ESD in Fluid Lines: Theory and Application in the Petroleum and Aerospace Industries

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Lessons learned about ESD in the petroleum industry can be applied to aerospace designs.

INTRODUCTION

Electrostatic charge generation as a result of fluid flow in pipes has been studied by the scientific community for the past century. A complete mathematical model has not been developed to explain all aspects of the charging process. In the petroleum industry, cases of electrostatic discharge (ESD) causing failures in fluid lines have been around since the early sixties. Very few cases of ESD fluid line failure in the aerospace industry have been discovered until now.

The purpose of this article is to document some ESD fluid line failures in aerospace applications, discuss the theory of how they can happen and point out design considerations necessary to avoid the problem.

THEORY

Fluid flowing through a pipe will generate electrostatic charge on the pipe as well as in the fluid (Figure 1). The magnitude of the electrostatic charge buildup is affected by many complex factors for which a complete quantitative analysis has yet to be developed.

Early scientific studies have shown that factors such as molecular interaction (electrochemistry), fluid flow rate, types of fluid flow (laminar/turbulent), material resistivity, fluid viscosity, solid inner surface roughness, and pipe diameter and length can affect the magnitude of the charge buildup.

Early theory set forth by Helmholtz (1879) and later theories by Couy-Chapman (1910-1913), Stern (1924), and Klinkenberg-Van der Minne (1958), have shown that ions from the flowing liquid will diffuse to the solid surface and be absorbed, forming an ion plate (Figure 2).[1] This ion transfer establishes a double-layer of charges of opposite sign with one layer of charge on the solid surface and the other layer at a very small distance within the liquid. This ion plate is called the classic electric double-layer. This layer can be treated as a parallel-plate capacitor. When the liquid and solid are in constant contact, the parallel-plate capacitance is large and the potential difference is small,normally less than 1 volt.[2] However, if the charges separate by the movement of the liquid away from the solid, the parallel-plate capacitance becomes small and there can be a significant rise in the potential difference. If the potential difference reaches the breakdown threshold, an electrostatic discharge can occur.

For fluid flow in conducting fluid lines, ions will diffuse to the solid surface, but instead of attaching to the surface as an ion plate, they flow to ground through the conducting surface. Therefore, the conductivity or resistivity of the fluid line inner wall is a very important characteristic in preventing ESD. For fluid flow in nonconducting fluid lines, the ions that diffuse to the solid surface form the ion plate and a charge builds up. This type of fluid line posed many hazards to the petroleum industry in the sixties. Problems with this type fluid line are showing up in the aerospace industry as well.

ESD FAILURES

From 1953 to 1971 over 35 accidents involving fire and explosions in aircraft during or after fueling were attributed to electrostatic discharge.[3] Most of these accidents involved JP-4 hydrocarbon fuel flowing through nonconductive fuel lines with TEFLON® as the hose liner. These fluid lines consisted of an extruded Teflon tube reinforced with a braided stainless steel outer jacket. Many of these ESD failures produced

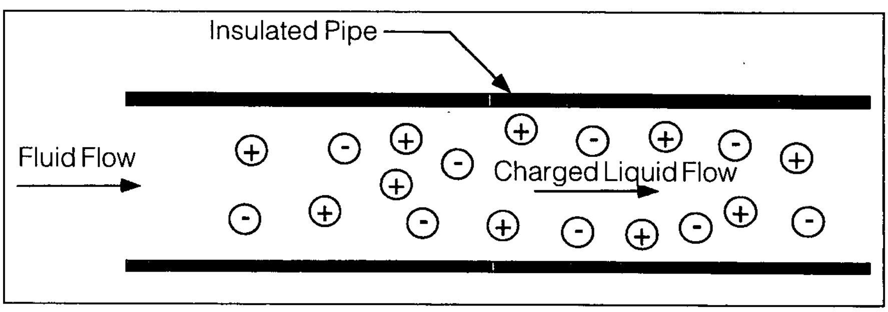

Figure 1. Charge Buildup Produced by Fluid Flow in a Solid Pipe.

leaks in the hose. Fluid line leaks were also observed during testing of the Pratt & Whitney J57P55, the Westinghouse J34WE46 and the General Electric CJ805 engines.[4]

Many of these leaking fluid lines were examined under microscopic magnification. Additional observations were made by cutting into the failed areas of the tubes perpendicular to the long axis and mounting them on specimen slides. Photographs were taken of each specimen. Many manufacturers, including Aeroquip and Titeflex, and independent groups have performed such failure analyses to aid the industry in understanding the problem. In addition, these manufacturers have performed laboratory testing to synthetically produce ESD failures in test specimens. Similarities of the failure observations are presented below.[4,5]

- Small pin-size holes with carbon residue were observed in the Teflon hoses.
- No failures were found in fluid lines with free hose lengths of less than 18 inches.
- Failures were concentrated toward the center of the lines away from the conducting coupling fittings.
- Inner surfaces of failed tubes showed a network of eroded lines and subsurface tunnels associated with the actual pin hole.
- The pin hole area appeared to be fractured as opposed to punctured.
- Many test specimens showed multiple pin holes.
- Time-to-failure varied from four minutes to two thousand hours.

It is difficult to generalize the failure characteristics because of the differences in test facilities and conditions of the tests. However, a pin-size hole with an internally fractured appearance is predominant in these ESD failures.

Several vendor laboratory test programs were established to find an acceptable fluid line resistivity that would preclude ESD failures. These experiments focused on two main factors, maximum allowable potential and maximum rate of charge accumulation which must be dissipated in order to

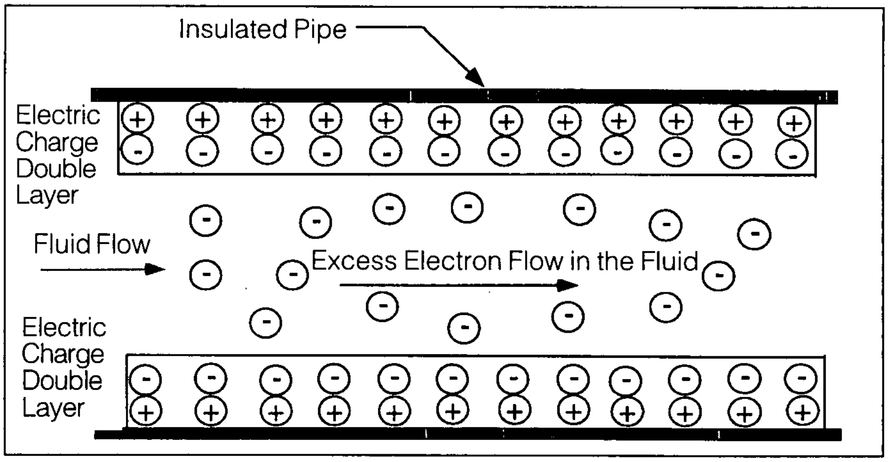

Figure 2. Electric Charge Double Layer at the Liquid-Solid Interface.

hold the potential below the safe value. A potential somewhere around 30,000 volts was considered a limit where ESD could penetrate approximately 50 mil of Teflon.[4] The maximum charging rate of 8.4 μC per gallon was selected because early tests by Klinkenberg produced similar results and this value was considered conservative.[1,4] Various diameter hoses were tested. The data indicated line resistivity should be maintained below 10^6 ohms/inch in all sizes to insure that accumulated charges drained to ground.

In researching the fluid line leaks caused by ESD, very few were found outside the petroleum industry. Most of the vendor laboratory tests utilize specific configurations related to petroleum type field failures. As a result, little to no data was found for applications where fluorocarbons are used in coolant loop systems.

As mentioned earlier, the magnitude of charge buildup is based on many factors, but one fundamental factor is the molecular interaction of the materials. This is commonly called the difference in the work function of the materials involved.[6] The work function is defined as the energy required for an electron to be emitted from a material surface into a vacuum. The higher the difference in the work functions of the materials, the more likely ESD will occur due to charge transfer at the material interface. In the aerospace industry, many fluid line applications utilize Freon 114 as the liquid and Teflon (PTFE) as the hose. Freon 114 and Teflon are both insulators with a resistivity of around 10^{12} ohm/m and 10^{18}ohm/m respectively.[7] Freon 114 has a different work function than the hydrocarbon fuels used by the petroleum industry. Therefore, direct correlation of all data from petroleum field and laboratory failures with coolant loop systems cannot be done.

AEROSPACE INDUSTRY

One failure that occurred in the aerospace industry during the late 1960's on a spacecraft launch vehicle had an interesting effect on the spacecraft. The guidance computer commanded the propulsion to shut down early, preventing the vehicle from reaching design altitude. After extensive review of the telemetry and the system design, it was concluded that ESD had caused the guidance computer to malfunction. The source of the ESD was researched extensively and found to be the nonconducting Freon lines which ran internal to the computer. The ESD arced through the Teflon and into the computer causing the malfunction to occur.

Laboratory experiments on this configuration were performed to verify that ESD could occur. It was discovered that it took around 20,000 volts to arc through this Teflon thickness. Also, it was found that the resistivity of the

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coolant did not follow Ohm's law. The liquid resistivity showed an increase when the electric field was increased.[8] This phenomena was also observed for hydrocarbons by Kinkenberg and Van der Minne.[1] This point is important when considering that some charge might flow with the liquid and drain at the coupling fittings. With some liquids, it seems that as the electric field builds, less charge flows with the liquid and more charge is available to form the electric double-layer at the Teflon surface. From this example, it is important to consider the routing and placement of nonconducting fluid lines in the system design.

A more recent event occurred in January 1996 with the integration and testing of the Spacelab Multi-Purpose Experiment Support Structure (SL MPESS) carrier for the United States Microgravity Payload-3 (USMP-3) on the STS-75 shuttle mission. During the Freon flow balancing of the USMP-3 Freon system, a leak was discovered in one of the Freon flex lines. This line is located between the Orbiter standard interface panel supply and the Freon pump package on the forward USMP-3 MPESS carrier. The Freon line was replaced and the failed line sent to the failure analysis laboratory at Kennedy Space Center (KSC). ESD was suspected and later confirmed by the KSC material science division laboratory and this author.[9]

Inspection of the area surrounding the hole revealed the same characteristics seen in many of the confirmed failures mentioned earlier. Looking at a cross section of the hole, a line is apparent. This line is a nonconducting fluid line with Teflon as the hose and nonconducting Freon 114 flowing at approximately 4 ft/sec with a mass flow rate of approximately 2800 lbm/hr in total volume of 3.52 ft^3. The line is approximately 3 feet long. McDonnell Douglas Aerospace provided the KSC materials laboratory with additional flex line hose from the same batch to analyze. The hose provided had, in one spot, characteristics of ESD as seen with a boroscope, but under pressure, the hose did not leak.

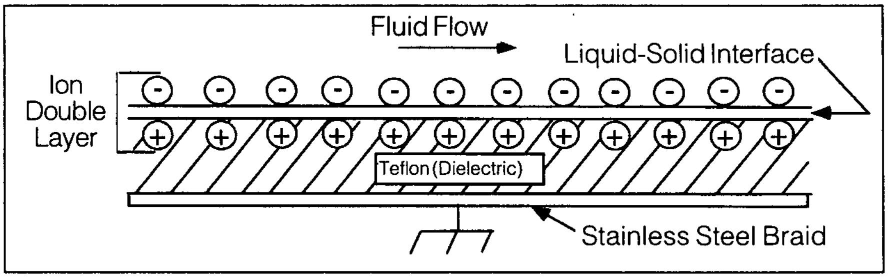

Figure 3. *Capacitor Model for a Spark Discharge through Teflon (Dielectric).*

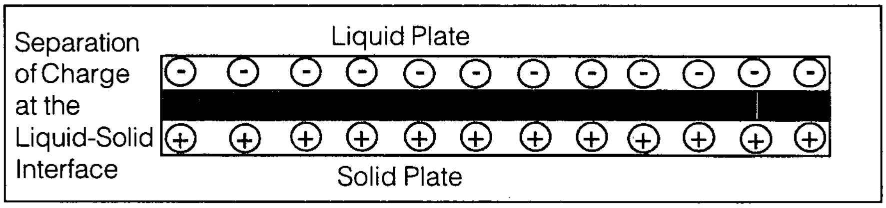

Figure 4. *Parallel Plate Capacitor Model of the Electric Charge Double Layer.*

Further examination revealed that the ESD had occurred but had not punctured the hose. This evidence leads to the supposition that both electrostatic discharges that arc through into the grounded braid and those that arc into the Teflon without puncturing the Teflon exist. Earlier field and vendor testing also indicated this but failed to explain how this could occur.

DISCHARGE TYPES

Theory discussed earlier indicates that the isolated charge buildup forms the electric double-layer which can be represented by a parallel plate capacitor. When the potential reaches the breakdown threshold of Teflon, a spark type discharge from the ion plate arcs through to the grounded braid. This is typical of spark-type discharges, where potentials reach the dielectric strength and a continuous discharge path forms. However, it is not characteristic of a spark discharge to exhibit partial discharge, or arcing into a material but not to ground, as has been seen in some hoses.

ESDs that appear as strikes into space or surrounding media but that do not require a grounded path are brush-type discharges. These type charges lead not to a discharge path between two electrodes but emanate from the site of highest field strength on the surface of one electrode.[6] Therefore, the possibility exists that fluid lines are susceptible to both electrostatic *spark* and *brush* discharges. An explanation of how each of these discharges occur in the nonconducting fluid lines will be described.

Separate capacitor models can be assumed for each discharge case. The capacitor model shown in Figure 3 will be assumed for the spark discharge case. The ion diffusion plate or double layer of charge is considered one electrode and the grounded braid with the Teflon as the dielectric is the other. When the field strength increases to the level at which dielectric breakdown occurs, a spark discharge will arc into the braid and go to ground (i.e., the capacitor will discharge). This model could explain many cases involving small pin-size holes that have carbon residue around the entrances and jagged interior traces. Some cases also show carbon residue on the braided stainless steel.

The capacitor model in Figure 4 will be assumed for the brush discharge case. The ion diffusion plate or double-layer forms a parallel plate capacitor itself at the surface of the Teflon and liquid interface. When the liquid is at rest, some charge accumulates. The relaxation time of the materials and the small separation distance between plates keeps the capacitance large and

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the potential difference small which, in turn prevents a discharge. When the liquid separates from the surface during flow, the separation distance is large and the capacitance is small, which drives the potential difference to a very high level. This separation of the solid/liquid charged plate could cause brush discharges to occur. These discharges arc into the Teflon and into the liquid which could cause some damage to the Teflon. Brush discharges are not likely to penetrate the Teflon to get to ground because the discharges branch out finely from the electrode surface. Brush discharges are more likely to have repeated strikes along the ion plate area as long as the liquid/surface separation is repeated.

Another possibility exists that the parallel plate capacitor brush discharges could start the damage to the Teflon by making small surface holes in the area of the charge plate. As the solid/liquid surface separates during turbulent flow and pump start/stop actions, multiple brush discharges could occur in the same area. If multiple strikes hit the same hole, it may be possible to arc into the braid and puncture the Teflon. Further laboratory testing would be required to support one possibility over the other. Efforts are underway to replace all Spacelab nonconducting fluid lines after the USMP-3 mission with conducting fluid lines.

During investigation of the Spacelab fluid line failure, another ESD failure was found on a space shuttle ground support equipment fluid line. This fluid line carried N_2O_4 at the fuel storage facility. The KSC materials laboratory used boroscopes and other observations to determine that ESD caused this failure. The KSC materials laboratory recommended conducting fluid lines in this application.[10]

DESIGN CONSIDERATIONS

Because of the problems now showing up in the aerospace industry, special design considerations should be included in all fluid line designs. As mentioned earlier, line resistivity is a very important characteristic to consider. To insure that significant charge buildup will not occur, line resistivity of 10^6ohm/inch should be selected. Manufacturers will provide this data in most cases, but care should be taken that test voltages in the 10^3 volt range are used in the measurements.[11]

Teflon flex hoses with a conductive inner layer with excellent resistivity are available. Metal fluid lines are also available, but added weight and less flexibility may present problems in system design.

Other options include using additives with the liquid to increase charge flow in the line. The petroleum industry has used this method to solve some of their ESD problems. Many factors must be investigated to determine if additives are effective for each design. Decreasing flow rates will have an effect on the charge buildup, but it is difficult to quantify. Whichever design consideration is used to minimize charge accumulation in the fluid line, all fluid lines should be grounded utilizing methods described in military specification MIL-B-5087, Class S.

SUMMARY

Based on theory developed over the last century and documented field failures, electrostatic charges will accumulate in fluid lines regardless of the application. Nonconducting fluid lines are susceptible to ESD failures. Depending on the application, these ESD failures can be catastrophic. Most failures have occurred in the petroleum industry, but because of lack of awareness, failures are occurring in other areas as well. It is hoped that this article will encourage greater awareness and that special care will be taken in the design and routing of fluid line systems in the future.

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