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Investigation of Electrostatic Discharge in Aircraft Fuel Tanks During Refueling

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High levels of electrostatic charge on JP-4 fuel during aircraft refueling, due to both the flow of fuel and the charge buildup generated by fuel contacting the explosion suppression foam installed in some aircraft fuel tanks, were eliminated in the test installation using a multihole-design fuel inlet which resembles a piccolo. This is an adaptation of a manifold inlet design investigated by various agencies as a means of reducing electrostatic charge. The piccolo inlet was selected as the result of a test program conducted to evaluate several fuel inlet configurations when used in conjunction with two generic types of polyurethane foam: polyester, presently used in aircraft fuel tanks, and polyether, proposed as a replacement for the polyester foam. Of the two types of foam tested, the polyether foam showed a greater potential for producing static discharges than did the polyester foam. Test results also indicated that the addition of an antistatic additive (ASA-3) to JP-4 fuel, in sufficient quantity to provide a minimum fuel conductivity, eliminated static discharges.

Introduction

THE development of high levels of electrostatic charge on JP-4 fuel or any jet fuel during aircraft refueling is a common occurrence.[1] Whenever a hydrocarbon liquid flows with respect to another surface, a charge is generated in the liquid. Aircraft refueling allows the jet fuel to contact large surface areas due to its passage through pipes, hoses, and filter/separators before entering the aircraft tanks, causing the fuel to become highly charged. JP-4 (as well as other jet fuels) usually possesses a high capacity for accepting a charge (high charge tendency) in conjunction with a low capacity to bleed off the charge (low conductivity). The low conductivity prevents the charge from readily bleeding off to ground, so that fuel enters the tank highly charged. This highly charged fuel may then discharge to ground in the form of sparks, most of which are too low an energy level to ignite the fuel, but some of which may contain sufficient energy to ignite the fuel/air mixture and cause an internal explosion. In addition to a spark of sufficient energy, the fuel/air mixture must be within a flammable range to produce ignitable vapors. For JP-4 fuel, this flammable range, expressed in terms of temperature, extends from −35°F to approximately +60°F.

Until recently, the primary charging medium was considered to be the filter/separator used to filter out impurities and to separate water from the fuel during refueling.[1] To a lesser extent the associated piping, valves, and other hardware in the refueling system also contributed to the charge build up. The aircraft plumbing system (primarily the tank inlet, if improperly designed) also has been considered an important mode of generating a static discharge. Based upon these factors, the primary thrust of most static electricity programs has been either to determine the most effective way of reducing the charging capabilities of the filter/separator devices or to determine how the charge imparted by the system can be effectively relaxed to a relatively harmless level.

Most Air Force combat aircraft now contain foam inside the fuel tanks to suppress explosions resulting from gunfire, but the question has been raised as to whether the foam causes a significant charge to be generated within these tanks.[2,3] If so, such a charge could be more serious than that introduced by the refueling system, because the charge relaxation time within the tank becomes virtually nonexistent. In addition, it was felt that if a significant charge should be generated within the tank, the addition of antistatic additives that decrease relaxation time might not only be ineffective, but might increase the level of charge and the likelihood of spark discharge if insufficient additive is used.

The test program was conducted using a full-scale facsimile of the A-10A aircraft forward fuselage tank, including the internal foam. Two generic types of polyurethane foam were tested: polyether (blue) and polyester (red). Several different inlet configurations were evaluated, including the aircraft forward and aft fuselage and wing tank fuel inlets. An optimum (piccolo) inlet was selected based on the test results obtained, and was evaluated with fuel containing an antistatic additive.

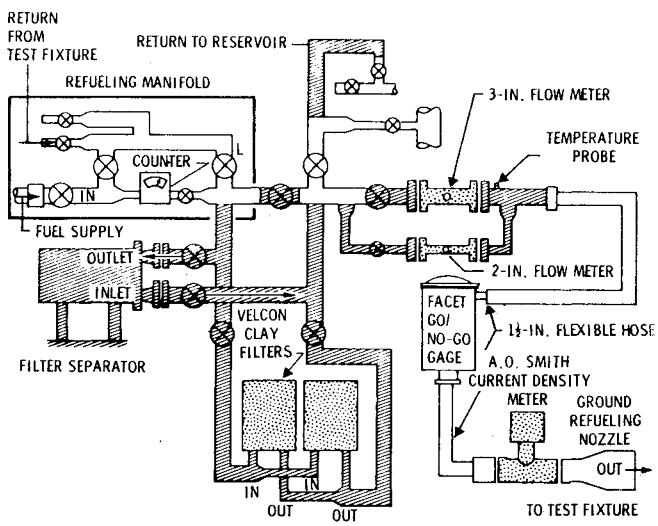

Fig. 1 Refueling and defueling setup schematic.

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This paper presents a comparison of the A-10 aircraft forward fuselage tank inlet and the optimum (piccolo) inlet, with respect to both foam-type untreated JP-4 fuel and JP-4 fuel treated with prostatic and antistatic additives.

Definitions and Equations

Charge Density

The concentration of a charged species in a fuel is its charge density. The charge density of fuel flowing in a pipe or into a tank can be calculated by electrically isolating a section of a pipe or a system and measuring the streaming current by means of an electrometer. The streaming current is the current resulting from the flow of a hydrocarbon stream. The charge density may then be calculated using the equation

$$Q = i/v$$

where Q = charge density, $\mu C/m^3$; i = streaming current, μA; and v = volumetric flow rate, m^3/s. The charge densities are identified as input (fuel in supply line prior to entering tank), inlet (fuel in inlet nozzle in tank), and tank (fuel in tank proper).

Field Strength

The strength of an electric field in the vapor space above a charged fuel is field strength. The magnitude of the field strength depends on the charge density of the fuel, the fuel conductivity, and the tank configuration. The field strength was measured by a field strength meter and recorded on an oscillograph chart. In this paper it is expressed in volts per inch (V/in.).

Surface Voltage

The voltage developed on the fuel surface inside the tank during refueling is surface voltage. It was calculated using the known field strength and the distance of the fuel surface from the field strength meter. This calculation was based on the assumption that the field strength meter reads the surface charge of the fuel as it fills the tank and not the stationary upper foam surface. The surface voltages are presented for comparative purposes, and the absolute values should be taken with reservation. Surface voltages are expressed in terms of kilovolts, kV.

Fuel Conductivity

Simply stated, fuel conductivity is the ability of the fuel to bleed off a charge. As used here, it is the conductivity at the initial instant of a direct current measurement of a fuel sample.[4] It is expressed in Conductivity Units (CU) where 1 CU = 1 picosiemen per meter, pS/m.

Test Setup

The test program was conducted in the Fuel Laboratory at the Fairchild Republic Company. The laboratory is equipped with two 5,000-gal tanks, one used for fuel storage and the other as a supply tank. Two pumps, each capable of pumping 600 gpm, are used to supply fuel from the supply tank to the laboratory.

Refueling and Defueling

The supply pumps were connected to a manifold (see Fig. 1) consisting of 2½-in. pipe, coupling the several hand-operated valves which allowed fuel to be supplied as required to the test tank or to two clay filters. The two clay filters were used to clean and/or treat the fuel supply prior to performing tests. By adjusting the proper valves, the fuel could be returned to the storage tank. The filter separator is a device which is used in the refueling systems. The unit normally contains filter/coalescer and water separator elements, but for this test program, the separator elements, wrapped with 3μ Millipore filter paper, were used without the coalescer elements, since this combination produced more highly charged fuel. The go/no-go gage was added to the refueling setup since it also aided in increasing the fuel charge. The ground refueling nozzle was connected to the test tank.

Test Fixture

The basic test fixture was an aluminum tank approximately $3 \times 9 \times 5$ ft, which was manufactured to simulate the A-10A aircraft forward main fuel tank, including tank interior components and tubing (Fig. 2). The tubing was located to approximate the forward tank installation, but did not necessarily duplicate the exact geometry of the installations.

The aircraft fuel tank internal foam installation was also simulated in the test tank. The foam blocks were manufactured from polyurethane foam (colored red) which is the present production foam, and polyether foam (colored blue) which is a proposed production foam.

One of the more critical features of the tank construction was the isolation of the tank and its components from Earth ground. This was required in order to measure streaming currents during the actual refueling tests. Teflon pads placed under each leg of the test tank isolated the tank from ground. The inlet nozzle was isolated from both the tank and the

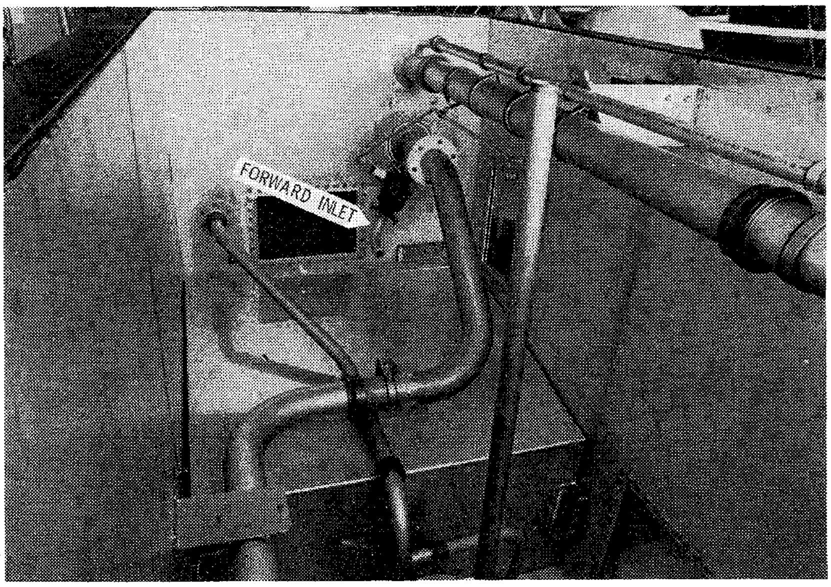

Fig. 2 Fuel tank interior installation.

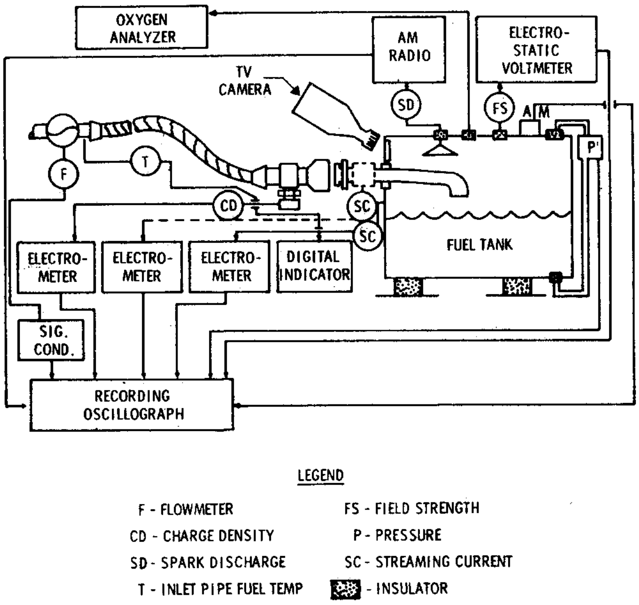

Fig. 3 Fuel system instrumentation.

Table 1 Test parameters

Parameters	Instrumentation
Static discharge in tank[a]	AM radio with shielded antenna
Static discharge in tank[a]	AM portable radio
Static discharge in tank	Video camera, TV set, tape recorder
Field strength[a]	Electrostatic voltmeter with sensor head
Surface voltage	Calculated from field strength values
Tank and inlet streaming current[a]	Digital electrometer
Input fuel charge density[a]	Charge density meter
Fuel flow rate	Two turbine-type flowmeters
Oxygen level in tank	Percent oxygen analyzer
Fuel level[a]	Differential pressure transducer
Fuel temperature[b]	Digital temperature recorder
Air temperature and relative humidity[b]	Temperature humidity indicator
Fuel conductivity[b]	Portable conductivity meter
Fuel conductivity[c]	Balsbaugh cell electrometer
Charge tendency[c]	Mini-static tester electrometer

[a]Output recorded on Visicorder (high-speed oscillograph). [b]Recorded manually on data sheet. [c]Tests performed by Fairchild Republic Quality Control Chemical Laboratory.

refueling line by using Teflon flanges. Teflon bushings were provided in flanges to prevent attachment bolts from contacting metal. Hoses and support brackets were isolated using Teflon flanges and insulators. Smaller hoses and instrumentation wires were wrapped with Teflon tape where they touched the tank. The tank and inlet nozzle could be grounded or isolated, as required, by switches located in the wiring circuitry.

Test Inlet Configurations

The following fuel inlet configurations were evaluated during the test program:

1) Forward Tank Inlet: The production A-10 aircraft fuel inlet, having a discharge orifice area of 0.519 in.^{2} was used. Flow from this inlet was parallel to the tank floor, from aft to forward in the tank.

2) Aft Tank Inlet: Identical to the forward tank inlet, but discharged fuel flow toward the tank floor.

3) High-Velocity Inlet: an aircraft forward tank inlet reworked to reduce the orifice discharge area from 0.519 to 0.372 in.^{2}

4) Piccolo Inlet: This inlet was manufactured from a 1¼-in. diam, 24-in. long aluminum tube. Both ends of the tube were sealed with welded caps. Twenty-three 0.250-in. diam holes, equally spaced, were drilled in one face of the tube. The total discharge area was 1.127 in.^{2} An orifice having a total discharge area of 0.519 in.^{2} was located upstream of the piccolo inlet. The inlet was located ¾ in. from the tank floor, with flow directed toward the tank floor.

5) Drop Tube Inlet: A 1¼-in. diam tube with a 0.049-in. wall thickness was used for this inlet. The upstream end of the tube was welded to a flange which connected the inlet to the tank fill valve. An orifice having a total discharge area of 0.519 in.^{2} was located in the center of the flange. The inlet was installed with the discharge end located ¾ in. above the tank floor. Flow from this inlet was toward the tank floor.

Although tests were performed with all of the above inlets, evaluation of test data early in the test program resulted in the concentration of test effort on the forward and piccolo inlets.

Test Fluid

The basic test fluid was JP-4 fuel per MIL-T-5624. The fuel was used without any additive during the initial tests. Gulf 178 prostatic additive was added to the JP-4 fuel prior to baseline tests with the forward and piccolo inlets with red and blue foam. Shell Chemical Company ASA-3 antistatic additive was added to JP-4 fuel containing some trace of prostatic additive, for the final tests.

Test Instrumentation

A diagram of the test instrumentation used is shown in Fig. 3. The test parameters measured and recorded during the test runs are shown in Table 1.

Test Procedure

The test procedure basically consisted of the following six functions:

1) Install required foam and inlet configuration in test tank. Condition fuel supply to attain required conductivity level.

2) Calibrate or adjust instrumentation as required. Install sensors on test tank. Verify tank and inlet isolation from ground.

3) Purge tank using gaseous nitrogen until oxygen content is 5% or lower.

4) Turn on instrumentation. Refuel tank at a 110-gpm flow rate until shutoff valve closes.

5) Ground tank and inlet. Obtain fuel sample.

6) Defuel tank.

Test Results

Inlet Comparison Based on Field Strength and Charge Density

The forward inlet and the piccolo inlet were compared on the bases of field strength, surface voltage, charge density, and frequency of static discharge during test runs using no foam, red (polyester) foam, and blue (polyether) foam. The data presented are typical of those obtained during the test program. Figure 4 illustrates the field strength generated using the forward inlet and the piccolo inlet without foam installed in the test tank. Without foam installed, the effect of the inlet, combined with the input fuel charge, is to charge the tank toward a positive polarity; thus, the field strength progressively increased in a positive-polarity direction. Figure 5 shows the field strengths obtained with the same inlets with red or blue foam installed. In contrast to the test runs without foam, the field strength generated at the beginning of these test runs has a positive polarity and reverses to a negative polarity at the end of each run, indicating that the foam tends to reverse the tank polarity toward negative. The maximum positive-polarity field strengths generated near the beginning

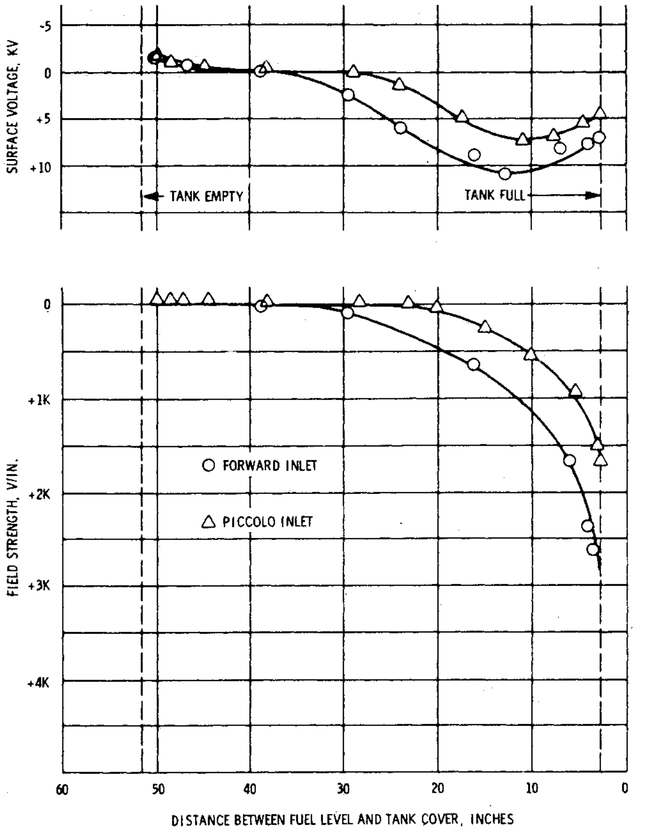

Fig. 4 Field strength comparison, forward inlet vs piccolo inlet, no foam installed.

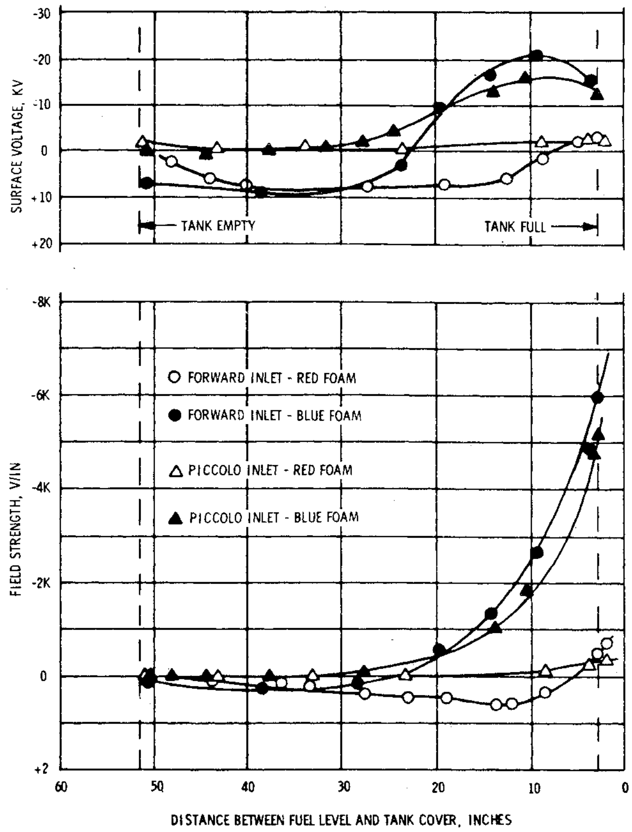

Fig. 5 Field strength comparison, forward inlet vs piccolo inlet, foam installed.

of the fill with the piccolo inlet installed were always less than those generated with the forward inlet installed. Since it would be expected that the inlet configuration, combined with the input fuel charge, would be the dominant influence on the tank charge at the beginning of the run (before the foam can begin to exert any appreciable effect), the lower positive field strength that occurs with the piccolo inlet at this time indicates that it causes less of a charge than the forward inlet. The relatively equal, negative-polarity field strengths at the end of the run indicate that the foam influence has dominated the influence of the inlet configuration fuel charge input, and therefore masks the improvement afforded by the piccolo configuration as the tank approaches the full point, in terms of instrumentation readings.

Surface voltages which were computed from the field strength readings follow the same trends as the field strengths.

To obtain comparable results it was desirable to maintain the input fuel charge as nearly equal as possible for all tests in a series. However, it was not possible to accomplish this. The resultant tank and inlet nozzle charge densities were dependent on both the input charge density and the effect of the tank inlet configuration and the foam. As indicated in Fig. 6, the charge density was greater during the initial portion of the run with the piccolo inlet than with the forward inlet. Tank charge densities appear to be influenced primarily by the input charge density and not by the inlet configuration.

Inlet Comparison Based on Discharge Frequency

A static discharge was considered to occur if one or a combination of events were recorded on the oscillograph trace. A typical oscillograph trace is presented in Fig. 7. Static discharges appeared as "spikes" in the tank and inlet streaming current traces, "blips" in the AM radio traces, and repeatable "blips" in only one AM trace. High-level energy discharges were considered to have occurred within the tank when the tank and inlet current spikes were simultaneous with at least one radio trace and a field strength discontinuity. The number of discharges of this nature are summarized relatively in Table 2. The piccolo inlet is obviously superior, since no discharges of this nature were ever detected, regardless of the type of foam installed.

Foam Comparison Based on Field Strength and Charge Density

As previously explained for the instrumentation readings of field strength and charge density, the inlet configuration is the predominant factor during the earlier part of the refueling, but the foam parameters are the predominant factors during the later part of the refueling. As indicated in Fig. 8, blue foam produced substantially higher field strengths than red foam, regardless of the inlet tested. This was typical of the test runs throughout the program, even when the input charge level of the fuel was relatively low.

The surface voltages were affected in the same manner as the field strength, and were much higher with blue foam.

The tank and inlet charge densities, computed from their streaming currents, were primarily a function of the input charge density, and for the field strengths presented in Fig. 8 were approximately the same as Fig. 6.

Foam Comparison Based on Static Discharge Frequency

Since the piccolo inlet did not produce any discharges, the comparison of red and blue foam was accomplished based upon forward inlet test results. Every test conducted using blue foam with the forward inlet installed produced evidence

Table 2 Frequency of discharges

	No foam	Red foam	Blue foam
Forward inlet	None	Frequent	Most frequent
Piccolo inlet	None	None	None

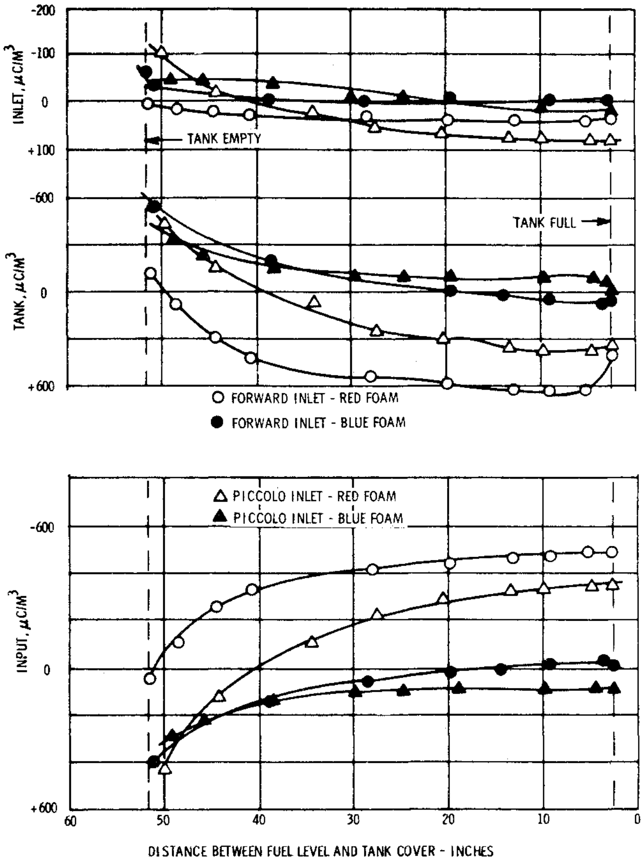

Fig. 6 Charge density comparison, forward inlet vs piccolo inlet.

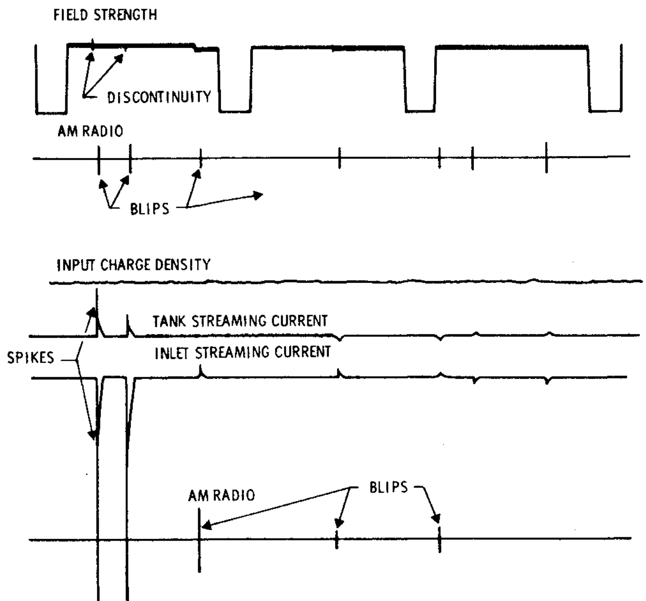

Fig. 7 Typical oscillograph trace with static discharge indications.

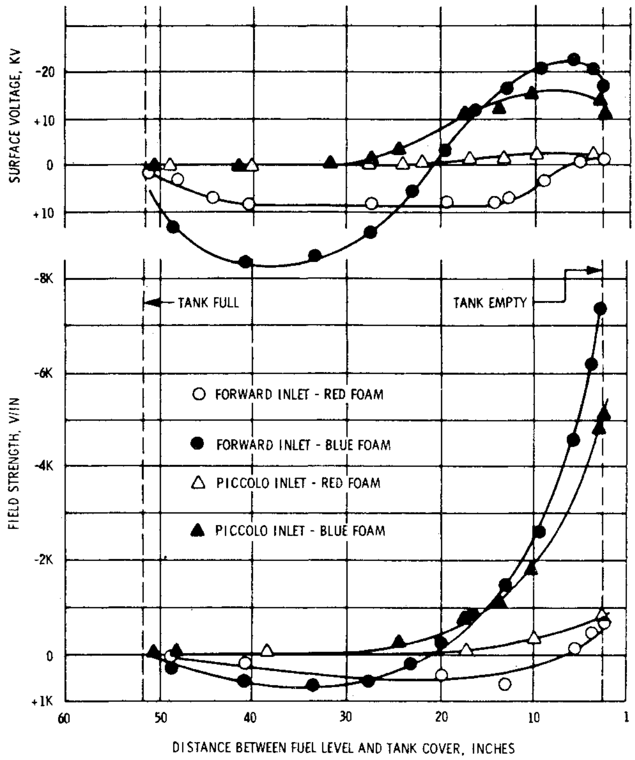

Fig. 8 Field strength comparison, forward inlet vs piccolo inlet.

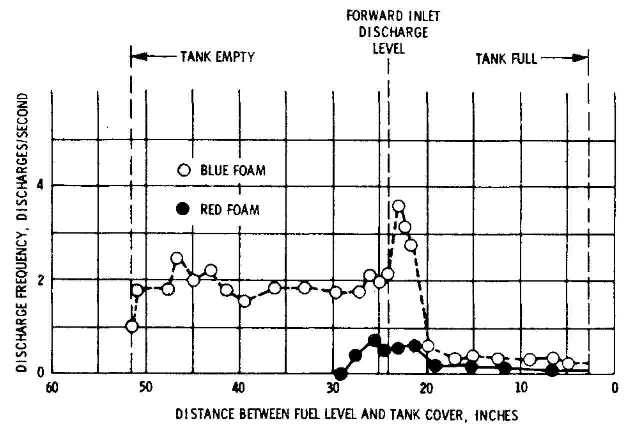

Fig. 9 Discharge frequency comparison, blue and red foam with forward inlet.

of discharges on the oscillograph traces, regardless of the input charge density level. Discharges occurred with an input charge density of less than 30 $\mu C/m^3$ using blue foam, but did not occur with red foam until the charge density approached 300 $\mu C/m^3$. The occurrence of discharges with blue foam was virtually independent of input charge density.

A comparison of the frequency of static discharges between red and blue foam is presented in Fig. 9. Discharges that produced current spikes and field strength discontinuities were counted; by dividing total discharges during a unit time period by that time period, the discharge frequency plot was generated.

In addition to producing more frequent discharges, the blue foam also generated discharges of a higher intensity level, many of which were considered potentially incendiary. Typical discharges are presented in Figs. 10 and 11. Figure 10 shows discharges occurring in the fuel froth on top of the foam approximately 20 s after the start of refueling. These discharges are dangerous since they occurred on top of the fuel in a basically empty tank, where a flammable fuel/air mixture could exist. Figure 11 indicates a discharge from the forward inlet toward the foam in the tank. This discharge occurred after the fuel inlet was covered by fuel, and was approximately 6 in. long. Several discharges of this type were witnessed during the test program.

In order to determine if isolating the test tank from Earth ground affected the discharge frequency, several tests were performed with red foam and blue foam, and with the test tank and the forward inlet both grounded, or each grounded

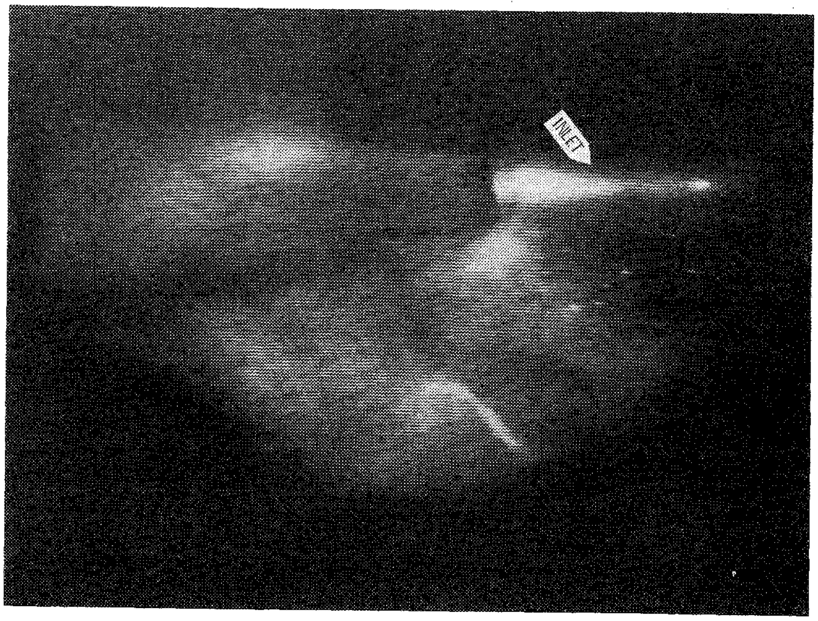

Fig. 10 Static discharge during refueling.

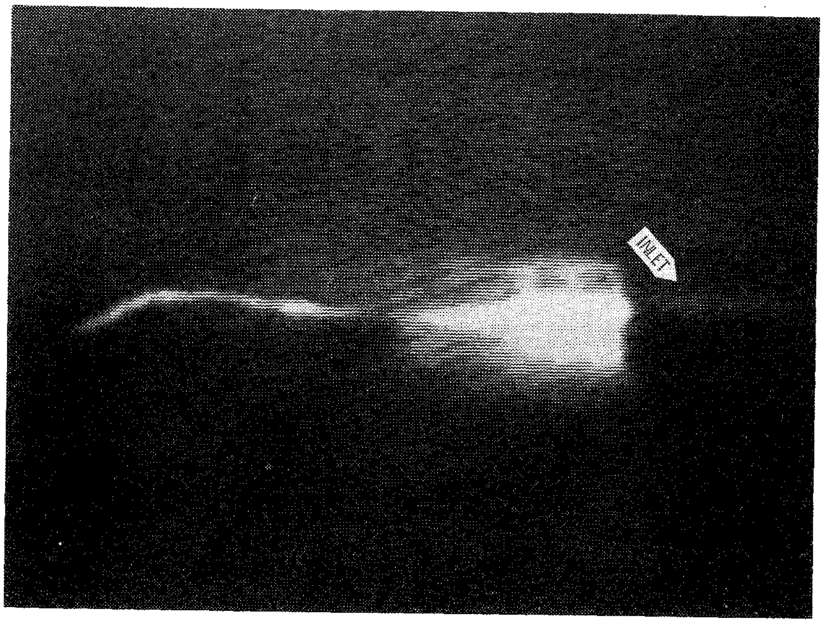

Fig. 11 Sparks occurring under fuel.

separately. The results indicated that with blue foam installed, grounding both the test tank and the forward inlet had little effect on reducing the discharge frequency. With red foam installed, grounding the tank and the forward inlet reduced, but did not eliminate, the static discharges.

Antistatic Additive with Blue Foam

Since it had been established that the forward inlet produced static discharges with red foam and blue foam, test series were performed to determine what effect would result from the addition of an antistatic additive to the JP-4 fuel. The additive increases the conductivity of the fuel, thereby reducing the charge on the fuel before it reaches the fuel tank.

Tests were performed using the forward inlet in conjunction with blue foam, because this combination had been established as having the most potential for static discharge generation. Baseline tests were performed using prostatic-treated fuel having a fuel conductivity of 6 pS/m, with typical results: many high-level discharges and relatively high field strengths. Shell Chemical Company ASA-3 antistatic additive was then added to the JP-4 fuel supply to increase the conductivity first to 95 pS/m and then to 195 pS/m. As indicated by Fig. 12, the field strength generated decreased after the addition of the additive; however, the decrease was approximately the same for both the fuel conductivity levels. The field strength did not decrease with the increase in input fuel conductivity. No tests were performed to determine if additional additive would have further decreased the field strength. The surface voltages followed the same trend as the field strengths. The charge densities are presented in Fig. 13. The input charge densities were lower than the baseline value, but did not decrease as expected. The initial addition of additive reduced the input charge density, but a further application of the additive did not produce a corresponding decrease in the input charge density.

No static discharges were recorded during the test series with the antistatic additive. All previous test runs with the forward inlet and blue foam configuration tested with untreated or prostatic-treated fuel had produced static discharges. The antistatic additive at the tested levels of fuel conductivity eliminated static discharges.

Similar tests were performed using the piccolo inlet and blue foam configuration in conjunction with the antistatic-treated fuel. The generated field strengths and surface

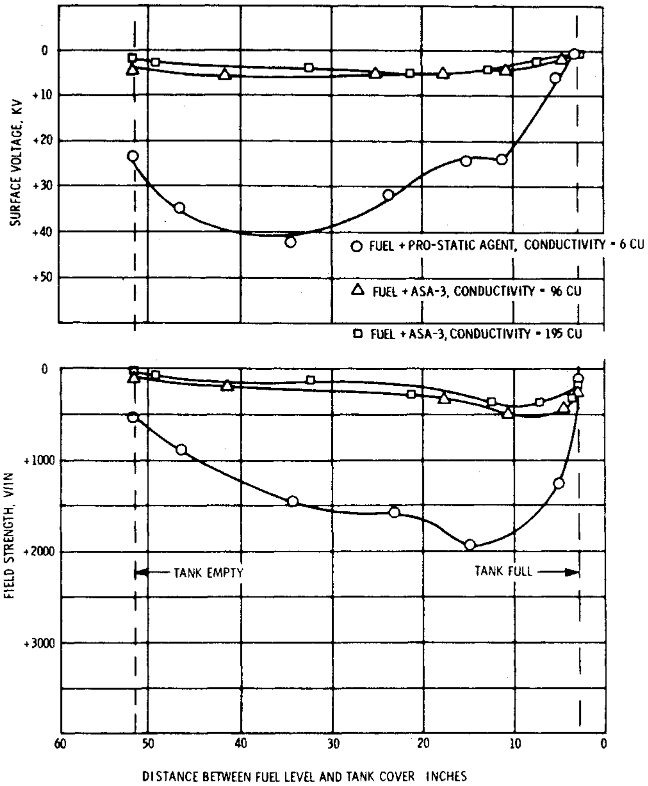

Fig. 12 Field strength comparison, forward inlet with blue foam.

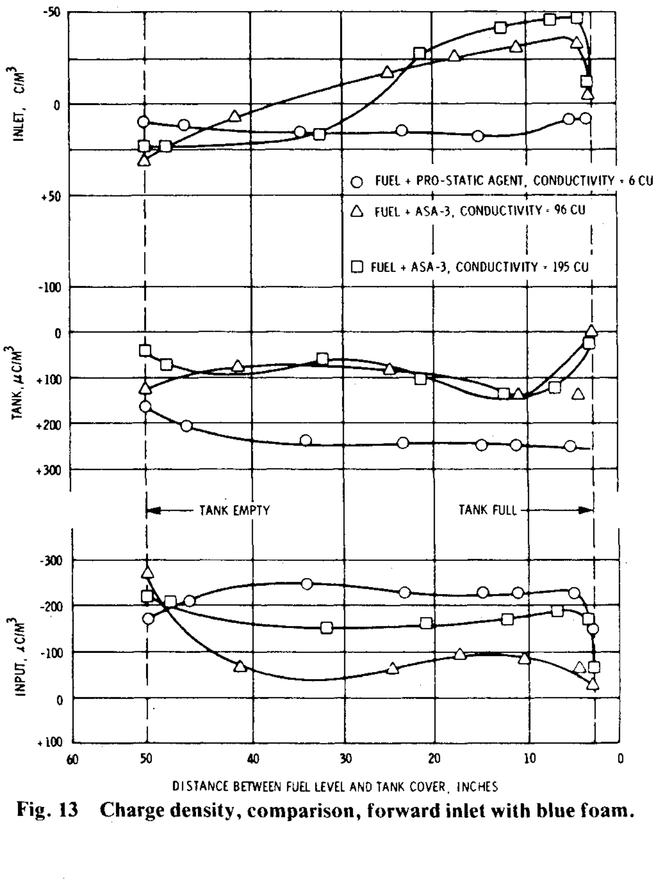

Fig. 13 Charge density, comparison, forward inlet with blue foam.

voltages were reduced to negligible values, while the input charge and tank charge density values were approximately the same as those obtained during the forward inlet tests. The inlet charge densities were not obtained during this test series.

No static discharges were recorded during the piccolo inlet tests at the increased fuel conductivity levels.

Conclusions

The conclusions[5] from the data obtained during the test program are the following:

1) Of the inlet configurations tested, the multiholed (piccolo) design proved to be the optimum design. No static charges were generated when the piccolo inlet was used in conjunction with red or blue foam and low- or high-input charge fuel.

2) Polyurethane foam, as installed in the aircraft fuel tanks, contributes to the electrostatic charge buildup within the tank. The potential for static discharges is greater with polyether (blue) foam than with polyester (red) foam. Blue foam produced higher field strengths than red foam or no foam, regardless of the inlet configuration used. Static discharges with blue foam and the forward inlet were produced at any fuel input charge level, whereas static discharges with red foam and the same inlet nozzle required a higher fuel input charge level.

3) The addition of Shell Chemical Company ASA-3 antistatic additive to JP-4 fuel increases the fuel conductivity and decreases the fuel input charge density, thereby reducing the tank and nozzle charge densities and the generated field strength.

4) The addition of Shell Chemical Company ASA-3 antistatic additive to JP-4 fuel in sufficient quantity, to increase the fuel conductivity to between 95 and 200 pS/m, eliminated static discharges when the forward inlet was used in conjunction with blue foam, which was the worst-case configuration.

Acknowledgment

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