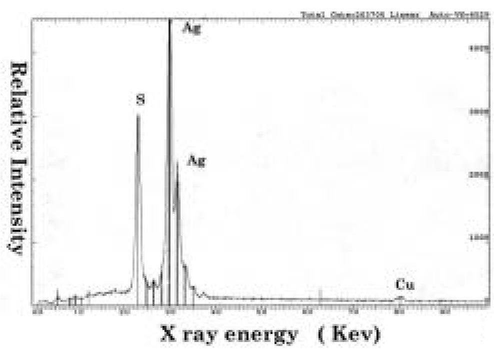
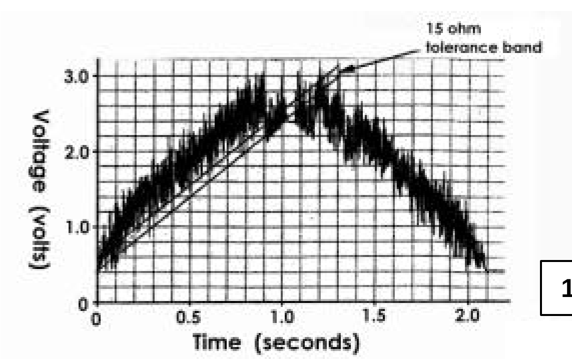


10b



10c

Figure 10. *Examples of Ag rich layer that was adhesively transferred from the ink to the contact surface. a) surface SEM view, b) X-ray spectra of transferred layer showing sulfide tarnish, c) noise spectra from sulfide tarnished layer.*

The last concern regarding the ink is a phenomenon called Ag migration. It is generally caused by water trapped in the gas tank leading to the formation of soluble Ag salts. Under the influence of the imposed potential used to operate the sensor, the Ag is galvanically deposited and will begin to bridge the gap between the two potentials. As seen in figure 11, in the extreme case, it can lead to a short and damage the sensor. Again the higher Pd containing inks are less susceptible to this problem.

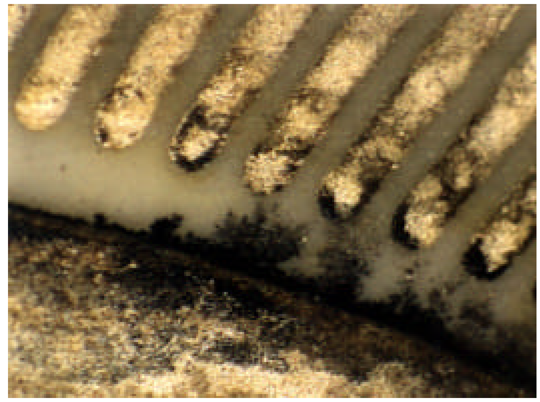


Figure 11. *An example of Ag migration. This example was from a 99% Ag ink tested in the presence of water.*

It should also be noted that a new noble metal based ink has recently been introduced. Initial results look very encouraging. With a greatly reduced Ag level, the ink has a reduced susceptibility to sulfide tarnish. Unfortunately, the lower Ag level also means there will be a slight cost premium for this new technology. Figure 12 show the noise free output spectra for a sensor using this ink after a simulated 100,000 miles of use. Very low levels of contact wear accompanied this noise free performance.

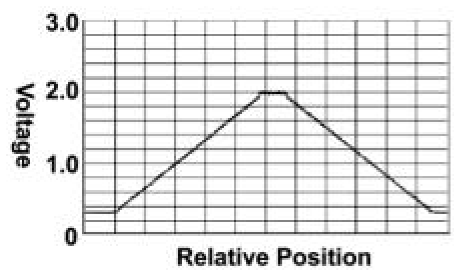


Figure 12. *Voltage output for the new noble metal based conductive ink after a simulated 100,000 mile laboratory test. Contact material was Paliney® 6, bifurcated button with a normal force of 8.5 grams per finger.*

Contact Materials and Design

Perhaps the widest variations in the design of fuel level sensors can be found in the contact materials and contact geometry. Materials range from pure Ni (or Ni electroplate), pure Ag, Ag-Pd alloys, and a Pd- Ag-Cu alloy. The design /fabrication techniques vary from coined rivets to welded buttons to thin stamped strips. In general, these variations relate to different ways of handling the tradeoffs between noise, wear and gram force.

*Paliney is a registered trademark of the J. M. Ney Company.

In terms of the materials, the most important properties relate to tarnish resistance and hardness (wear). As noted earlier, all commercial gasolines contain some level of sulfur. The sulfur will react with the contact material to form a surface sulfide film. For systems designed with a single point of contact such as the mechanically staked rivet (see figure 13), the film acts as a series resistance in the circuit and raises the overall sensor resistance. In addition, similar tarnish films can form on isolated wear particulate embedded in the ink. This can lead to localized noise spikes rather than a systematic offset.

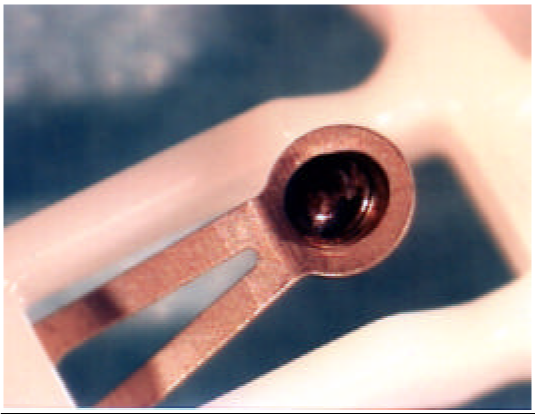


Figure 13. *Typical geometry for a mechanically staked rivet contact. When this style contact is used in a sliding application, it usually represents the only point of contact to the conductive inks.*

Figure 14 shows the relative reaction rate of typical sliding contact materials exposed to a S rich environment. Although the kinetics are assumed to be different with various grades of gasoline, the relative ranking should remain consistent. As one might expect, pure Ag shows a rapid rise in contact resistance when exposed to S fumes. Once steady state reaction levels have been reached (beyond 5 days for this test), adding 30% Pd reduces the film resistance by a factor of 10 with Ni being somewhere in between. The Pd- Ag-Cu alloy (Paliney 6) shows film resistance levels that are an order of magnitude lower than the 70%Ag- 30 % Pd alloy.

In attempting to deal with the films, two approaches are taken relative to the number of independent electrical paths used in the contact design. For designs using a single point of contact such as a rivet, the abrasive nature of the thick film ink is used to mechanically scrub the film from the contact surface. This approach requires reasonably high gram force levels and sufficient contact volume to allow for a continuous material loss during sliding. For this reason, the rivet or welded button style contacts are often used. Gram forces with Ag contacts often exceed 25 grams per contact point. For the less reactive materials such as Paliney 6, normal forces in the range of 3-5 grams per contact point are common.

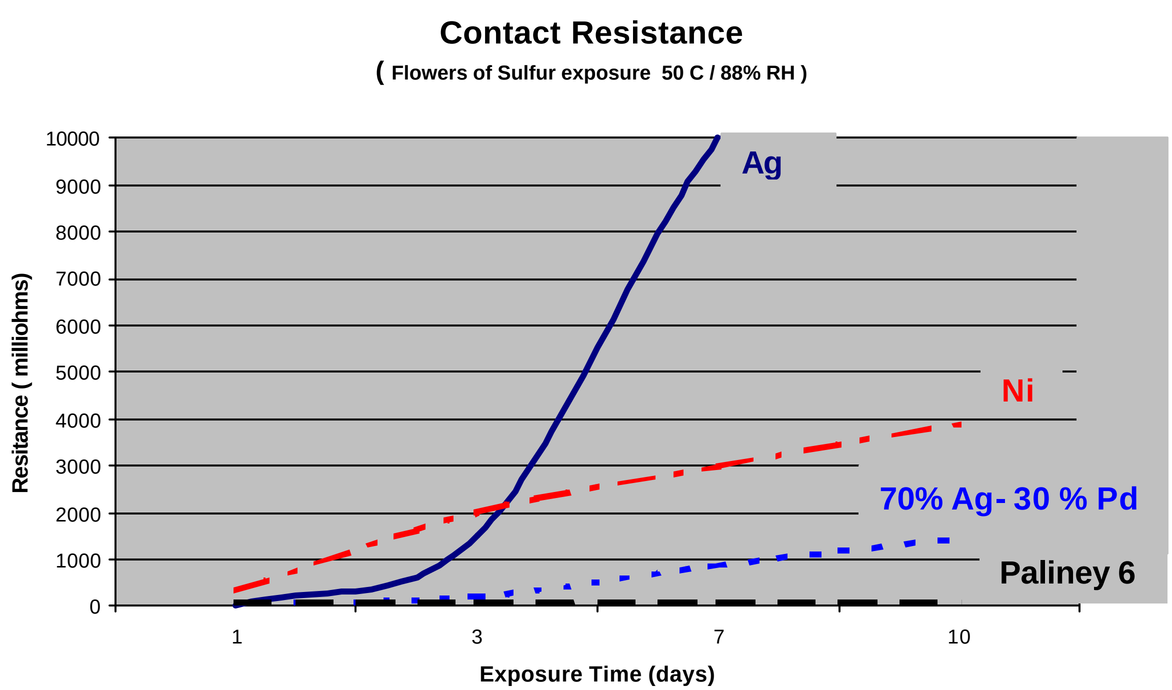


Figure 14. *Static contact resistance measurements for typical sliding contact materials taken as function of exposure to a Flowers of Sulfur environment held at 50 C and 88% relative humidity. The sulfur rich environment is used for ranking purposes only and not meant to simulate reaction kinetics found in commercial gasolines.*

The second approach is to use multiple points of contact. A typical design using this bifurcated approach is shown in figure 15. Figure 7b also contains an example of a multi-finger contact design, using three contact fingers per arm.

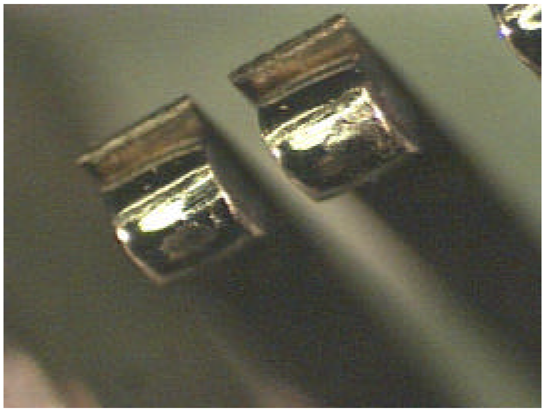


Figure 15. *Example of a bifurcated contact design using two mechanically independent arms with a Paliney 6 button welded to the tip of each arm.*

If each finger is both electrically and mechanically independent, the overall resistance can be calculated as though the resistance at each fingertip is part of a parallel array. Therefore, the total resistance is:

$$\frac{1}{R_{Total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots \frac{1}{R_n}$$

Where n=# of contacts, and
R_x= the isolated resistance for each finger x

The resulting theoretical static contact resistance is plotted in figure 16.

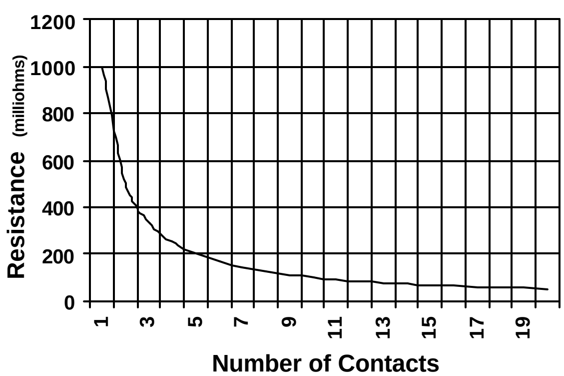
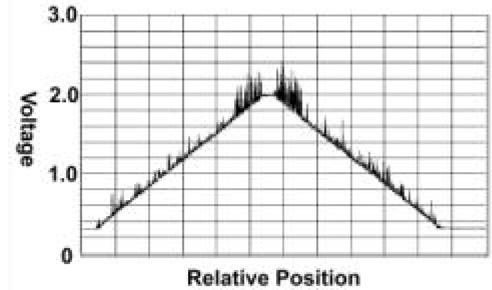
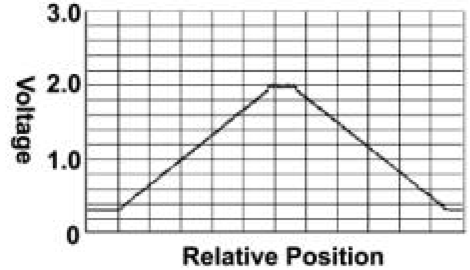


Figure 16. *Theoretical calculation showing the reduction in contact resistance achieved by using multiple points of contact. The calculation assumes an initial uniform film resistance of 1000 mohms per individual finger.*

In a sliding potentiometer contact, the net result of multiple contact points is a reduction in signal noise. Figure 17 shows the signal outputs for single finger and two finger contact design (similar to that shown in figure 15) riding against a 2.4Ag:1Pd ink in gasoline.



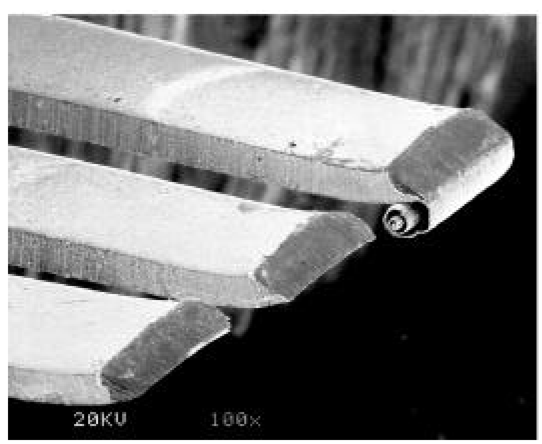
17a



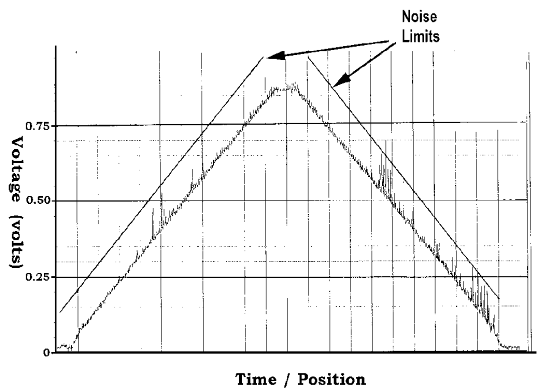
17b

Figure 17. *Sensor outputs for a single and a two-finger contact sliding against a 2.4Ag: 1 Pd ink in gasoline. a) single point of contact b) two finger contact design (see fig. 15)*

In addition to materials with good sulfide tarnishing resistance, it is important that the contact be hard enough to withstand the abrasive characteristics of the glass containing inks. For these applications, controlled abrasive wear is the best way to ensure low noise performance. However, if the contact material is too soft, it is difficult to provide sufficient contact volume to meet today's extended warranty requirements. This is especially true for multiple finger designs made from a thin strip. Figure 18 shows the relative wear performance of a three finger contact made from two different .003" thick materials. Complete wear through of the contact was found in just 600,000 cycles on the softer CDA 770 contact (Hk=205). In this example, the gram force on the CDA770 was lowered to 10 g in an effort to reduce the wear. (Higher gram forces created faster wear.) The lower gram force and S reactivity combined to create the noise shown in figure 18b. In contrast, the harder, more noble, Paliney 6 material showed very low noise and wear levels after 1.1 million cycles at a gram force of 12g. (see figures 18c–d). In both cases, the contacts started with a three fingered spoon geometry as shown in figure 18d.



18a



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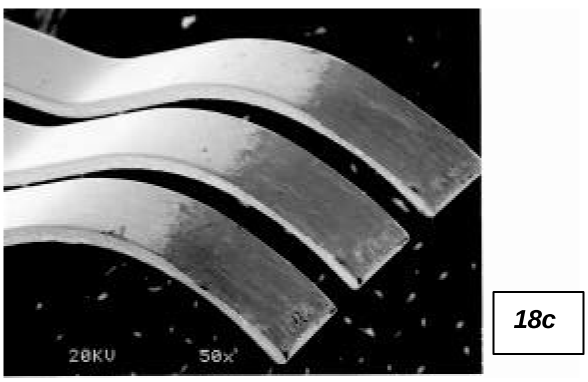

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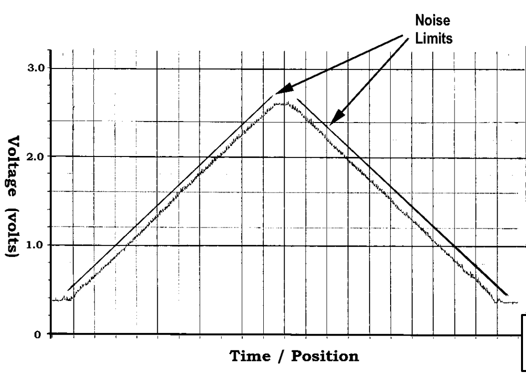

18d

Figure 18. *Contact wear and associate noise spectra for two different hardness materials riding against a 3Ag: 1Pd ink.*
CDA 770 (Hk=205), 600,000 cycles, 10 grams
a) Contact wear b) Noise spectra
Paliney 6 (Hk= 330) 1,100,000 cycles, 12 grams
c) Contact wear d) Noise spectra

For the current generation of conductive thick film inks, it is recommended that a minimum contact hardness of 300 Hk be used for all thin strip design. Although the higher volume rivets and welded buttons are a little more forgiving because of their increased volume, the 300 Hk minimum hardness is still a good practice since it acts to minimize wear debris and transfer of the contact material to the ink surface.

The last consideration in contact design for fuel level sensors is the actual contact shape. As noted earlier, the use of the thick film inks requires the spoked or segmented shunt approach (see figure 5). With this ink pattern, it is important that the geometry be such that as the contact slides over the segments it always bridges across two adjacent segments. It must be set so the contact always touches the ink, but does not bottom out against the alumina substrate. The alumina is extremely abrasive, and any rubbing of the contact on the alumina will severely shorten the useable life of the sensor. This often results in a large radius of curvature on the sliding contacts, as is evident in figures 7 and 18c.

Conclusions

With the proper design approaches, thick film potentiometric fuel level sensors provide an excellent balance between cost and performance. Current designs using Paliney 6 contacts riding against Ag-Pd inks have been shown to provide cyclic lifetimes in excess of 5 million rotations. In order to achieve this level of performance, we recommend using the following best practice suggestions and design guidelines:

1) Use Thick film ceramic inks fired on an alumina substrate.
2) Current resistive thick film inks are extremely abrasive. Segmented shunts printed from a less abrasive, conductive thick film ink are recommended.
3) When using a Ag-Pd conductive thick film ink, a minimum 25% Pd level is recommended. This acts to reduce smearing and increase tarnish resistance.
4) Proper glass distribution in the conductive ink is critical for long life. The number and size of any surface glass particles should be kept small and the firing parameters adjusted to minimize any sharp edges.
5) Dual trace circuit patterns are recommended because they easily allow for noble metals at all sliding interfaces.
6) The sliding contact material should have a minimum hardness of 300 Hk in order to resist excessive abrasive wear from the inks.
7) Most noise related problems are related to sulfide films on either the ink or the contact material. Although some designs can be made to work in the presence of thick sulfide films, the use of materials that produce thinner films result in a more robust design.
8) Thinner sulfide films require less contact abrasion to clean the contact surfaces. This allows for lower gram forces and reduced wear debris.
9) Paliney 6 has the highest resistance to sulfide film formation of all the potential contact materials tested.
10) The use of multi-fingered (bifurcated) contact designs reduces the sensitivity to surface films. This allows for the use of reduced gram forces.
11) The sliding contact should always be in contact with two adjacent segments of the conductive ink. This is usually accomplished by using a large radius. This prevents the contact from sliding against the alumina substrate.

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