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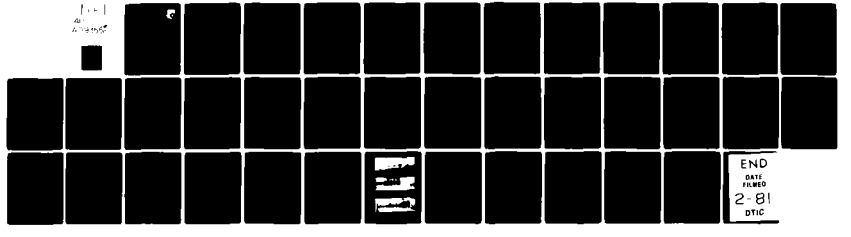

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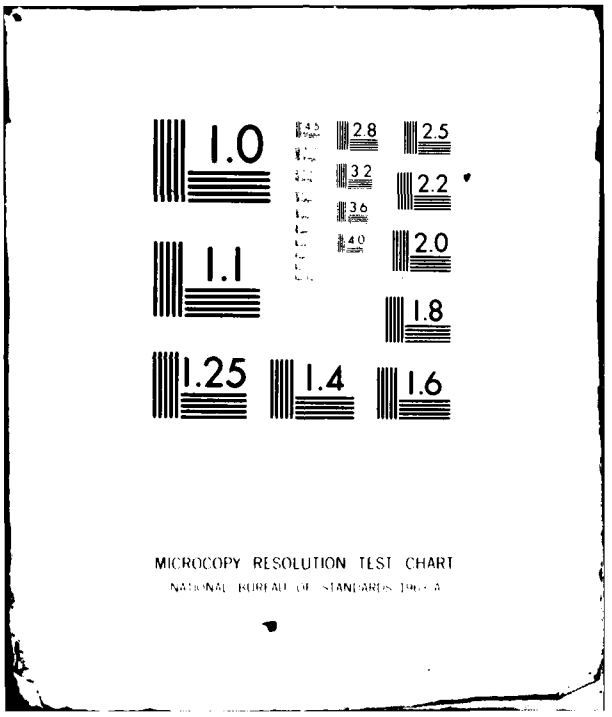
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STATIC CHARGE IN AIRCRAFT FUEL TANKS

Department of Electrical Engineering
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And

Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

September 1980

TECHNICAL REPORT AFWAL-TR-80-2049

Final Report for Period July 1977 to September 1979

Approved for public release; distribution unlimited.

AERO PROPULSION LABORATORY
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This report has been reviewed by the Information Office (ASD/PAM) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program investigates electrostatic hazards associated with aircraft fueling. The triho electric phenomena of reticulated polyurethane foam charging was examined using JP-4. An attempt was made to understand the basic electrostatic phenomena involved when fuel is pumped into aircraft fuel tanks containing reticulated, polyurethane foam. The investigation also involved the development and study of alternative foam materials having enhanced electrical and charge dissipation characteristics as a

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20. ABSTRACT (Continued)

means of eliminating the electrostatic hazards during refueling.

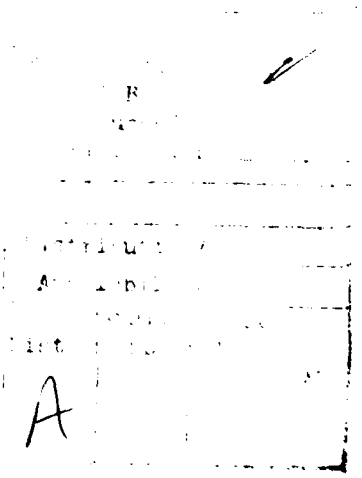
FOREWORD

This report presents a summary of an investigation into the electrostatic phenomena involved in fueling aircraft whose fuel tanks are filled with reticulated polyurethane foam. The principal investigator was the late Professor A. W. Bright, who died early in 1979. He was succeeded by Dr. J. F. Hughes as principal investigator. The associate investigator was Dr. D. B. Farrer, all of Southampton University.

The program was funded in Fiscal Year 1977 by the European Office of Aerospace Research and Development (AFOSR) under Project 2301, Task D1. Fiscal Year 1978 funds were provided by the Aero Propulsion Laboratory (AFWAL/AFSC) under Project 3048, Task 05, Work Unit 88. The study covered the time period from July 1977 through September 1979.

Special appreciation is hereby given to Major George F. Uhlig and his successor, Lt Colonel Richard F. Felton of the European Office of Aerospace Research and Development, for their assistance in initiating and monitoring the program.

This report was written by Mr. C. R. Martel, AFWAL/POSF, from various progress and summary reports prepared by Professor A. W. Bright and Dr. D. B. Farrer of Southampton University. The report was submitted in April 1980.



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SECTION I

INTRODUCTION

During the winters of 1974 through 1977, eight USAF aircraft experienced fires within their fuel tanks during refueling. These eight aircraft fires occurred in fuel tanks equipped with reticulated (i.e., open pore) polyester urethane foam. The purpose of the foam is to suppress fires and explosions initiated by gunfire. Electrostatic charge generation and subsequent spark discharges resulting from the flowing of the fuel into the fuel tank (and through the foam) was suspected as the source of the ignition of the fuel vapor-air mixture within the fuel tanks.

An unsolicited proposal was submitted by Southampton University to the European Office of Aerospace Research and Development (EOARD) to investigate the contribution of the reticulated polyester foam to the fuel tank fire problem. This proposal was accepted by the Air Force, and AFOSR Grant 77-3373 was given to Southampton University with a start date of 1 July 1977. This grant was renewed in July 1978 for a second year's effort.

The objective of the Southampton program was to understand the basic electrostatic phenomena associated with refueling aircraft whose fuel tanks contained reticulated polyurethane foam. This work involved the examination of the tribo-electric phenomena of reticulated polyurethane foam charging with JP-4 aviation turbine fuel. Also, the work was directed towards the study of alternative fuel tank foam materials having enhanced electrical and charge dissipation characteristics as a means of eliminating the electrostatic hazard during fueling.

The program emphasis was placed on the polyether urethane, reticulated foam which has superior life as compared to the polyester urethane foam. Also, prior to the start of the Southampton program it was found that the newer polyether urethane foam tended to aggravate the electrostatic problem.

SECTION II

TECHNICAL APPROACH

The program was directed towards two basic areas: (1) the development of foam materials which would have enhanced electrical conductivity, and (2) the examination of the tribo-charging properties of standard and modified foam materials with JP-4.

Three basic types of test facilities were used in the program: (1) a laboratory scale apparatus based on the Exxon Mini-Static Testing Device to assess the relative tribo-charging characteristics of various foam materials with JP-4; (2) a laboratory scale apparatus to assess the relative charge dissipation characteristics of foam materials using artificially charged fuel; and (3) a one-fourth scale, high velocity, experimental refueling system based on a forty-five gallon (U.K.) fuel tank. These devices are described in more detail below.

1. CONDUCTIVITY-ENHANCED POLYURETHANE FOAMS

In conjunction with I.C.I. Organics Division, Manchester, U.K., considerable effort was directed towards producing a polyurethane foam with enhanced electrical conductivity. The approach used was to add electrically conducting additives to the foam. Carbon black, short (3mm long) carbon fibers, and a conductivity enhancing salt, Resist Salt L, were used with limited success.

A second approach taken was to apply a conductive coating to the polyether urethane foam. Scott coarse blue, polyether urethane foam (supplied by the USAF) was coated with a conducting co-polymer formulation containing carbon black. The coating process was carried out by Canespa (U.K.) Ltd. The approximate foam conductivity obtained was 3×10^{5} ohm-meters as compared to about 5×10^{13} ohm-meters for the uncoated foam. The coating weight varied between 18% to 30% of the foam substrate, but no effort was made to control coating weight at this stage of development.

2. FOAM CHARGE DISSIPATION IN JP-4

Charge dissipation tests were performed on various foams using the small scale apparatus shown in Figure 1. Gaseous nitrogen at 10 psi was used to force fuel at constant flow rate into a steel tank (approximately one-gallon capacity) into which cores of foam could be placed. Charge of either polarity could be injected into fuel before entry into the tank. Measurements were made of the electrostatic field at the top of the tank during and after fuel injection. The charge relaxation rate to the tank wall was measured, and this was contrasted with the relaxation rates of the foams. The fuel was JP-4 with fuel system icing inhibitor and corrosion inhibitor additive, but no anti-static additive. The conductivity of the JP-4 was 19 pS/m.

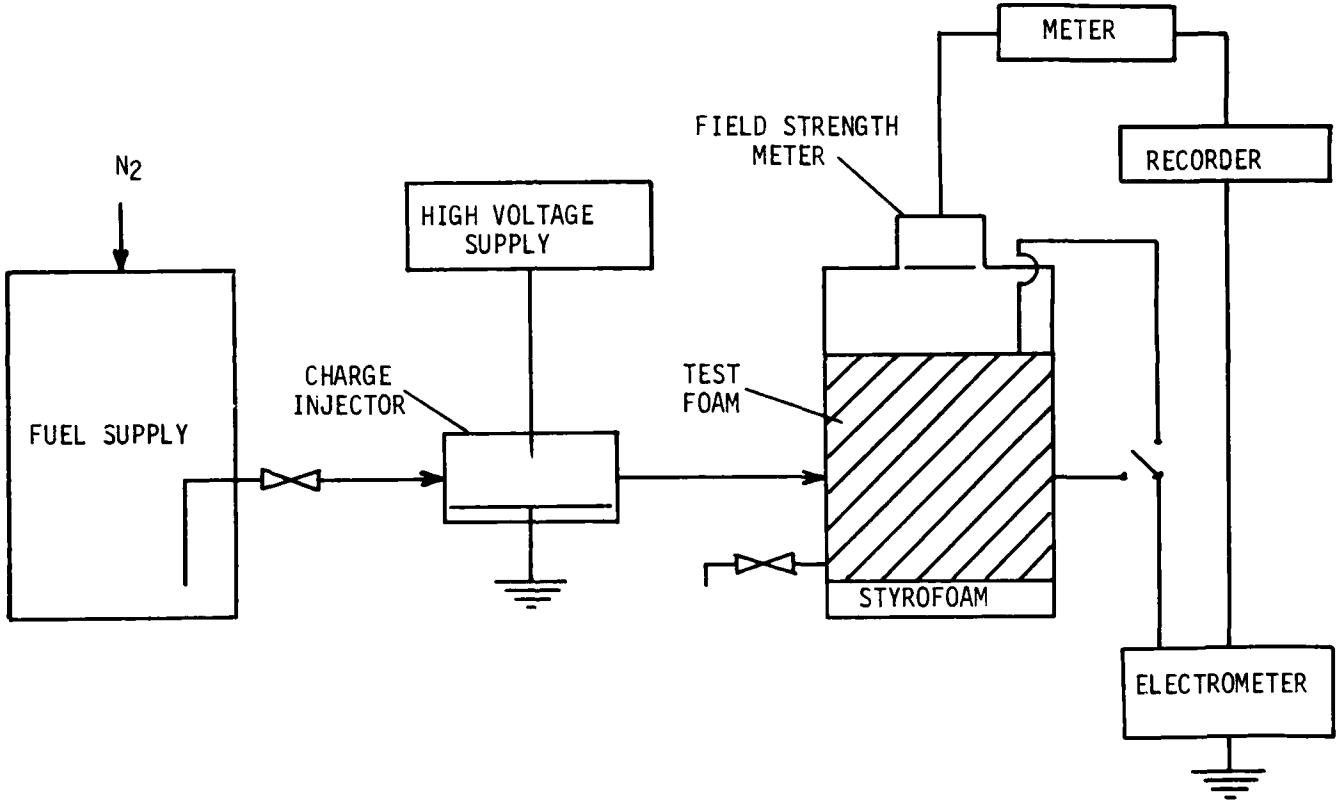

FIGURE 1 SMALL SCALE EXPERIMENTAL RIG

3. EXPERIMENTAL REFUELING SYSTEM

A. Description of the Experimental Refueling System

The experimental refueling system (Figure 2) was based around an electrically isolated, 45-gallon (U.K.) metal tank situated within a Faraday Cage. Fuel could be cycled through the tank with the level held at any desired position, or the tank could be filled and drained in the normal manner. Maximum pumping capacity was 18 gallons (U.K.) per minute. The pump motor was deactivated by an ultrasonic level sensing device at the level of maximum fill.

Fuel charge density was controlled using an active charge injector located between two charge relaxation meters situated in the main fill line. Fuel charge densities were controllable over the range of -1000 $\mu C/m^3$ to +1000 $\mu C/m^3$. The system was equipped with a fuel refrigeration and heating unit which enabled experiments to be made over the temperature range of -30°C to +30°C. Temperature control was to within +2°C.

The 45-gallon (U.K.) fuel tank (Figure 3) was equipped to contain polyurethane foam and a variety of inlet fuel nozzles. The nozzle could be varied in length and orifice diameter and permitted studies at high flow rates and low fuel velocities. The nozzle/foam void was observable through a 6" X 4" conductive coated, borosilicate glass window. Spark discharge signals between the nozzle and ground were detected as the transient voltage across the 100-ohm resistor (Figure 3).

The complete system was inerted with nitrogen and completely sealed to prevent serious loss of the volatile components of JP-4 over a period of time.

B. Fuel Quality Control

Recycling relatively small quantities of fuel can lead to serious contamination or depletion of additives or fuel components. In addition, fuel quality varies from drum to drum, and these variables must be taken into account in a serious experimental program if experimental continuity and reproducibility of results are to be kept within acceptable limits. The following procedures were used to ensure this:

(1) Water content of JP-4 was determined by use of an automatic Karl Fischer titration appartus. Fuel water content could be controlled by use of a coalescer filter unit which comprises part of the fueling system.

(2) The concentration of the fuel system icing inhibitor (ethylene glycol monomethyl ether) was determined by quantitative IR spectroscopy. Adjustments to the concentration in the fuel were made accordingly.

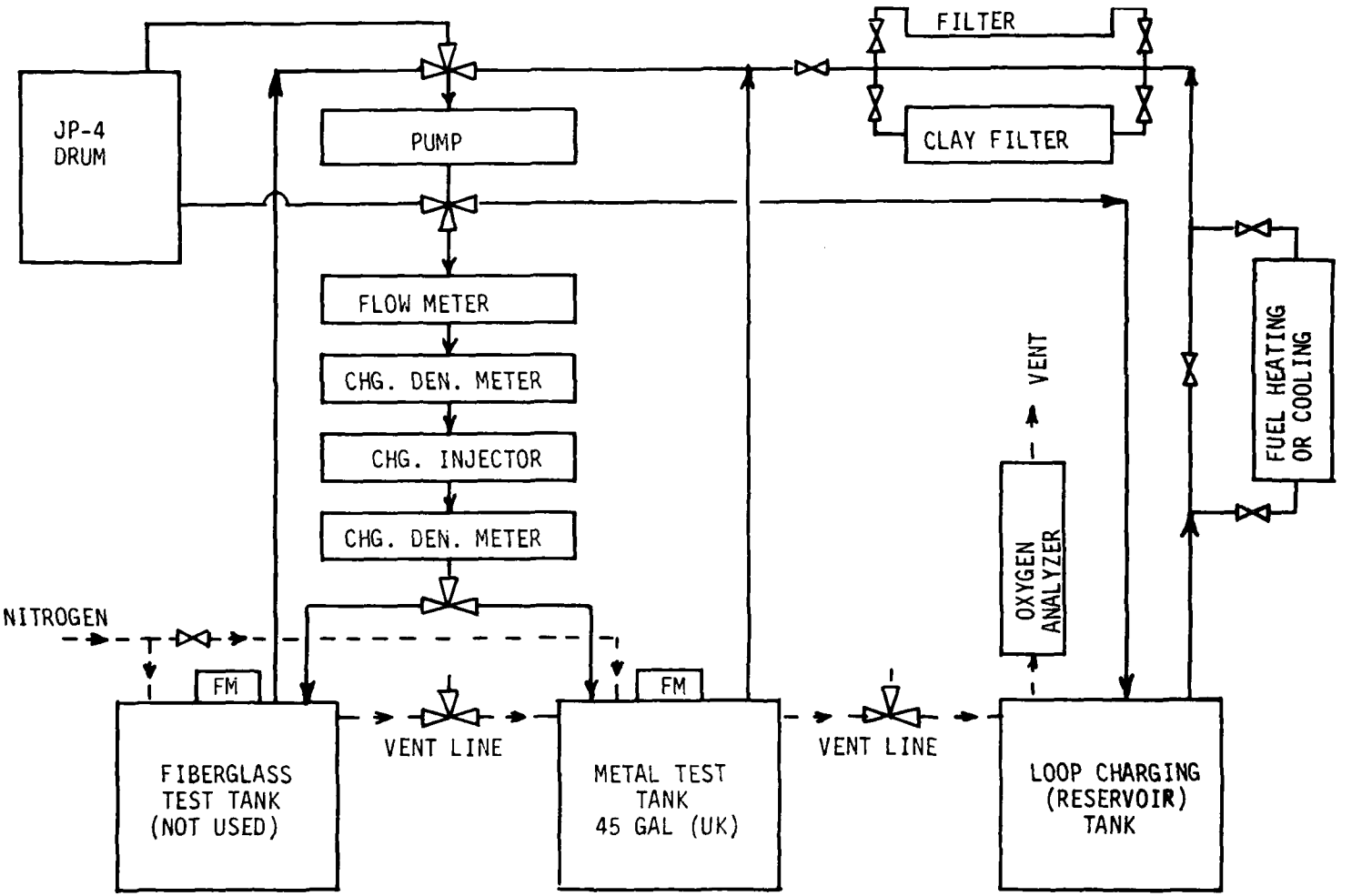

FIGURE 2 EXPERIMENTAL REFUELING SYSTEM

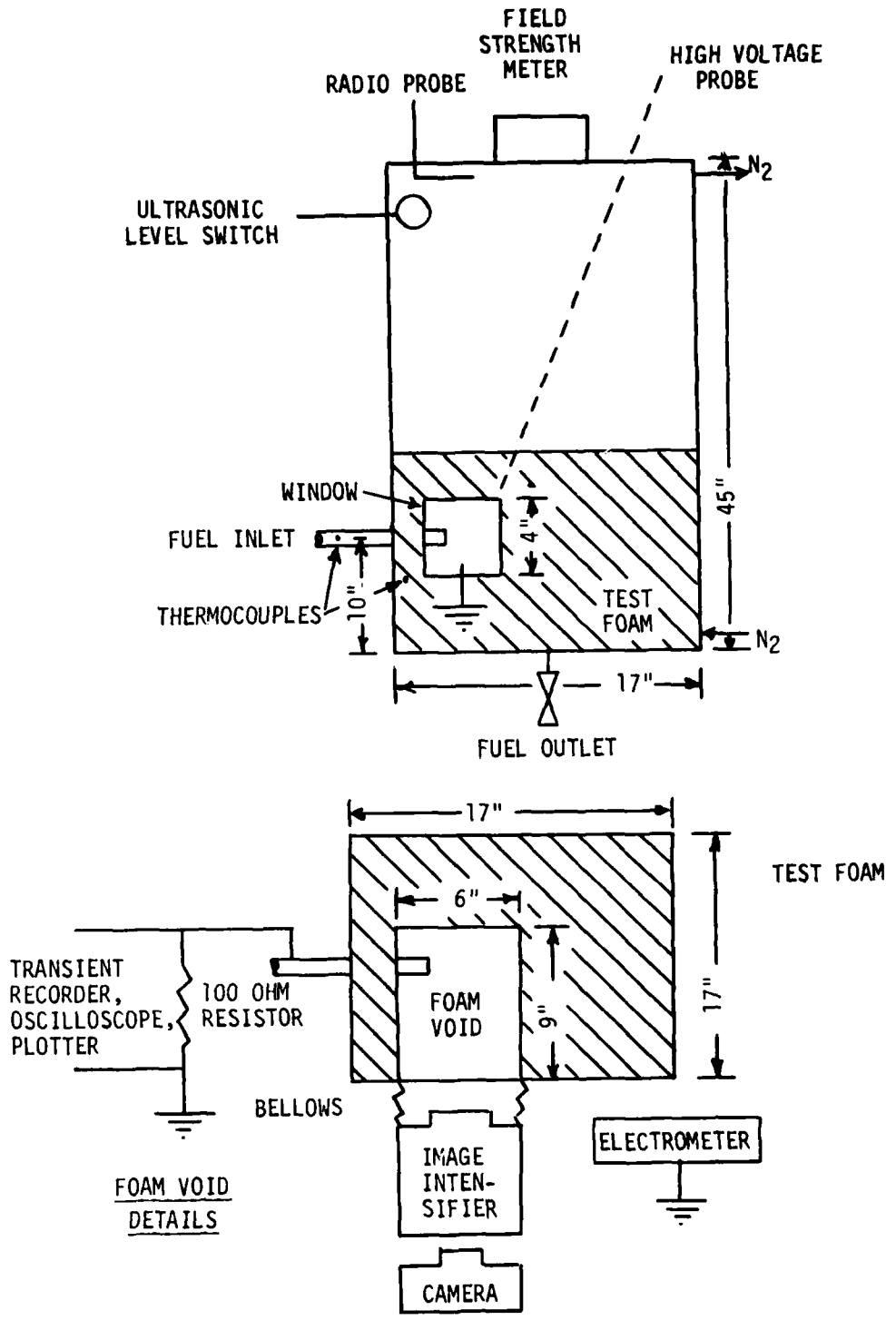

FIGURE 3 FUEL TANK CONFIGURATION

(3) The concentration of the corrosion inhibitor in the fuel was not determined. However, it was assumed that this material was almost totally removed by clay treatment. Thus, the treated fuel would be redoped to the requisite concentration.

(4) The volatile components of JP-4 were monitored by quantitative gas chromatography. A batch of fuel would be discarded if significant depletion of the volatile fractions of the fuel occurred over a period of time.

SECTION III

DISCUSSION OF RESULTS

1. CONDUCTIVITY ENHANCED POLYURETHANE FOAMS

The use of a reticulated polyurethane foam having significantly increased electrical conductivity was anticipated to reduce the static charging hazard. Two approaches were taken to increase the conductivity of the polyurethane foam: (1) incorporate conductivity additives into the foam, and (2) add a conducting coating to the foam (see Section II. 1.).

A. Foams Incorporating Conductivity Additives

Carbon black, carbon fibers, and a conductivity enhancing salt, "Resist Salt L", were incorporated into white, polyether urethane foam during the foaming process. No attempt was made to optimize pore size or to refine the formulation. A standard pore size of 100 pores/inch was adopted and the sample size was a 6-inch cube. The target resistivity was 10^9 ohm-meters, which corresponds to a fuel having a conductivity of 1000 pS/m. This would be a significant increase in conductivity over the Scott coarse pore, blue, polyether urethane foam (Type IV per MIL-B-83054), which has a resistivity of about 5×10^{13} ohm-meters.

Severe viscosity problems were encountered when adding more than 5% carbon black to the foam reactants, making foam production difficult. The Resist Salt L additive was extremely effective in reducing resistivity without producing viscosity problems. An addition of 2% Resist Salt L produced a volume resistivity of 7×10^9 ohm-meters, and an addition of 20% Resist Salt L produced a volume resistivity of 4×10^8 ohm-meters.

Handling problems were encountered when using the 3mm long carbon fibers at concentrations greater than 1% as an additive to the foam reactants. At the 1% concentration, a conductivity of 5×10^{10} ohm-meters was obtained. Other length carbon fibers were available but were not tried.

The most encouraging results were obtained using a combination of 1% carbon fibers (3mm length) and 5% Resist Salt L. This combination reduced the volume resistivity of the polyether urethane foam to 1×10^9 ohm-meters. Sixteen samples of foam using various combinations of carbon black, carbon fibers, and Resist Salt L were produced suitable for testing. In five cases a fire retardant material, Daltogard F, was incorporated into the foam. Table I summarizes the composition, volume resistivity, and density of these experimental foams produced. Note that duplicate measurements were made of the volume resistivity and density of these foams.

TABLE 1 EVALUATION OF FOAM CONDUCTIVITY ADDITIVES

FOAM NUMBER			1	2	3	4	5	6	7	8
LAB. REF. NUMBER			77	82	86	87	84	85	91	88
ADDITIVE: WT. % CARBON FIBRE (3 mm)			CONTROL	-	-	-	-	-	-	-
CONDUCTIVE CARBON BLACK				5	10	10	-	-	-	-
RESIST SALT L				-	-	-	2	5	5	10
DALTOGARD F				-	-	-	-	-	-	-
VOLUME RESISTIVITY	Ωm	A	1.3×10^{11}	1.4×10^{10}	2.4×10^{10}	4.4×10^{11}	7.9×10^{9}	2.2×10^{9}	2.0×10^{9}	2.3×10^{9}
		B	1.4×10^{11}	1.2×10^{10}	1.3×10^{10}	2.5×10^{11}	6.4×10^{9}	2.4×10^{9}	2.1×10^{9}	2.0×10^{11}
DENSITY	kg/m3	A	26.7	30.7	44.9	32.9	24.6	25.4	31.9	24.2
		B	22.4	30.6	58.6	33.7	23.5	25.5	30.7	26.5

TABLE 1 EVALUATION OF FOAM CONDUCTIVITY ADDITIVES (CONTINUE)

FOAM NUMBER			9	11	12	13	14	15	16
LAB. REF. NUMBER			96	116	117	118	119	120	121
ADDITIVE: WT. %									
CARBON FIBRE (3 mm)			-	CONTROL	0.25	0.5	1.0	2.0	1.0
CONDUCTIVE CARBON BLACK			-		-	-	-	-	-
RESIST SALT L			20		-	-	-	-	5
DALTOGARD F			-		10	10	10	10	10
VOLUME RESISTIVITY	Ωm	A	3.9×10^{8}	1.6×10^{11}	5.2×10^{11}	9.7×10^{10}	5.1×10^{10}	7.0×10^{10}	1.1×10^{9}
		B	4.0×10^{8}	1.9×10^{11}	5.1×10^{11}	8.7×10^{10}	5.0×10^{10}	3.1×10^{10}	7.3×10^{8}
DENSITY	kg/m^3	A	25.7	30.7	30.3	29.7	29.7	30.3	34.8
		B	25.9	29.6	29.6	30.8	29.0	29.1	35.0

Plans to obtain larger samples of polyether urethane foam having a pore size of 5-15 pores/inch (equivalent to the Type IV, blue, polyether urethane foam) did not materialize. Thus, no actual fuel charging tests were made with these bulk conductivity enhanced foams.

B. Conductive-Coated Polyurethane Foam

Type IV foam, per MIL-B-83054 (i.e., coarse pore, blue, polyether urethane reticulated foam), was coated using a conducting co-polymer formulation containing carbon black. The coating process was accomplished by Canespa (U.K.) Ltd., and the approximate foam conductivity obtained was 10^5 ohm-meter. The coating weight varied between 18% and 30% of the foam substrate, but no effort was made to control coating weight at this stage of development.

The cross-linked coating was found to be stable in JP-4 and had a negligible effect on fuel conductivity after a contact time of five weeks. The charge dissipation and the effectiveness in reducing foam-to-nozzle spark discharges were studied both on a small scale and in the Experimental Fueling System (discussed in Section III. 2. B.(5)). Table 2 gives the results of the electrical measurements made on the conductive coated foams.

C. Fuel Extraction Tests

One-half gram samples of various polyurethane foams were soaked in 50ml of JP-4 for different periods of time and at different temperatures. Conductivity measurements on the JP-4 extractant were carried out at 25°C. The conductivity test cell constant was 0.2 and the applied potential was 10 VAC. Results are given in Table 3. The resulting data have considerable scatter, but only the bulk conductivity foams incorporating 10% or greater concentrations of Resist Salt L appeared to significantly affect the conductivity of the JP-4.

D. Relative Charge Generation

The relative charge characteristics of the standard USAF polyurethane foams per MIL-B-83054, the bulk conductivity enhanced polyurethane foams (ICI types), and the conductive coated polyurethane foams (Canespa types) were examined using an Exxon Mini-Static Testing Device described in Reference 1. In this work, a linear relationship was found between charge density produced in a fuel and the square of the number of foam cells per linear inch. However, subsequent results suggest that data obtained with this testing device were somewhat dependent on the manner in which the sample was loaded, as there appeared to be pronounced orifice effects with most of the charging taking place close to the fuel exit point. A detailed account of this work is found in Reference 2.

E. Charge Dissipation in JP-4

Charge dissipation tests with various fuel tank/foam configurations were conducted using the small scale apparatus shown

TABLE 2

CONDUCTIVE COATED FOAM VOLUME RESISTIVITIES

Foam Type	P.D. Volts Applied	Amps Measured	Sample Thickness (m)	Vol. Res. (Ωm)
'Canespa' Treated 'B' Type II Yellow *	50	2×10^{-5}	0.033	2×10^{5}
'Canespa' Treated 'A' Type IV Blue**	50	1×10^{-5}	0.045	3×10^{5}
'Canespa' Treated 'B' Type IV Blue**	50	2.7×10^{-5}	0.05	1×10^{5}
'Canespa' Treated 'B' Type V Blue***	50	1.7×10^{-5}	0.025	3×10^{5}
'Canespa' Treated 'A' Ivory	50	5.2×10^{-5}	0.04	6×10^{4}

'A' = Air Dried Coating.

'B' = Cross-Linked Coating.

* = Type II, Yellow, Medium Pore, Polyester Urethane Foam Per MIL-B-83054.

** = Type IV, Blue, Coarse Pore, Polyester Urethane Foam Per MIL-B-83054.

*** = Type V, Blue, Fine Pore, Polyester Urethane Foam Per MIL-B-83054.

TABLE 3 FUEL EXTRACTION TESTS OF CONDUCTIVITY ENHANCED FOAMS

LAB. REF. NO. (Table 1)	FOAM DESCRIPTION	CONDUCTIVITY OF JP-4 EXTRACTANT (pS/m) Test A	Test B	Test C
96	ICI 20 Resist Salt L	175	100	120
116	ICI Control, No Additive	30	30	17
121	ICI 5 Resist Salt L, 1 Carbon Fibers (3mm)	25	15	15
88	ICI 10 Resist Salt L	100	50	75
84	ICI 2 Resist Salt L	30	22.5	15
82	ICI 5 Carbon Black	75	42.5	60
-	X/L Conductive Coated, Blue Polyether Urethane, Type IV	30	22.5	21.5
-	AD Conductive Coated, Blue Polyether Urethane, Type IV	15	15	15
-	Orange Polyester Urethane, Type I, MIL-B-83054	20	29	36
-	Blue, Polyether Urethane, Type IV, MIL-B-83054	30	32.5	32
-	JP-4 Control	50	50	61.5

KEY: X/L = Heat Cross Linked
AD = Air Dried

Test A - 20 Hours at 50°C
Test B - 20 Hours at 50°C Plus 5 Weeks at 25°C
Test C - 20 Hours at 50°C Plus 5 Weeks at 25°C Plus 20 Hours at 50°C

in Figure 1. Gaseous nitrogen at 10 psi was used to force fuel at constant flow rate into a steel tank (approximately one-gallon capacity) into which cores of test foam were placed. Charge of either polarity was injected into the fuel before the fuel entered the tank. Measurements were made of the electrostatic field at the top of the tank during and after fuel injection. The charge relaxation rate to the tank wall was measured and this was compared with relaxation rates to the foams. The fuel used was JP-4 (without an anti-static additive) with a conductivity of 19 pS/m.

The conducting foam tested was the Type IV, blue polyether urethane type coated with the Canespa Ltd., cross-linked co-polymer, a formulation containing carbon black and giving the foam a volume resistivity of 3×10^5 ohm-meters. The coated foam was compared and contrasted to the uncoated, Type IV polyether urethane foam which had a resistivity of 3×10^{13} ohm-meters.

Typical field build-up and decay measurements are shown in Figure 4, and the results of these charge dissipation tests, listed in Tables 4 and 5, are the average values measured for several runs. With negative charge injected into the incoming fuel (Table 4), measurements were made of the electric field at the top of the tank and of the current collected from the grounded tank wall. The surface potential was calculated from the measured electric field when the fuel reached the top surface of the foam. The Table 5 data are from the tests with positive charge injected into the incoming fuel.

Since charge was injected into the JP-4, the relative relaxation rates of the electric field for the unfilled and foam-filled tank were similar (Runs 1 and 2 of Figure 4). However, the Type IV blue foam probably absorbed charge from the JP-4 to some extent, as it had a slightly slower decay rate.

A significant finding was that the rate of charge dissipation by the conductive foam to ground with the tank electrically isolated (Table 5, Test 2) is comparable to that for the grounded, unfilled metal tank (Table 4, Test 1). Also, from Figure 4 it is seen that the conductive-foam-filled tank (Run 3) did not allow a significant electric field to build-up within the test tank as occurred with the foam-filled tank (Run 1) and the empty tank (Run 2). Thus, it was concluded that the conductive foam was effective in dissipating charge from JP-4.

2. EXPERIMENTAL FUELING SYSTEM RESULTS

A. Charge Decay for Positively and Negatively Charged Fuel

A comparative test was carried out to ascertain if any significant difference existed between the rate of relaxation of positively and negatively charged species in JP-4. The primary

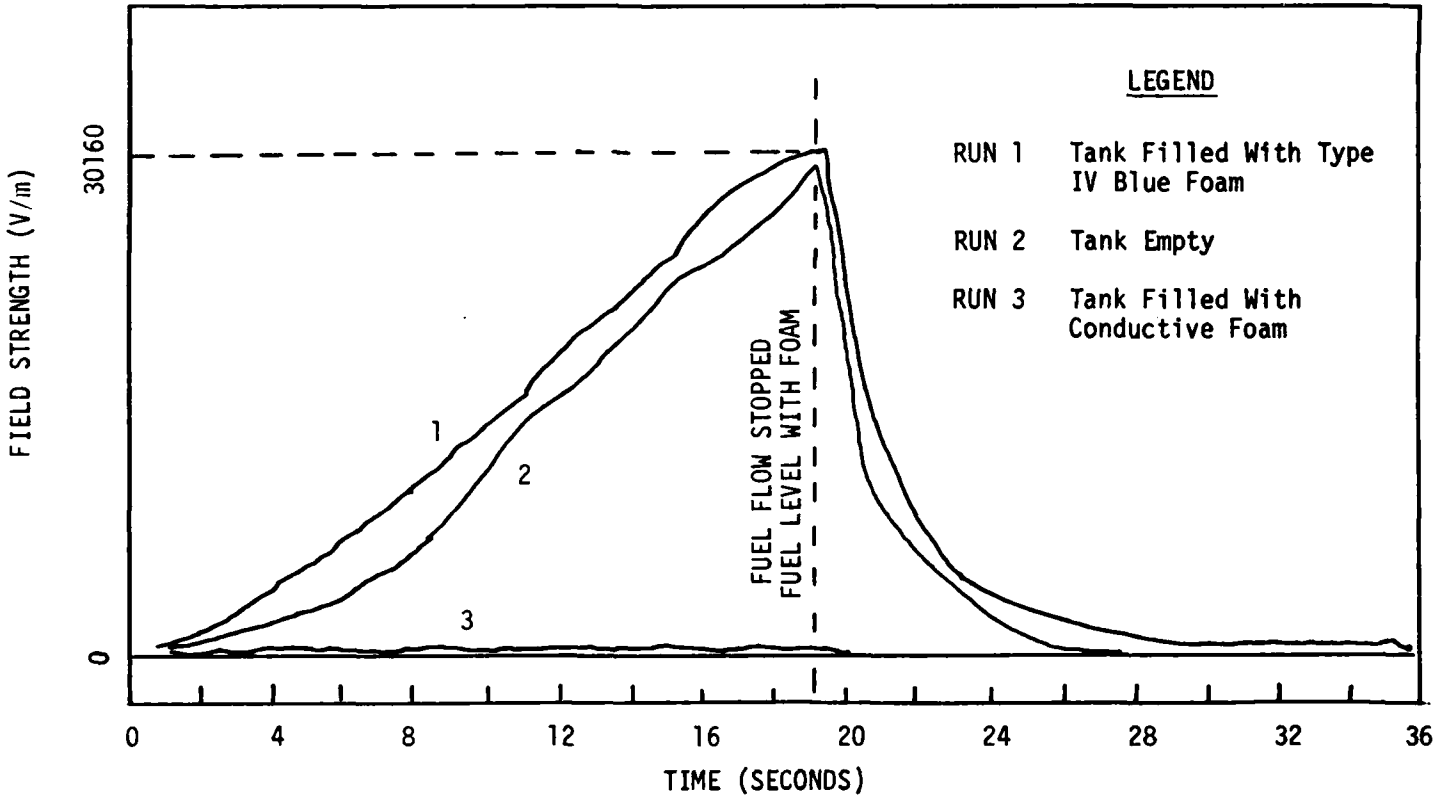

FIGURE 4 TYPICAL FIELD BUILD-UP AND DECAY CURVES

TABLE 4

ELECTROSTATIC CHARGE IN TANK

TANK FILLING	INJECTION POTENTIAL (kV)	INDICATED MAXIMUM FIELD (Vm^{-1})	SURFACE POTENTIAL (V)	COLLECTED CURRENT (A)	JP CHARGE DENSITY (μCm^{-3})
1. NO FOAM	-10	29500	1475	-1.7×10^{-7}	1930
2. CONDUCTIVE FOAM	-10	270	13	-1.5×10^{-7}	1670
3. TYPE IV BLUE FOAM	-10	30200	1510	-1.25×10^{-7}	1390

TABLE 5

CURRENTS COLLECTED FROM TANK AND FOAM

CONDITIONS	INJECTION POTENTIAL	COLLECTED CURRENT AMPS
1. TYPE IV BLUE FOAM GROUNDED THROUGH ELECTROMETER, TANK ISOLATED	+ 10 kV	$+1 \times 10^{-10}$
2. CONDUCTIVE FOAM GROUNDED THROUGH ELECTROMETER, TANK	+ 10 kV	$+4 \times 10^{-8}$
3. TANK GROUNDED THROUGH ELECTROMETER (CONTAINING CONDUCTIVE FOAM)	+ 10 kV	$+5 \times 10^{-8}$

reason for this was that charge density measurements depended on charge relaxation rates.

The test tank was filled with artificially charged fuel (initially 1000μC/m^3). The charge decay after the filling was complete (for both positively and negatively charged fuel) was measured by the field strength meter. Relaxation times and effective conductivities were calculated from the field half-life decay curve. Typical results are shown in Table 6. No significant differences in decay rates for positively or negatively charged fuel were seen.

B. Observations of Electrostatic Phenomena in Tank Filled with Type IV Foam

Electrical discharges were detected in the 45-gallon test tank filled with the Type IV, blue, polyether urethane reticulated foam. These discharges were initially detected using a radio probe during the initial and subsequent fillings of the tank at low fuel velocities and low mass transfer rates (about 4 m/sec and 3.5 gallons/min). The discharges ceased once the nozzle inlet was covered with fuel. Also, the discharges initially obtained at the low flow rates with the nozzle above the fuel level could not be reproduced after a period of pumping at high flow rates.

On increasing the fueling rate, discharges were again detected (18 gallons/min, about 19 m/sec). With the nozzle above the level of the fuel surface, low intensity blue flash discharges were visible with the naked eye. However, with the nozzle covered, the discharges were no longer visible.

The characteristics of the electrical phenomena occurring in the foam void were examined using a high gain image intensifier. Observations of the discharges using the image intensifier revealed the following:

(a) Nozzle above the fuel level:

(i) A corona halo around the nozzle was visible.

(ii) Intermittent low intensity brush discharges from all foam surfaces were seen at high fueling rates.

(iii) At high fuel flow rates, high intensity brush discharges were seen around the fuel/foam impact area, streaming to the inlet nozzle.

(iv) On cessation of pumping, the nozzle remained in corona discharge, indicating very high surface potentials residing on the foam surface.

TABLE 6 FIELD DECAY FOR POSITIVELY AND NEGATIVELY CHARGED FUEL

	+VE CHARGE DECAY	-VE CHARGE DECAY
FIELD HALF LIFE $t_{1/2}$, s	1.65, 1.70, 1.40	1.8, 1.55, 1.30
FIELD DECAY TIME CONSTANT τ, s	2.38, 2.45, 2.02	2.6, 2.34, 1.88
FUEL EFFECTIVE CONDUCTIVITY pS/m	7.6, 7.4, 8.9	6.9, 7.7, 9.6
MEAN EFFECTIVE CONDUCTIVITY pS/m	7.97	8.07
FUEL REST CONDUCTIVITY pS/m, 10°C	18.0	18.0

(b) Nozzle below the fuel level:

(i) No observable discharges were visible, although high intensity discharges were occurring to the nozzle and possibly other areas in the tank.

(ii) A corona halo around the nozzle was visible.

(iii) A corona plume or jet entrained in the fuel stream was visible.

The phenomena listed above are summarized schematically in Figure 5.

As noted above, the discharges obtained initially at low flow rates with the nozzle above the fuel level could not be reproduced after a period of high flow rates. It appears that once sufficiently high potentials have been developed on the foam surface, the nozzle was capable of spraying sufficient corona charge to prevent potentials from rising above the threshold necessary for a discharge to occur at the lower flow rates. This is supported by the observed fact that the nozzle remained in corona discharge for a considerable time after pumping was stopped.

(1) Foam-to-Nozzle Charge Transfer Measurements

Measurements of the amount of charge transferred between the Type IV blue foam surface and the single orifice (0.95 cm diameter) nozzle were undertaken in conjunction with the discharge observations. With the charge density of the incoming fuel adjusted as near to zero as possible, the discharge signals were detected as the transient voltages across the 100 ohm resistor to ground (Figure 4). The charge transfers were calculated from the maximum currents and the decay characteristics of the discharges. The mean charge transfer values at various flow rates appear in Table 7. These results have been plotted as (i) charge transfer versus flow rate (Figure 6); (ii) charge dissipation per second versus flow rate (Figure 6); and (iii) the square root of the charge dissipation per second versus fuel velocity (Figure 7).

Although the data are limited, there appears to be an approximate linear relationship between charge transfer and flow rate (Figure 6) and a parabolic relationship between charge dissipation per second and flow rate (Figure 6); i.e.,

(i) spark charge transfer is proportional to fill rate; and

(ii) spark charge transfer/second is proportional to $(\text{fill rate})^2$.

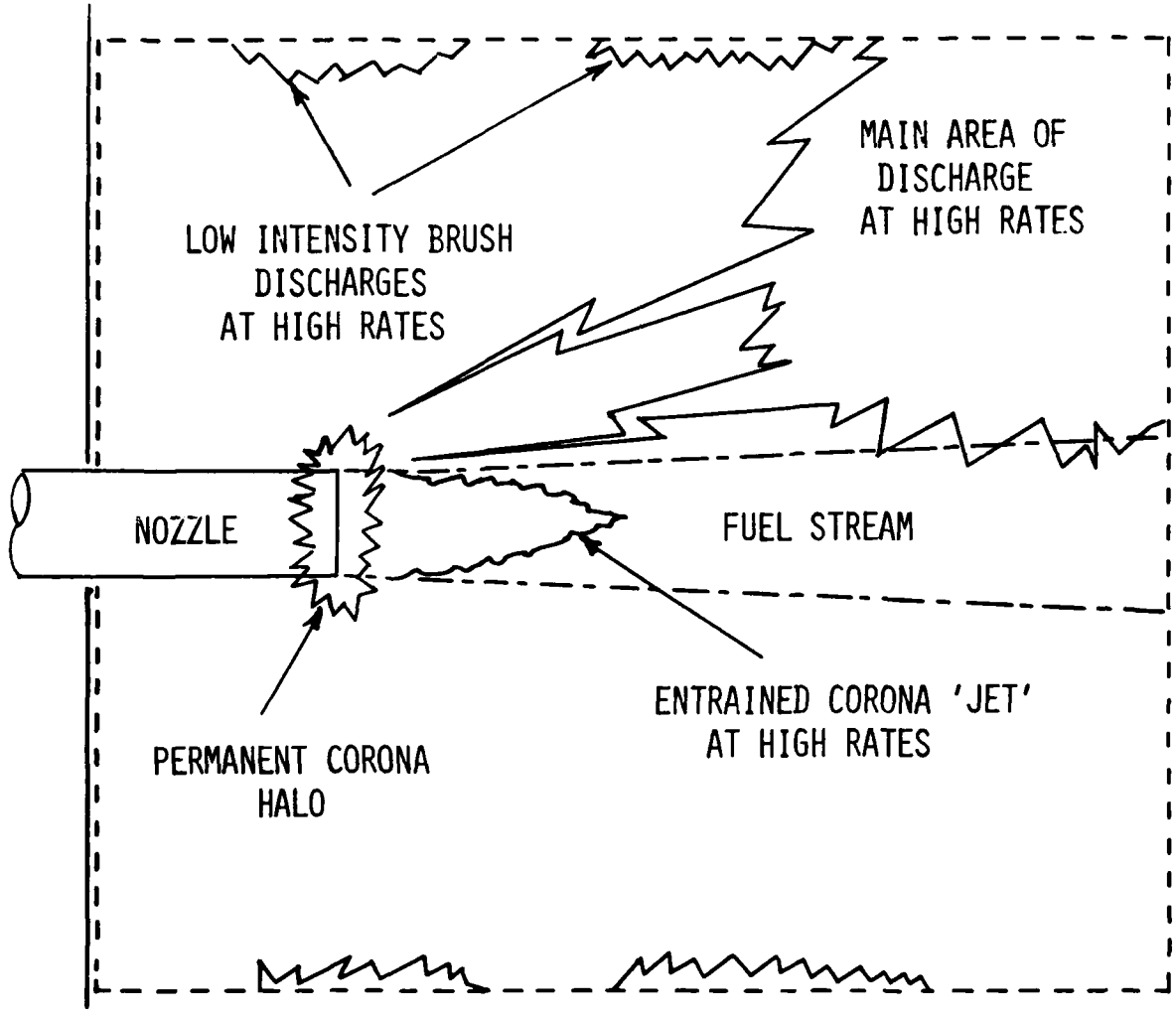

FIGURE 5 SCHEMATIC OF ELECTRICAL ACTIVITY IN FOAM VOID

TABLE 7 FOAM TO NOZZLE DISCHARGES (JP-4, TYPE IV BLUE FOAM, Nz INERTED)

RUN NO.*	NOZZLE DIAM CM	FUEL CONDUC-TIVITY C.U. $10^{0}C$	v, FLOW RATE G.P.M ($4.54Lm^{-1}$)	Q, MEAN CHARGE TRANSFER COULOMBS	τ, SPARK TIME CONSTANT s	F, MEAN SPARK FREQUENCY s^{-1}	Q X F Cs^{-1}	$\sqrt{Q \times F}$	V, FUEL VELOCITY ms^{-1}
1	0.95	32	6.0	4.8×10^{-7}	8.4×10^{-7}	0.5	2.4×10^{-7}	4.9×10^{-4}	6.4
2	0.95	32	10.0	6.6×10^{-7}	12.0×10^{-7}	0.76	5.0×10^{-7}	7.1×10^{-4}	10.5
3	0.95	32	15.0	8.4×10^{-7}	9.6×10^{-7}	1.30	10.9×10^{-7}	10.4×10^{-4}	14.5
4	0.95	32	19.2	12.0×10^{-7}	19.4×10^{-7}	1.60	19.2×10^{-7}	13.9×10^{-4}	21.1
5	0.95	32	18.0	25.2×10^{-7}	12.6×10^{-6}	1.65	41.6×10^{-7}	20.0×10^{-4}	19.8
6	0.95	32	19.2	66.0×10^{-7}	15.6×10^{-6}	1.50	99.0×10^{-7}	99.5×10^{-4}	21.1

* Runs 1 - 4, Fuel Level Below Nozzle.
Runs 5 & 6, Fuel Level Above Nozzle.

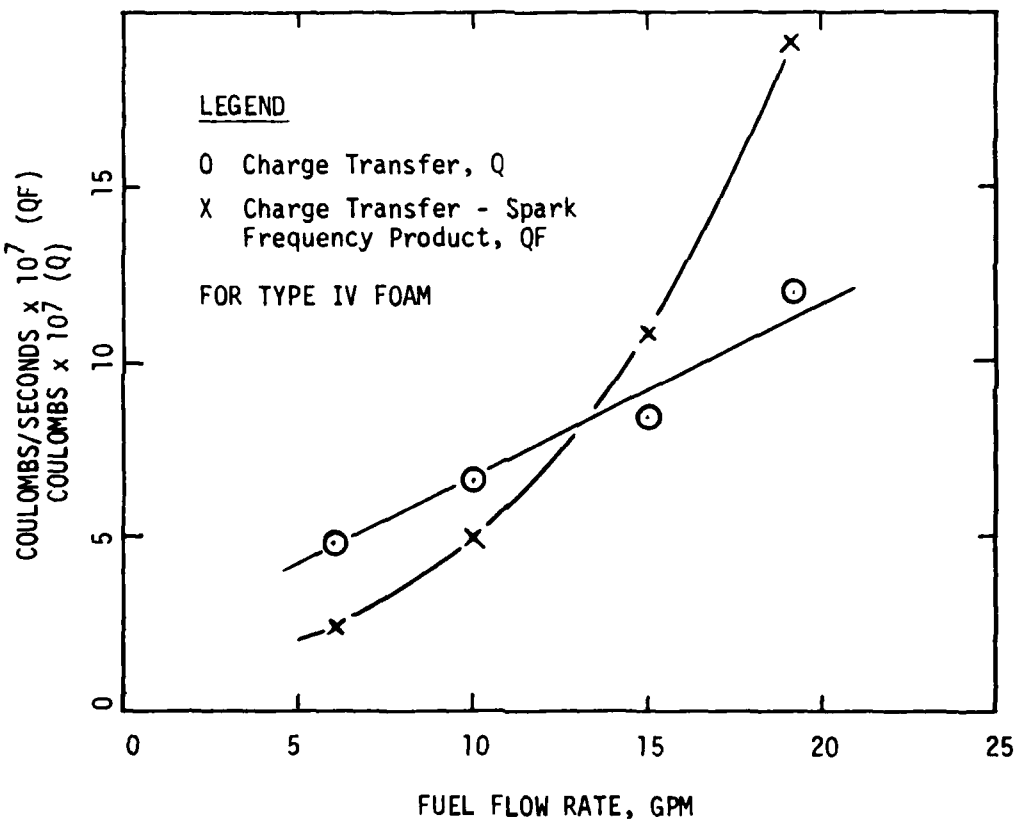

FIGURE 6 FLOW RATE EFFECTS ON CHARGE TRANSFER

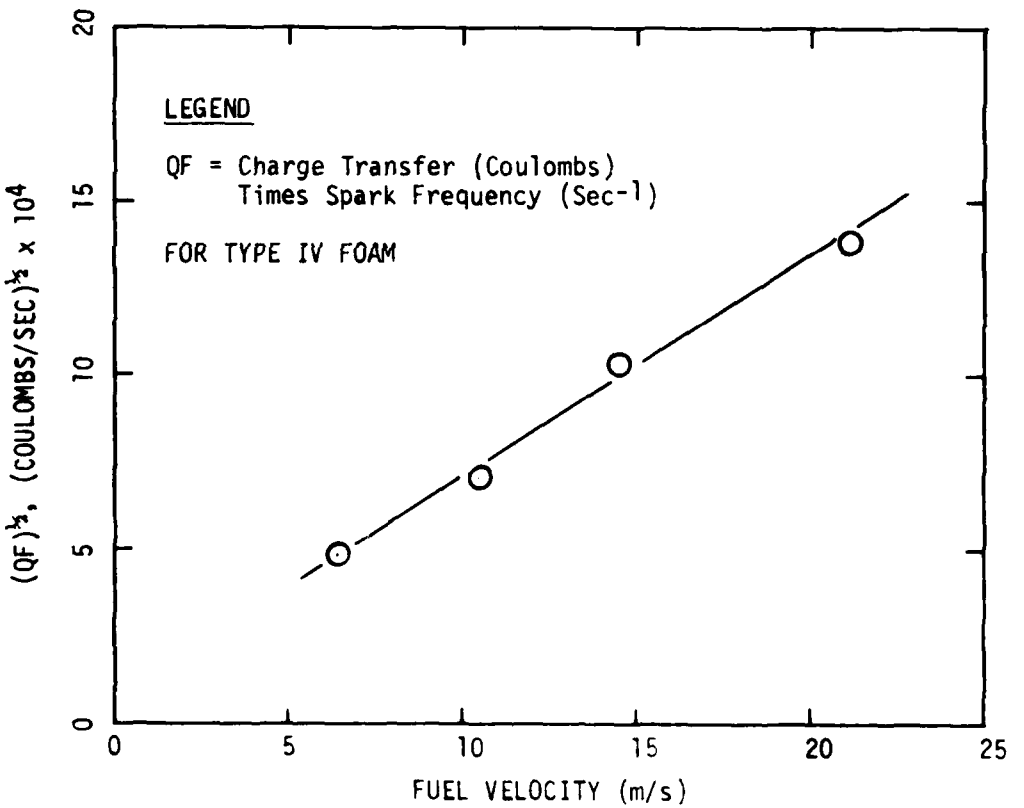

FIGURE 7 FUEL VELOCITY EFFECTS ON CHARGE TRANSFER-SPARK FREQUENCY PRODUCT

(2) Fuel State and Foam Aging

The initial conductivity of the JP-4 was 8 pS/m at 10°C. After contact with the Type IV foam, the conductivity rose to a maximum of 32 pS/m at 10°C. This indicates that an amount of extractable material had contaminated the fuel. There was a noticeable decrease in discharge activity as the foam underwent this "aging" process; i.e., spark discharge frequency was reduced. No attempt was made to decontaminate the fuel for this preliminary study which was carried out at 32 pS/m at 10°C.

Multiple sparks were detected by radio a few seconds after the initiation of the first pumping operation at minimum flow rate (5.5 gallons/min, 4 m/sec). Sparking frequency was considerbly reduced after the foam had aged; i.e., there was a reduction in the sparking frequency at the above flow rate. This indicates that new foam is more active electrostatically than aged, fuel-swollen foam. This could be due to bleeding of a prostatic agent from the foam during swelling, although this is purely speculative.

(3) Spark Discharge Incendiveness

The magnitude of foam-to-nozzle charge transfers (Table 7) indicates that these discharges might be incendive. However, the type of discharge nozzle size and foam void/nozzle geometry possibly have greater influence on a spark's incendiveness than purely the amount of charge transferred during the discharge; i.e., factors which affect the power characteristics and quench of the discharge. The possibility of potentially incendive discharges with new foam (first fuel fill) even at low fueling rates and velocities cannot be ruled out.

The large discharges (Runs 5 and 6 of Table 7) which occurred when fuel was above the nozzle level were not visible even through the image intensifier. The location of these particular discharges remains unknown.

(4) Spark Discharges at Critical Fuel Level

Large spark discharges were produced between the nozzle and the Type IV blue foam when the fuel level was carefully adjusted such that the nozzle was partially or barely covered with fuel. Figure 8 shows the fuel nozzle discharging into the empty fuel cavity; no spark discharges are apparent. Figure 9 illustrates the critical level for which large discharges occur. Large discharges were produced with the nozzle partially covered by fuel but were not directly observable due to the generation of fuel froth in the foam cavity.

With the nozzle-fuel level configuration shown in Figures 9 and 10, air (nitrogen for these tests) was drawn from the fuel surface and entrained in the fuel jet. This considerably enhanced the tribo charging of the foam. Spark discharges of

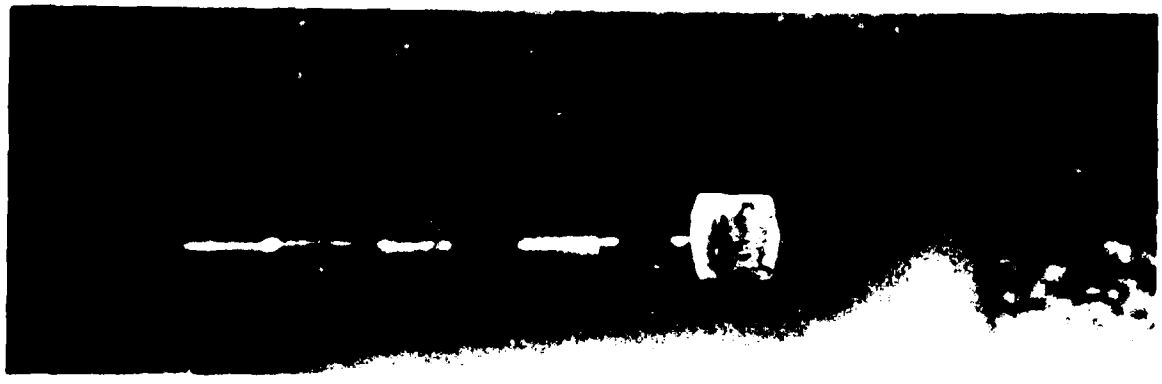

FIGURE 8 FUEL DISCHARGE INTO FOAM CAVITY

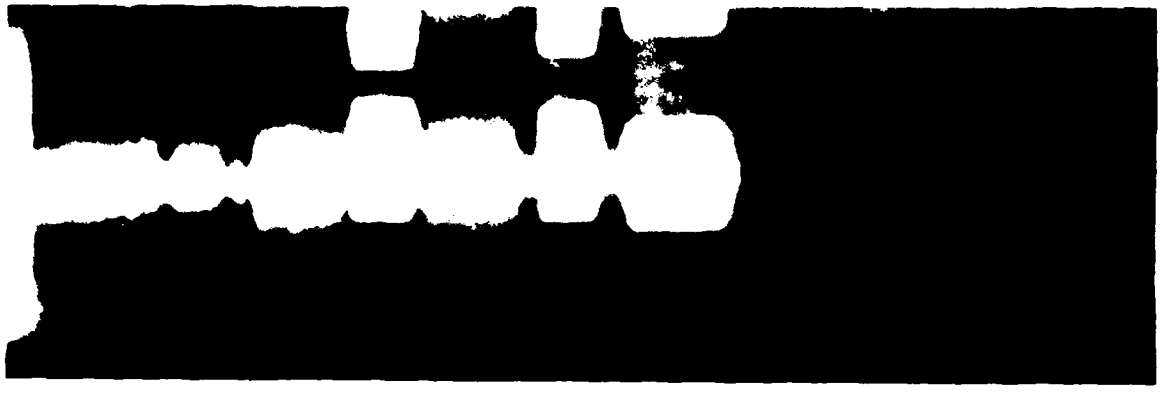

FIGURE 9 CRITICAL FUEL LEVEL AT WHICH LARGE DISCHARGES OCCUR

FIGURE 10 TYPICAL SPARK DISCHARGE BELOW FUEL SURFACE

approximately 1/2 - 1 cm in length were produced and observed to pass from the foam surface to nozzle. Discharge paths appeared to follow well defined bubble filled regions in the turbulent zone in front of the nozzle and pass to the foam cavity roof which was in close proximity to the nozzle.

During these observations, the fuel conductivity was approximately 35 c.u. at 18°C. However, the occurrence of sparking appeared to be relatively unaffected by change in temperature over the range -15°C to +20°C. The discharges were sufficiently brilliant to be observable several feet back from the fuel tank view-port and were filmed with a motion camera under floodlit conditions.

Discharges of this nature were only seen when pumping at maximum flow rate (19.2 gallons/min at 21 ms^{-1} fuel velocity). Any significant reduction in pumping rate eliminated the discharges. However, the discharges persisted as long as pumping was maintained at the maximum rate.

It was subsequently discovered that quite enormous spark discharges occurred shortly after the initiation of pumping within the first 2-3 seconds. Multiple discharges would occur within this time period but the frequency rapidly diminished as pumping continued and only occasional discharges could be observed or sometimes none at all after the short initial period of electrical activity.

These types of discharge passed through bubble-laden fuel jet zone and occasionally through bubble-free fuel regions as illustrated in Figure 10. Figure 10 is scale size and the length of the discharge is approximately 3 cm. The bright zone in this figure is due to overexposure of the film caused by multiple discharges prior to "capture" of the single spark traversing the bubble-free region. These discharges were audible above the background noise of the pump and fuel jet and were extremely bright. The energy of such discharges could be approaching the order of 100 mJ.

(5) Conductive-Coated Foam

Preliminary fueling tests demonstrated that the conductive-coated, Type IV, blue foam is an effective antistatic technique. No discharges were detected with this material using the same configuration as in previous tests on the uncoated, Type IV, blue foam.

3. ELECTROSTATIC CHARGE NEUTRALIZER

As part of the grant with Southampton University, a prototype Electrostatic Decharger (i.e., a charge neutralizer) was developed by Bestobell Mobrey Limited, Slough, U. K., and delivered to the

Aero Propulsion Laboratory. This device was based on [illegible] inventions of Professor A. W. Bright and was licensed under the National Research Development Corporation (Reference [illegible]).

The electrostatic charge neutralizer device consists of the ADS-1 active discharge system, the ICG-2 prototype charge injector, and the ICM-1 prototype charge density monitor. Electrostatically charged fuel flowing through a pipeline is automatically neutralized by this feedback system so that the fuel emerging downstream has zero net residual charge. As seen in the schematic of the electrostatic charge neutralizer in Figure 11, positive or negative charges are injected into the flowing stream so that the charge density monitor, immediately downstream of the charge injectors, sees a neutrally charged fuel.

Early development models of the charge density [illegible] and the active charge injector system were incorporated into the Experimental Refueling System described in Section [illegible] of this report and were successfully used. The [illegible] charge neutralizer system differs from these early devices by [illegible] the charge density monitor and the active charge [illegible] a single, integrated instrument with [illegible].

[illegible] prototype electrostatic charge neutralizer [illegible] scheduled to be delivered to Southampton [illegible] during the course of the [illegible] program. [illegible] prevented the [illegible] to [illegible].

IN-LINE ELECTROSTATIC DECHARGER

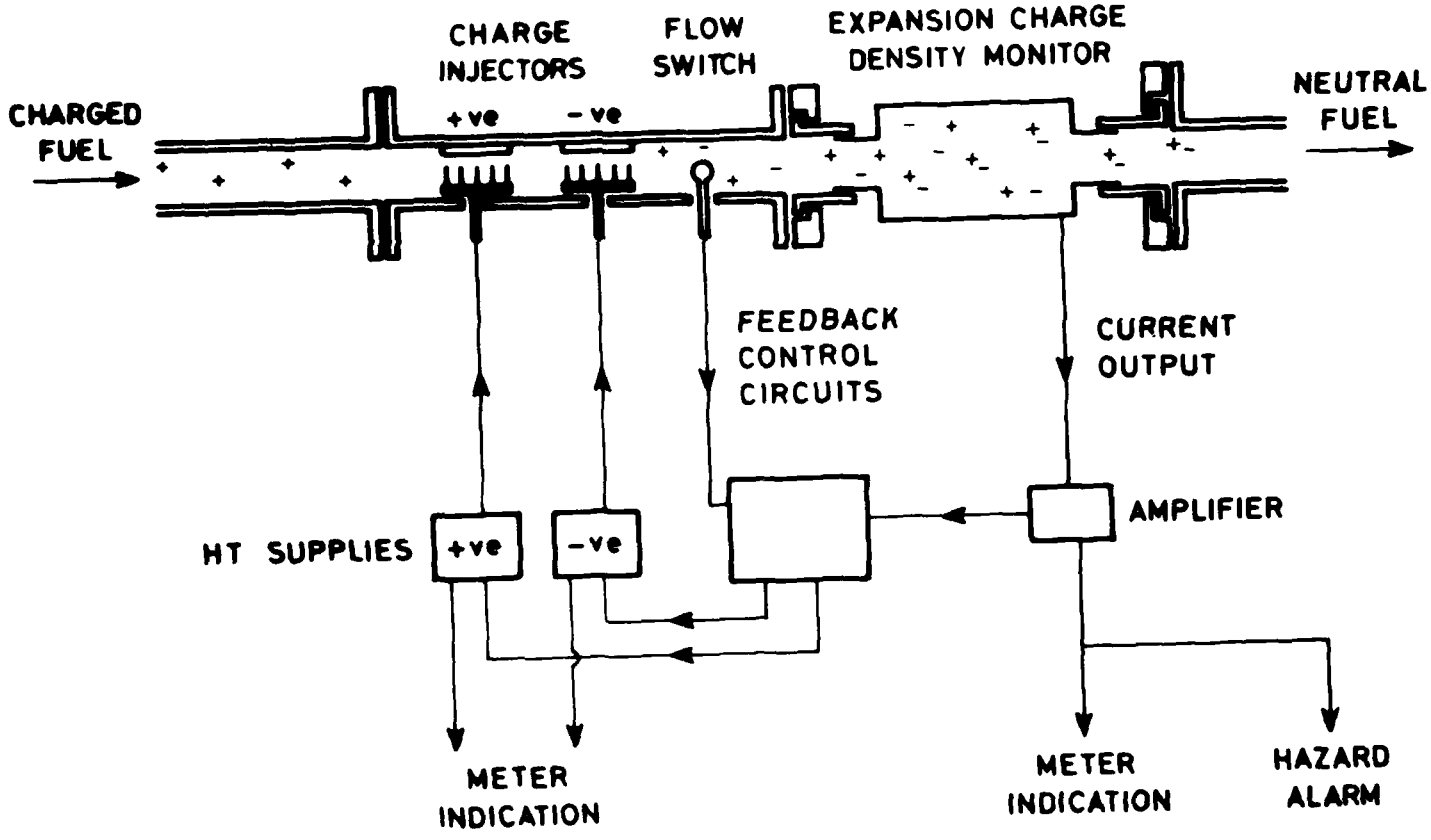

FIGURE 11 IN-LINE ELECTROSTATIC DECHARGER

SECTION IV

CONCLUSIONS

It appears that the critical time for the production of incendive spark discharges is when the foam cavity is flooded and the fuel nozzle is in the process of being covered with fuel. At this time there appears to be a considerable enhancement in tribo charging between foam and fuel due to air entrainment in the fuel jet, and violent discharges can occur. Depending on the nozzle design and cavity geometry, such discharges could pass through unflooded regions of the foam cavity resulting in an ignition in the foam cavity. However, such discharges could not be produced below the maximum pumping rate of the experimental system; i.e., 19.2 UK gallons per minute at a fuel velocity of 21 ms^{-1}. Sparking was completely eliminated by fitting the tank with conductive coated foam, although the serviceability of coated foam is suspect due to local coating erosion produced by the fuel jet.

In addition to the possible enhanced tribo charging due to gas entrainment in the high velocity fuel jet, it is likely that there occurs a rapid rise in foam surface potential as the fuel impact area of the foam becomes flooded with fuel due to inhibition of corona discharge, which occurs in the unflooded cavity at high fueling rates and which would otherwise tend to neutralize or reduce foam surface charge.

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