1.0

4.5
5.0
5.6

2.8

2.5

3.2

2.2

3.6

4.0

2.0

1.1

1.8

1.25

1.4

1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFWAL-TR-83-2015

ELECTROSTATIC SAFETY WITH EXPLOSION SUPPRESSANT FOAMS

AD A137503

A. F. Grenich
F. F. Tolle

Boeing Military Airplane Company
Seattle, Washington 98124

March 1983

Final Report for Period March 1980 - September 1982

Approved for Public Release; Distribution Unlimited

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE, OHIO 45433

DTIC
ELECTE
FEB6 1984

D

D

T. A. HOGAN
Project Engineer/Scientist
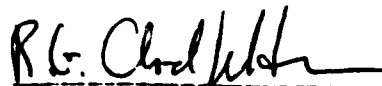Fire Protection Branch
Fuels and Lubrication Division

R. G. CLODFELTER, Chief
Fire Protection Branch
Fuels and Lubrication Division

FOR THE COMMANDER

R. D. SHERRILL, Chief
Fuels and Lubrication Division
Aero Propulsion Laboratory

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-83-2015	**2. GOVT ACCESSION NO.** A-A	**3. RECIPIENT'S CATALOG NUMBER**

4. TITLE (and Subtitle)

ELECTROSTATIC SAFETY WITH EXPLOSION SUPPRESSANT FOAM

5. TYPE OF REPORT & PERIOD COVERED
Final Report for Period
March 1980 - September 1982

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
A. F. Grenich and F. F. Tolle

8. CONTRACT OR GRANT NUMBER(s)
F33615-79-C-2093

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Boeing Military Airplane Company
P.O. Box 3707
Seattle, Washington 98124

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Program Element 62203F
Project 3048 Task 304807
Work Unit 30480738

11. CONTROLLING OFFICE NAME AND ADDRESS
Aero Propulsion Laboratory (AFWAL/POSH)
Air Force Wright Aeronautical Laboratories (AFSC)
Wright-Patterson Air Force Base, Ohio 45433

12. REPORT DATE
March 1983

13. NUMBER OF PAGES
161

14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electrostatic Hazards
Electrostatic Charging and Discharging
Explosion Suppressant Foam
Foam Filled Fuel Tanks
Fuel Fire Safety

Aircraft Fuel Systems
Composite Fuel Systems

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

Studies were made of the accumulation of electrostatic charges and subsequent discharges in aircraft fuel systems using explosion suppressant foams. The studies included a fuel system survey, small scale experiments, and fuel inlet nozzle designs. The results were used to develop guidelines for minimizing electrostatic hazards in aircraft fuel systems.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

PREFACE

Accession For		
NTIS GRA&I	☒	
DTIC TAB	☐	
Unannounced	☐	
Justification		
By		
Distribution/		
Availability Codes		
Dist	Avail and/or Special	
A/1		

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

TABLE OF CONTENTS (cont.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont.)

LIST OF TABLES

1.0 INTRODUCTION

Fires and explosions resulting from electrostatic discharges in aircraft fuel systems have long been and continue to be an important concern for both aircraft designers and operators. As discussed by Leonard in Ref. 1, electrostatic charges accumulate during fueling because of separation of ionic impurities which are present in very small quantities in the fuel. Charges of one polarity become swept along with the fuel while those of the opposite polarity leak to ground. If sufficient charge separation occurs, subsequent discharges may be incendive. The obscure nature of electrostatic phenomena in fuel systems has caused the development of design and operating guidelines for electrostatic safety to be an evolutionary process, often as the result of the investigation of accidents and incidents. According to Bachman, Dukek and Popkin (Ref. 2), 33 aircraft incidents attributed to electrostatic discharges were reported during the 1959 - 1969 time period. Of the 28 where the fuel type was reported, 12 involved aviation gasoline, 15 involved JP-4 and one involved kerosene. These accidents prompted an extensive review of airplane fuel system designs and operating procedures. The resulting changes significantly improved electrostatic safety.

The electrostatic problem reappeared in 1970 when two accidents occurred in the U.S. while fueling commercial airplanes with kerosene type fuel. A fuel filter was thought to have caused these accidents and banning the use of that type of filter seemed to solve the problem. Electrostatic problems all but vanished until the mid 1970's when the Air Force began encountering fires in aircraft which used explosion suppressant foam. This led to a number of studies which proved that the foam is a charge generation/accumulation medium when fuel flows through it, and that the refinery run fuel conductivity would have to be increased by about two orders of magnitude to prevent incendive electrostatic discharges. In 1977 the Air Force specified fuel conductivity improving additive for JP-4 and JP-8 operational fuels, which in conjunction with modified foam installation and fuel system design criteria, was expected to minimize the likelihood of any further electrostatic incidents during aircraft refueling.

However, fire caused by electrostatic discharges in aircraft fuel systems containing explosion suppressant blue foam continues to be a problem. As recently as March 1983, fires occurred in foam filled fuel tanks of C-130 airplanes during refueling with purging fluid or JP-5 fuels which did not contain fuel conductivity additive. In addition, several incidents have occurred on C-130 airplanes during over the wing refueling with JP-4 fuel which contained fuel conductivity improver additive. Further, several foam containing A-10 airplanes have experienced fires thought to be caused by electrostatic discharges. Although the foam in each case effectively prevented fuel tank explosions, it is expensive and time consuming to remove and replace the charred material.

This study was undertaken to help develop a basis for revising or originating design standards to further minimize or eliminate electrostatic hazards in aircraft fuel systems. The method was by a combination of a literature review, a review of existing airplane fuel system designs, small scale tests on charging and discharging across foam and other dielectric samples, and development of new aircraft tank refueling inlet nozzle designs.

The explosion suppression foam referred to above and subsequently in the report is a sponge-like material composed of a skeletal network of tiny lightweight interconnecting strands which act as a three-dimensional fire screen. The foam is combustible but when properly installed in a fuel tank, any fires which develop will be localized and not produce explosive overpressures in the tank. Explosion suppressant foams are commonly referred to by color. Orange foam, which is a coarse pore polyester polyurethane material, was the first type used in aircraft. It was usually installed so that the foam was compressed slightly to ensure that the tanks were fully packed. Subsequently, lower density yellow and red polyester polyurethane foams were developed to reduce fuel displacement and fuel retention. Yellow foam is a coarse pore type designed to fill the fuel tanks except for clearance cutouts for fuel tank components. Each piece is designed to fit a specific area of the tank analogous to a jigsaw puzzle. Red foam is fine pore foam which is designed to allow foam to be omitted (gross-voided) from certain portions of the tank

while still providing explosion protection. The gross-voiding concept results in lower weight and fuel retention penalties. Subsequently, light (applicable to gross voiding) and dark blue foams (for foam filled tanks) made of a polyether polyurethane material were developed to obtain longer service life because in some cases the polyester foams decomposed markedly in only a few years. The blue foams apparently solved the wear problem, but unfortunately exacerbated the electrostatics problem.

2.0 DISCUSSION OF ELECTROSTATIC INVESTIGATIONS
RELATED TO AIRPLANE FUEL SYSTEMS

The literature on electrostatic hazards is particularly valuable because it provides increased understanding of charging and discharging mechanisms and at least inferentially, various safety improvements. It also discloses lines of investigation which should be pursued. The literature was reviewed not only to compile a list of relevant reports, but also to point out and discuss conflicting or questionable results, many of which can be attributed to different test fuels.

2.1 LITERATURE SURVEY

The literature survey results have been divided into sections covering
  o An overview of electrostatic issues
  o Charge generation and discharging in fuel systems employing explosion suppression foam including the effects of fuel additives
  o Charge generation and discharging in fuel systems without explosion suppression foam
  o Spark characterization and ignition energy of fuel air mixture

A brief review of the literature for each of these sections follows. Summaries, conclusions and recommendations of individual reports are presented in the annotated bibliography in Appendix B.

2.1.1 Electrostatics Overview
Leonard (Ref. 1) presents an excellent overview of electrostatic issues in fuel handling systems. He not only cites 99 references in an annotated bibliography, but also provides useful tutorial discussions for reference or review. His survey, which concentrated on the period between 1973 and 1980, discusses the mechanism of charge generation when fuel flows through a pipe, pump, filter/separator and finally into a receiver such as an airplane fuel tank. He also discusses static charge generation and dissipation processes.

4

Although the charging mechanism is not completely understood, ionic impurities in very small quantities in the fuel are believed to create the electrostatic charge. When the fuel is at rest, impurities are adsorbed at the interface between the fuel and the walls of the container. However, when the fuel is in motion, the charges separate and charges of one polarity are swept along with the flow while those of opposite polarity leak to ground. When a filter/separator is compared to simple pipe flow, the level of charging may be greatly increased. Since charge separation is a surface effect, the very large increase in surface area may cause the charge to be 100 or more times that created by flow in a supply line.

When charged fuel enters the receiving tank, the charge may relax harmlessly to the walls or the charge may accumulate producing high surface potential. If the local potential exceeds the breakdown voltage for the vapor space, a discharge will occur. Whether the discharge will cause ignition depends on the composition of the vapor and the nature of the discharge.

Leonard states that the minimum energy required for a spark discharge between metal electrodes to ignite an optimum combustible mixture under ideal conditions is 0.26 millijoules. Substitution of a high resistivity material, such as a hydrocarbon fuel surface, for one of the electrodes increases the energy requirements for ignition. The minimum ignition energy for a discharge from a fuel surface is in the range of 0.26 to 4.7 millijoules. Defining the minimum ignition energy is a difficult task and some contend that ignition can be produced with spark discharge energies lower than 0.26 millijoules. Furthermore, using the energy stored in a charged capacitor to infer the spark discharge energy across a set of electrodes may significantly overpredict the spark discharge energy. A technique which offers the possibility of measuring the discharge energy much more accurately is presented in Section 4.4.

If a pipe is made from a nonconductor such as Teflon, polyethylene or glass, the charge residual on the pipe surface cannot flow readily to ground. If the resistivity of the pipe is greater than 10^{14} ohm-centimeters, voltage can build on the inside of the pipe to the point that puncture type breakdown can

occur to metal objects outside the pipe. Pinhole failures in Teflon tubing have been attributed to electrostatic charging of JP-4 flowing through the tubing.

Leonard offered solutions for reducing or eliminating the electrostatic hazard during refueling operations, although none were without negative features. Full time fuel tank inerting would certainly solve the problem but retrofit of the large number of existing airplanes whose fuel tanks now vent to the atmosphere would be very costly. Removal of the final refueling filter/separator is not practical because of the degree of cleanliness required for jet fuels. Reduced fueling rates are not a good solution because rapid fueling is often required in commercial and military operations. The best solution so far is to specify a static dissipator fuel additive. The Air Force has changed the specifications for both JP-4 and JP-8 fuels to require the use of an additive to increase fuel conductivity from 200 to 600 picoSiemens per meter (pS/m) at the point of injection into bulk storage and to a minimum of 100 pS/m at the point the fuel enters the aircraft. Even this procedure is not without problems; for example the specifications for JP-5 Navy fuel do not require a conductivity improver. This may have contributed to recent C-130 incidents which experienced fuel tank fires when switch loading between JP-4 and JP-5 fuels.

2.1.2 Charge Generation and Discharge Characteristics of Explosion Suppressant Foam, Including the Effect of Fuel Additives

This section covers the effect of explosion suppressant foam in aircraft fuel tanks on hazards due to electrostatics. Many of the data sources also present the effect of additives, (especially anti-static additives) on fuel conductivity and charge generation in filter/separators and explosion suppressant foam.

Two major conclusions from the data sources of this section are: that explosion suppressant foam acts as a charge generator and accumulator so that its presence increases electrostatic hazards; and that spark discharging can be eliminated or reduced by the use of fuel conductivity additives. Although

there is some disagreement among data sources on detailed points, all data sources support these conclusions. The balance of this section discusses the other important conclusions and disagreements among sources.

The charging tendency of explosion suppressant foam has been found to be a function of foam type. Small scale charging tests of different foams were conducted by Mills (Ref. 3), Leonard and Affens (Ref. 4), and Dukek, et al (Ref. 5). The latter two investigations used the Mini-Static Tester (MST) which was developed by Exxon. In the MST, fuel contained in a syringe is forced at a constant rate through a sample of foam contained in a filter holder. Mills used a continuous flow rig to flow fuel through a sample of foam contained in a filter holder. The charging tendency of blue polyether polyurethane foam as compared to polyester polyurethane foam was found to be: five times greater by Mills; six times greater by Leonard and Affens; and only slightly greater by Dukek. This inconsistency could be due to the fact that the foam sample used by Dukek was 23 mm in length while those used by Mills and Leonard and Affens were 76 mm and 100 mm, respectively.

In the referenced tests Dukek, and Leonard and Affens determined that foam charging was not a function of the foam porosity, while Mills found that foam charging was inversely related to pore size. The major difference between the MST and the continuous flow rig used by Mills which could account for this discrepancy is the difference in local fuel velocities. The MST uses a fuel velocity of 9.53 cm/sec while the tests by Mills used a fuel velocity of 79.6 cm/sec. It is likely that at the high flow rates experienced in actual aircraft refueling, foam pore size would have an affect on foam charging. Lending weight to this hypothesis is the finding by Leonard and Affens that when the foam samples were compressed in the filter holder (a condition that magnifies the affect of porosity), foam charging was related to foam porosity.

In other porosity tests by Mills under conditions simulating actual refueling, fine pore blue foam formed a concave surface when the fuel stream impinged on it and much of the fuel was deflected back into the void space. Coarse pore foam, on the other hand, allowed all of the fuel to penetrate the foam.

Results of these tests indicated that charging was about equal for fine and coarse pore foam. Mills speculated that while the coarse pore foam had a lower charging tendency, the larger fuel flow actually passing through it resulted in equal generation. Perhaps at lower flow rates, the fine pore foam would not deflect as much fuel and foam porosity affects would be observed.

Another important characteristic of foam is its ability to accumulate an electrostatic charge. The charge accumulation on a foam is directly related to the foam's electrical conductivity. If the foam is of low conductivity the charge will not bleed off easily and charge will accumulate to a greater degree. There are some discrepancies between data sources on the magnitude of the foam conductivities. Both Mills and Hillman, et al (Ref. 6) measured the conductivity of blue foam to be about 0.025 pS/m and red foam to be about an order of magnitude greater (Mills 0.36 pS/m and Hillman 0.25 pS/m). However, Dukek measured the conductivity of coarse blue foam as 2200 pS/m and red foam about four times greater at 8550 pS/m. Using the values of conductivity as measured by Dukek, the relaxation time constant of the blue foam was calculated to be 0.014 sec. while the values as measured by Hillman and Mills yielded a relaxation time constant of 1232 seconds. If the relaxation time constant was 0.014 seconds, there would be virtually no charge accumulation on the foam. Since experimental data indicate that charge accumulation is greater for blue foam than red, foam conductivities as measured by Hillman and Mills are probably more realistic.

The problem of charge generation and accumulation on explosion suppressant foam appears to be aggravated by high fuel velocities and high fuel tank fill rates. Both Mills and Dukek found that in tests simulating fueling of aircraft which use explosion suppressant foam, spark magnitude and frequency increased with increasing fuel velocity and fill rate. Mills concluded that sparking was more sensitive to fill-rate than to fuel velocity.

The type of fuel inlet nozzle used and the foam void configuration associated with it has a pronounced affect on discharging during refueling. Tests by Dukek and Radgowski and Dantunono (Ref. 7) showed this clearly. Single

8

orifice inlet nozzles in which a single stream of high velocity fuel impinged directly onto a small area of a foam surface resulted in the most frequent and highest magnitude discharges. The multiple orifice inlet (piccolo tube) which releases the fuel over a large area, at low velocities, and directly against the tank floor (rather than a foam surface) resulted in the lowest order discharging. Both Mills and Radgowski and Dantunono concluded that the piccolo inlet was the safest of the various types of nozzles tested.

The effect of fuel additives, especially conductivity improvers, was studied extensively. It was found in simulated aircraft fuelings that electrostatic discharging was greatly diminished or eliminated by increasing fuel conductivity. The fuel conductivity level necessary to eliminate sparking was found to be a function of the specific additive used. Different conductivity additives required different levels of fuel conductivity to eliminate sparking under the same conditions. This can be explained by the fact that the presence of the additive can increase the fuels charging tendency as well as its conductivity; relatively higher fuel conductivity levels are then required to overcome the effect of increased charging. This was borne out by tests that indicate that sparking is more frequent at moderate fuel conductivity levels than at either lower or higher levels for some conductivity additives. The effect of fuel conductivity improver also depends on the fuel.

2.1.3 Electrostatic Charging and Discharging in Fuel Systems Not Containing Explosion Suppressant Foam

Literature in which charge accumulation and subsequent discharging occurred in fuel tanks without explosion suppressant foam is discussed in this section.

In refueling aircraft which do not contain fire suppressant foam, electrostatic charge generation is primarily due to filter separators located upstream of the fuel tank inlet. Dukek, Lunt and Young (Ref. 8) conducted field tests of DOD filter separators and found only low levels of charge in JP-4 fuel delivered to aircraft. This was attributed to the relatively high conductivity of the JP-4 caused by the presence of corrosion inhibitor and the relatively long relaxation times provided by downstream volumes associated

with DOD filter separators. This does not mean that there is no cause for concern. JP-4 of low conductivity is occasionally found and the use of static reduction methods such as auxiliary relaxation tanks in the refueling system should be considered.

Both Bruinzeel (Ref. 9) and Backman and Dukek (Ref. 10) conducted tests which simulated fueling of aircraft which did not contain explosion suppressant foam in the fuel tanks. Bruinzeel observed sparks with energies ranging from less than 0.2 mJ to several tens of millijoules while under similar conditions Beckman and Dukek measured spark energies of less than 0.06 mJ. In fact, the largest spark Bachman and Dukek could produce (0.8 mJ) could be produced only by the presence of an unbonded charge collector in the tank. Part of the reason for the high energies measured by Bruinzeel is that Bruinzeel assumed that the energy of the spark was equal to the product of total charge transfer and fuel surface potential; since voltage is not constant, a better estimate would be the time integral of current and voltage. Total charge transfers up to 4.5 µC were observed which is about 32 times greater than the 140 nC which Johnson (Ref. 11) concluded was the incendiary level. This indicates that even though Bruinzeel's spark energy computation may be suspect, he was in fact producing very energetic sparks. The difference between the sparks produced in Bruinzeel's test rig compared to Bachman and Dukek's rig cannot be determined from the available information on the test rigs or test procedures.

Bruinzeel also concluded that fuel inlets which split the fuel flow between several compartments produce only minor improvement, and that the best solution was to increase fuel conductivity. He then conducted tests which showed that sparking could be eliminated with fuel conductivities of 50 pS/m. Bachman and Dukek, on the other hand, conducted tests which simulated multiple refueling inlets by reducing the flow rate to their single inlet. They found that sparking was eliminated under normal conditions and reduced below an incendiary level even when an ungrounded charge collector was present.

A general assumption had been that sharp points in a system could be used to dissipate charge accumulations through corona type discharges in which energy

levels are below those necessary for ignition. However, work by Leonard (Ref. 12) indicates that true sparks can be drawn from a charged fuel surface to a 60^0 included angle point electrode with small gap distances while no energy measurements were made, the sparks were produced from fuel with relatively modest surface voltage. Anytime a true spark can be produced there is danger of reaching incendiary energy levels. Thus, the sharp points would have to be needle-like to be effective, and the possibility of damages during operation suggests that this should not be primary method of protection.

In summary, it appears that
   o   refueling safety for aircraft which do not contain explosion suppressant foam can be improved if the flow of fuel is split between several aircraft compartments
   o   additional safety is afforded by the use of fuel conductivity additives
   o   care should be taken to assure that no unbonded charge collectors are present in the fuel tank
   o   the use of sharp points to induce corona discharges should not be a primary means of protection against hazardous discharges

2.1.4 Spark Characteristics and Ignition Energy of Fuel/Air Mixtures

This section reviews reports of the characteristics of different types of sparks and studies of the spark energies necessary for the ignition of fuel/air mixtures.

Throughout the many data sources, the minimum ignition energy of various hydrocarbons ranges from 0.26 mJ to 2 mJ. Work done by IIT Research Institute (Ref. 13) indicates that certain of these measurements may be as much as an order of magnitude too high.

Johnson (Ref. 14) measured ignition energies and charge transfers of fuels at three vapor to droplet ratios. The approximate threshold charge transfers for ignition were 0.1 µC for 100% vapor, 1 µC with 65% of the fuel as droplets and 2 µC with 95% of the fuel as droplets. The increase in threshold charge transfer required for ignition with an increase in percentage of droplets

apparently was due to the interaction of the droplets with the discharge mechanism. The data revealed that the duration of individual sparks varied and that the form of the sparks could change from a single stem with branches to a cluster of stems, each with a separate root.

2.2 ACCIDENTS/INCIDENTS DUE TO ELECTROSTATIC DISCHARGES

A complete discussion of documented accidents or incidents involving electrostatic discharges has been given by Hillman, Manheim and Spencer (Ref. 6). Certain similarities among the accidents or incidents are:

o Where the tank material data was recorded, it was most often a fuselage bladder tank.

o Initial fueling of new or refurbished (dry) foam filled tanks was much more hazardous than subsequent refueling operations when the foam was fuel wetted.

o The accidents or incidents occurred mainly on comparatively dry days when the temperatures were cooler than normal, corresponding to the high flammability region for JP-4 fuel. The relative humidity ranged from 24% to 77% but when reduced to absolute humidities, the corresponding range was only 8 to 24 grains of water per pound of dry air which implies that hazardous electrostatic discharges are much more likely when the moisture content of the air is low.

o JP-4 fuel was involved in most cases, but JP-5 fuel and purging fluid, both without conductivity additive, were involved in certain C-130 incidents.

2.3 STATUS OF ELECTROSTATIC HAZARDS RESEARCH ON EXPLOSION SUPPRESSANT FOAM

In the experimental investigation of electrostatic hazards associated with refueling of aircraft fuel tanks containing explosion suppressant foam, the variables of note included upstream charge induction, conductivity additives,

12

fuel velocity, fuel distribution systems, fuel-foam impingement factors, and temperature of the fuel. Questions remain as to the relationships among these variables to the electrostatic charging and discharging which occurs during refueling, especially since few of the tests were done in full scale test facilities. For example, full scale tests should be run in foam filled tanks in which the fuel velocity is varied while all other conditions remain constant. These results would indicate whether electrostatic discharging frequency and intensity increases with fuel velocity in a linear or non-linear fashion. Similar tests might be conducted in which the inlet orifice size is changed in such a manner that the fuel-foam impingement velocity remains constant as fill rate increases. In this way it may be possible to develop fuel system design criteria which specify maximum fuel velocities which could be used with a given fill-rate per unit area of foam involved.

In such a test series, it would be important to use a constant fuel quality since it has been shown that the charging tendency of different fuels on foam cannot be predicted from the fuels conductivity or charging tendency with respect to filter media. Temperature control will also be important. It has been shown that the field strengths produced in filling a tank which contains explosion suppression foam vary greatly with temperature.

Standardizing results between laboratories may require development of a reference fuel for electrostatic testing. Leonard and Affens (Ref. 4) used a Silica Gel Treatment (SGT) which removed all the ionic species from n-heptane and caused the n-heptane to have a negligible charging tendency. If it could be shown the SGT of JP-4 also resulted in a negligible charging tendency, this process could be used to produce a reference fuel. After SGT of the JP-4, known additives could be used to produce a fuel with a consistent charging tendency. A formula might be developed for producing a worst case fuel and a fuel with an average charging tendency. This would provide an opportunity to achieve consistent results between laboratories and to arrive at design standards. For instance, the worst case fuel could be used to determine

design limits on fuel velocity, fill rate, inlet nozzle dispersion characteristics and other fuel system design quantities.

Spark characterization and the minimum-ignition energy of hydrocarbon vapor and air mixtures are other areas in which there has been extensive study but where the results are controversial. The reported minimum ignition energy of most hydrocarbon vapors is in the vicinity of 0.25 mJ. Recent work has cast serious doubt on this data. It appears that the actual ignition energy may be much lower than this under idealized conditions or because of procedural error. Tests should be run in which current and voltage across the discharge gap are measured simultaneously to ascertain accurate ignition energy values.

In actual operations or tests which simulate fueling, the spark discharges which occur are usually from a fuel or foam surface which is relatively non-conductive. In these cases it is not possible to measure the time varying voltage across the discharge gap, so that only the total charge transferred can be calculated. Although some data has been developed on the total charge transfer criterion for ignition, more extensive testing is needed. It is desirable that these values be developed with confidence limits. In the determination of these values the effect of the current waveform, gap, width, electrode material, and electrode shape on the total charge transfer required for ignition should be determined. Alternatively, it may be possible to develop optical techniques to infer discharge energy.

It has been proposed by some that the presence of sharp points in fuel tanks would result in the charge on the fuel or foam surface being bled-off in a corona type discharge which is nonincendiary. There is now evidence that the included angles of the point has an effect on whether a corona or a spark discharge occurs. Research should be conducted to resolve these questions.

Fuel additives, especially anti-static additives, have been developed to alleviate explosion suppressant foam electrostatic problems. It has been shown that a fuel conductivity of 200 pS/m provides safety in virtually all refueling situations and that 100 pS/m is probably safe in most cases if the

14

fuel does not directly impinge at a high velocity on explosion suppressant foam. Tests have been conducted to determine the compatibility of the anti-static additives with other fuel additives and with fuel handling and storage equipment. There do not appear to be any major problems in the day to day operation of fueling systems which handle fuels with anti-static additives. However, operational requirements may cause the aircraft to be fueled with fuel without additive. If additive fuel is then introduced, with high charging tendency, incendive sparks could result. The hazards involved in switch loading need to be better quantified.

In conclusion, it can be said that there has been much research in the area of electrostatic hazards during aircraft refueling, and much qualitative and some quantitative information has been gained. However, more research should be conducted to gain more insight into the problems and to provide specific fuel system design criteria. In addition, research into the fundamental physics of fuel charging under different boundary conditions should be carried out.

3.0 ELECTROSTATIC SAFETY ASSESSMENT OF CURRENT AIRCRAFT FUEL
AND FUEL SYSTEM DESIGNS

A fuel system survey was performed to help determine why some airplane fuel system configurations have experienced electrostatic discharge problems while others have not. The survey encompassed specific fuel system features of designated airplanes and gathered available information on design philosophy. The survey considered tank filling (fuel flow rates and velocities), foam characteristics (pore size, voiding concept and foam cutouts around inlet nozzles), fuel tank characteristics (tank size, tank wall coatings, tank materials and location of components), unbonded charge collectors and Boeing experience in electrostatics. The survey also included a preliminary evaluation of fuel tanks constructed from advanced composite materials.

Fuel electrostatic properties and means of modifying them were also reviewed.

3.1 BOEING FUEL SYSTEM DESIGN

Since a number of comments in this survey are based on Boeing experience and practice, a discussion of Boeing fuel system designs will be given first. Although Boeing has not designed fuel systems which use explosion suppressant foam, a discussion of Boeing's approach was considered relevant to the present study.

3.1.1 Electrostatics Computer Design Analysis
Whether a fuel tank is acceptable from an electrostatic hazards viewpoint on Boeing airplanes is determined in large part by results from an electrostatics computer program. This program was based on the work of Carruthers and Wigley (Ref. 15), who developed solutions for potential and field patterns inside a rectangular metal tank partially filled with charged fuel. Their solutions are presented in terms of double infinite Fourier series which can be reduced to single term approximations for practical application. They compared their results with experimental data in terms of measured versus calculated electric

field strengths. At the lower fuel levels the analysis yielded field values
which were significantly larger than measured values. However, as the fuel
levels neared the top of the tank, the agreement became quite good. Their
paper provides valuable insight into some of the electrostatics phenomena
involved and techniques for developing the mathematics required to obtain
quantitative results.

The Boeing computer program, unlike the Carruthers and Wigley approach, solves
the double infinite Fourier series instead of using the single term
approximation. It also models the fuel tank interbay-fuel-flow and resultant
electrical charge convected between bays during tank fueling. The analysis
also yields values of the accumulation of charge on the surface of the fuel.
This distinction provides a better model of the physical situation since fuel
charge migrates to the surface due to the potential gradient in the fuel and
cannot bleed off as it can at the walls.

The Boeing electrostatics computer program permits modeling the fuel tanks as
several rectangular bays, an important point because the form of the solution
is quite dependent on tank geometry. Other inputs include the fuel flow rate
into each bay, fuel property data, tank bay dimensions and height
information. The fuel properties required are the charge density of the
incoming fuel and the fuel relaxation time, which is defined as the ratio of
dielectric constant to electrical conductivity. Other inputs include the
heights of the top and bottom of each bay, fuel heights at the start and end
of fueling and the height increments at which bay charge and interbay flow
rates are desired. The height inputs serve to determine the rates at which
each of the bays receive fuel, since the fuel surface is assumed to be at a
uniform level in all bays.

The important outputs are the fuel surface potential, the field strength
(based on the distance between the fuel surface and the top of the tank) in
the ullage and the fuel surface energy density at the center of the bay. In
application, the approach is based on the belief that calculations of absolute
values of electric fields in complex aircraft fuel tanks are not possible, but

17

that comparative calculations between airplanes can be carried out. New designs are thus compared to older designs which have stood the test of time. Boeing has accumulated an electrostatic incident data base for a number of airplanes and a number of fuel tanks. This growing data base together with calculational comparison serves as a basis for accepting or rejecting a proposed fuel system design. In time it is hoped that a computational technique can be developed which will provide absolute values.

Certain general observations can be drawn from the analytical results. The maximum fuel surface potential, field strength and fuel surface energy density occur at the center of the fuel surface, because of the greater distance to the grounded metal walls. Larger tank bays containing fuel at the same bulk charge density as smaller tank bays therefore have higher electrostatic energy density. The principal dependent variable used in evaluating Boeing designs is the maximum fuel surface energy density in the fuel tank.

3.1.2 Inlet Nozzles

Most fuel tanks on Boeing airplanes have more than one bay. If fuel is discharged into only one bay of a multi-bay tank, the calculated surface charge density is usually unacceptably high. The solution is to use "tuned" piccolo tubes to distribute the fuel evenly among various bays. Tuned piccolo tubes also provide velocity diffusion and direct the flow toward a tank wall or bottom. Boeing's analytical procedure does not now distinguish among inlet nozzle locations, e.g., top, middle or bottom of the tank. However, in practice the inlet nozzles are placed as close to the bottom of the tank as practical.

As a matter of interest, fuel inlet nozzle configurations used for the 757 and 767 airplanes are sketched in Figure 3-1. In the 757 where the piccolo tubes could not be located at the tank bottom, a series of vertical tubes were attached to the manifold to direct fuel to the bottom of the tank. The lower ends of the tubes were cut off at a 45° angle and the flow directed parallel to the stringers. In the case of the 767 which has fewer bays, a different
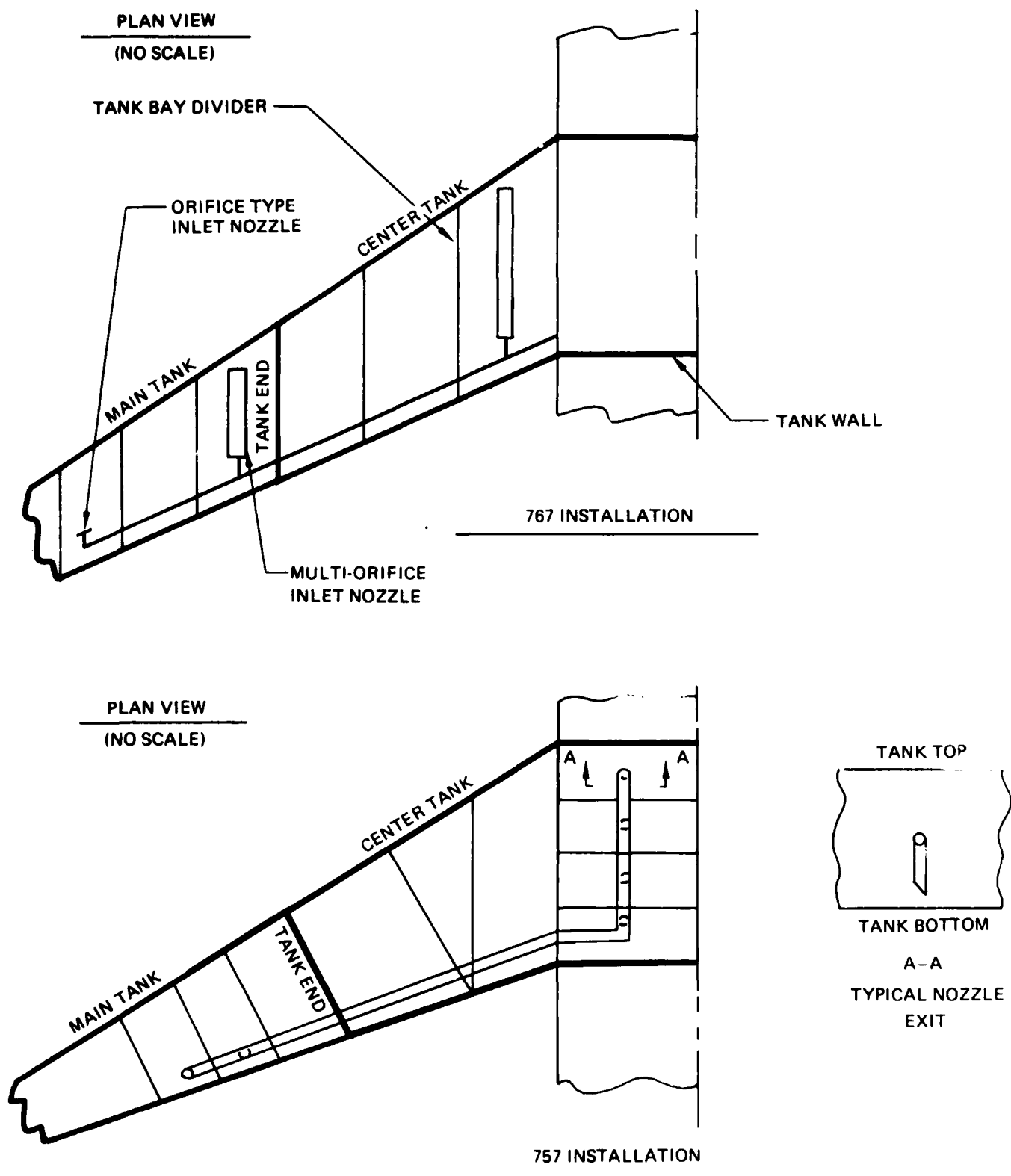
Figure 3-1. Sketches of Fuel Tank Inlet Nozzle Configurations
for 767 and 757 Airplanes

19

procedure was followed. Multi-holed piccolo type diffusers were located at the bottom of the center tank and inboard wing bay, while an orifice type outlet was used in other bays to equalize tank filling.

3.1.3 Tank Wall Resistance

All evidence suggests that conventional aluminum integral fuel walls have negligible electrical resistance. Since bladder cell tanks have a much higher resistivity and have been involved in electrostatic incidents, their resistance and relaxation times were investigated. However, considering that the charging current during refueling is at most a few microamperes, the tank resistance may be quite large and still be insignificant. Typical bladder cell material has a resistivity in the 10^9 ohm-m range (as measured by Goodyear) and a wall thickness of .039 inches. Under these circumstances, a 500 gallon cubical tank could have an interior to exterior resistance on the order of $2x10^6$ ohms. However, for a surface potential of 20 KV volts which is in the range where sparks may be incendive and a charging current of 10 micro-amperes (considered realistic for refueling operations based on Boeing's measurements), the tank resistance could be as high as $2x10^9$ ohms and still prevent further charge accumulation. As can be anticipated from these calculations, tests by Dukek, et al (Ref. 16) revealed that a drum with a bladder liner was essentially the same as a bare metal tank in terms of charge generation or accumulation.

3.1.4 Foam Filled Tanks

Boeing has not designed airplanes with foam filled tanks and has not attempted to analytically model such tanks. Until the electrostatics computer program is modified to include foam, reliance would be placed on empirical data. Assuming that blue foam would be required for longer life, a Boeing tank design would probably feature

o a multiple orifice inlet (piccolo tube) which discharged the fuel directly against the tank floor at low velocity. This puts the charge convected with the tank in close proximity to a conducting surface.

o a requirement for a fuel conductivity improver to increase the conductivity to at least 100 pS/m

o distribution of the fuel among tank bays to allow the fuel level to rise equally in all bays, preventing high electrostatic levels in any one bay.

If foam was not used and the fuel tanks were small, an alternative to a piccolo inlet nozzle might be considered. However, with foam and its demonstrated propensity toward electrostatic problems, the piccolo tube inlet nozzle would probably be specified for any size tank.

3.1.5 Marriage Clamps

Boeing permits isolated conductors such as marriage clamps if the maximum discharge energy is sufficiently low. Each type of isolated conductor is or has been tested in place by measuring its capacitance, C, and breakdown voltage, V, and calculating the energy, $E = 1/2 \ CV^2$, which is the maximum energy which can be stored on the conductor. If the discharge energy is too high, the design is modified. Ground straps as a solution are not common because of their nuisance factor. Not every isolated conductor is tested -- some are passed because of similarity to other configurations which have been successfully tested.

3.1.6 Filling Rates in Tanks Without Foam

Boeing uses filling rates up to 700 gallons per minute (gpm) for the center tank of the AWACS airplane and about 675 gpm for tanks 2 and 3 of the 747 airplane. The newer design 757 and 767 commercial airplanes use much lower rates: the single tank maximum filling rate on the 757 is about 400 gallons per minute on the center wing tank and about 100 gallons per minute for the main tanks; the 767 single tank maximum filling rate for the main tank is about 320 gallons per minute.

3.1.7 Fuel Velocities

The maximum fuel velocity in the flow network and the exit velocity from the inlet nozzle are both important considerations, since charging rate shows some

dependence on velocity, and since charge relaxation time is inverse to velocity. Guidelines of 20 feet per second in the flow network and 10 feet per second at the nozzle have been established as goals, but not strict design criteria. Most Boeing airplanes have velocities which are slightly higher than these guidelines. In addition to the maximum velocity in the flow network, it is important to minimize pipe runs. Charging associated with high velocity through a short section of plumbing would be expected to be lower than that associated with the same velocity flow through a long section.

3.1.8 Summary of Boeing Practice

The attention given to electrostatic charge accumulation in fuel tanks was increased as the result of two electrostatic discharge incidents in 1970. Calculation and design procedures have been developed whose adequacy has since been validated by millions of airplane service hours without an electrostatic incident. Though no Boeing airplane has foam filled tanks, the design procedures are in accord with results from USAF studies with foamed tanks, i.e., it is best to introduce the fuel near the bottom of the tank using a piccolo type diffuser to reduce exit velocities. In addition, Boeing has determined that it is crucial to minimize unequal fuel bay fill rates; in a multi-bay tank this means that the bays should be filled at nearly equal rates.

Particular attention is given to isolated conductors in the tank. Marriage clamps and similar devices are tested in-situ for safety by measuring maximum possible discharge energy. The possiblity of accidentally creating isolated conductors by breaking bonding wires or introducing isolated charge collectors when fuel tanks are opened for maintenance or inspection always exists and receives special attention when developing fuel tank maintenance procedures.

3.2 USAF AIRPLANE FUELS AND FUEL SYSTEMS

Fuel systems of a number of USAF airplanes were surveyed in terms of electrostatic safety and the results are summarized in the matrix shown in Figure 3-2. The matrix presents basic features of the various fuel systems but does not attempt to provide complete details of all the different airplane

AIRPLANE		A-7	A-10 (ORIFICE)	A-10 (PICCOLO)	C-130	F-4	F-5	F-15
TANK CONFIGURATION	BODY	BLADDER	BLADDER	BLADDER	BLADDER AUX. TANK	BLADDER	UNIROYAL BLADDER	BLADDER
	WING	INTEGRAL	INTEGRAL	INTEGRAL	INTEGRAL	INTEGRAL	NONE	INTEGRAL
CELL INNERLINER		REFER TO DISCUSSION IN TEXT						
FOAM MATERIALS	BODY TANKS	NONE → ORANGE → DK.BLUE	RED	RED → LT. BLUE	NONE → ORANGE & YELLOW → DK. BLUE	NONE → ORANGE & YELLOW (1 BLUE PROTOTYPE)	ORANGE & YELLOW	RED → YELLOW
	WING TANKS	NONE → ORANGE → DK. BLUE	RED	RED → LT. BLUE	NONE → ORANGE & YELLOW → DK. BLUE	NO FOAM	—	RED → LT. BLUE
MARRIAGE CLAMPS		REFER TO DISCUSSION IN TEXT						
FUEL INLET NOZZLE TYPE/ LOCATION	BODY TANK	FLAPPER VALVE/ BOTTOM	ORIFICE/ MIDDLE	PICCOLO/ BOTTOM	SHOWER HEAD/TOP	SHOWER-HEAD/TOP	SHOWER-HEAD/TOP	SHOWER-HEAD /BOTTOM(NO. 1) TOP (NO. 2 & NO. 3a)
	WING TANK	FLAPPER VALVE/ MIDDLE	ORIFICE/ BOTTOM	PICCOLO/ BOTTOM	SHOWER-HEAD/TOP	SHOWER-HEAD/BOTTOM	—	SHOWER-HEAD/BOTTOM
FOAM PORE SIZE (PPI)	BODY TANK	7-15 → 8-18	20-30	20-30	8-18	7-15	7-15 → 8-18	20-30 → 8-18
	WING TANK	7-15 → 8-18	20-30	20-30	8-18			20-30

Figure 3-2. Fuel System Summary

		A-7	A-10 (ORIFICE)	A-10 (PICCOLO)	C-130	F-4	F-5	F-15
FUEL FILL RATE (MAX PGM) (RATE PER TANK)	BODY TANKS	110	115	115	189	250	110	220
	WING TANKS	66 [1]	130	130	235	160		193
INLET AREA (IN²)	BODY	2.16	3.14	5.27	1.21	1.73	0.98	3.27
	WING	1.33	6.77	5.96	1.21	1.73	–	3.27
MAXIMUM FUEL TANK VELOCITY (FPS)	BODY	16.4	11.7	7.0	44.7	46.4	32	21.9
	WING	15.9	5.9	7.0	62.2	29.7	–	18.9
FOAM CUTOUT AROUND INLET NOZZLE		SEE FIGURE 3-3	SEE FIGURE 3-4	BOTTOM MOUNTED PICCOLO TUBE/ NO DIRECT FOAM IMPINGEMENT	SEE FIGURE 3-5	SEE FIGURE 3-6	SEE FIGURE 6	SEE FIGURE 7
APPROXIMATE VOID VOLUME (%)	BODY	18	20	20	0 (FILLED)	17	31	SEE TEXT
	WING	24	21	21	11	NO FOAM	–	70% VOID

NOTES : 1. [1] CAN VARY BASED ON NUMBER OF INLET NOZZLES WITHIN TANK SYSTEM

2. INLET NOZZLE AREA IS ESTIMATED

3. FUEL VELOCITY (V) WAS CALCULATED FROM $V = \dfrac{\text{FLOW RATE (GPM)}}{\text{INLET AREA (IN}^2)} \times 0.321$

Figure 3-2. Fuel System Survey Summary (continued)

series involved. Figures 3-3 through 3-8 are sketches of typical foam voiding configurations around the fuel inlets for the aircraft surveyed.

The airplanes in the survey all have integral wing tanks and/or bladder cells in the body tanks. A factor favoring most of the tank configurations was their relatively small size which reduces their tendency toward static charge accumulation. Since the surface of fuel in the center of the tank usually has the highest charge, the smaller the distance from this point to the tank walls, the shorter the relaxation time. The tank fill rate was also examined; other factors being equal, the greater the fill rate the greater the possibility of accumulating charge in the fuel tank. Other components and materials found in fuel cells were also examined.

3.2.1 Fuel Cell Innerliner Materials

Since tank linings, coatings and sealants may significantly increase electrical resistance to bleeding off electrostatic charge, these are all included under the heading of cell innerliners.

3.2.1.1 Integral Tanks

The survey did not reveal any unusual innerliners in integral tanks, although details on coatings, sealants and other materials were not obtained from the various contractors. In general the integral tanks on the USAF airplanes in the survey were conventional built-up aluminum structure with polyurethane coatings and polysulfide sealants according to AFWAL and ASD personnel. Boeing's procedure for internal tank sealing and corrosion protection on commercial airplanes is believed to be similar to that used in airplanes in the survey and is discussed for illustrative purposes.

Prior to assembly, the first step is to anodize bare aluminum parts and alodine aluminum parts with clad coatings; next all parts are primed with Boeing Material Standard (BMS) 10-20 Type II epoxy primer. After assembly the tanks are sealed using BMS 5-95 (polysulfide) sealant on the spar chord to spar web, spar chord to wing skin faying joints, and under the heads of non-aluminum fasteners. The fillets inside the tank are then sealed with BMS

PLAN VIEW

FWD

INBD

INLET NOZZLE

5.0"

6.1"

3.9"

6.1"

FOAM VOID

SIDE VIEW

INLET NOZZLE

2.0"

UP

INBD
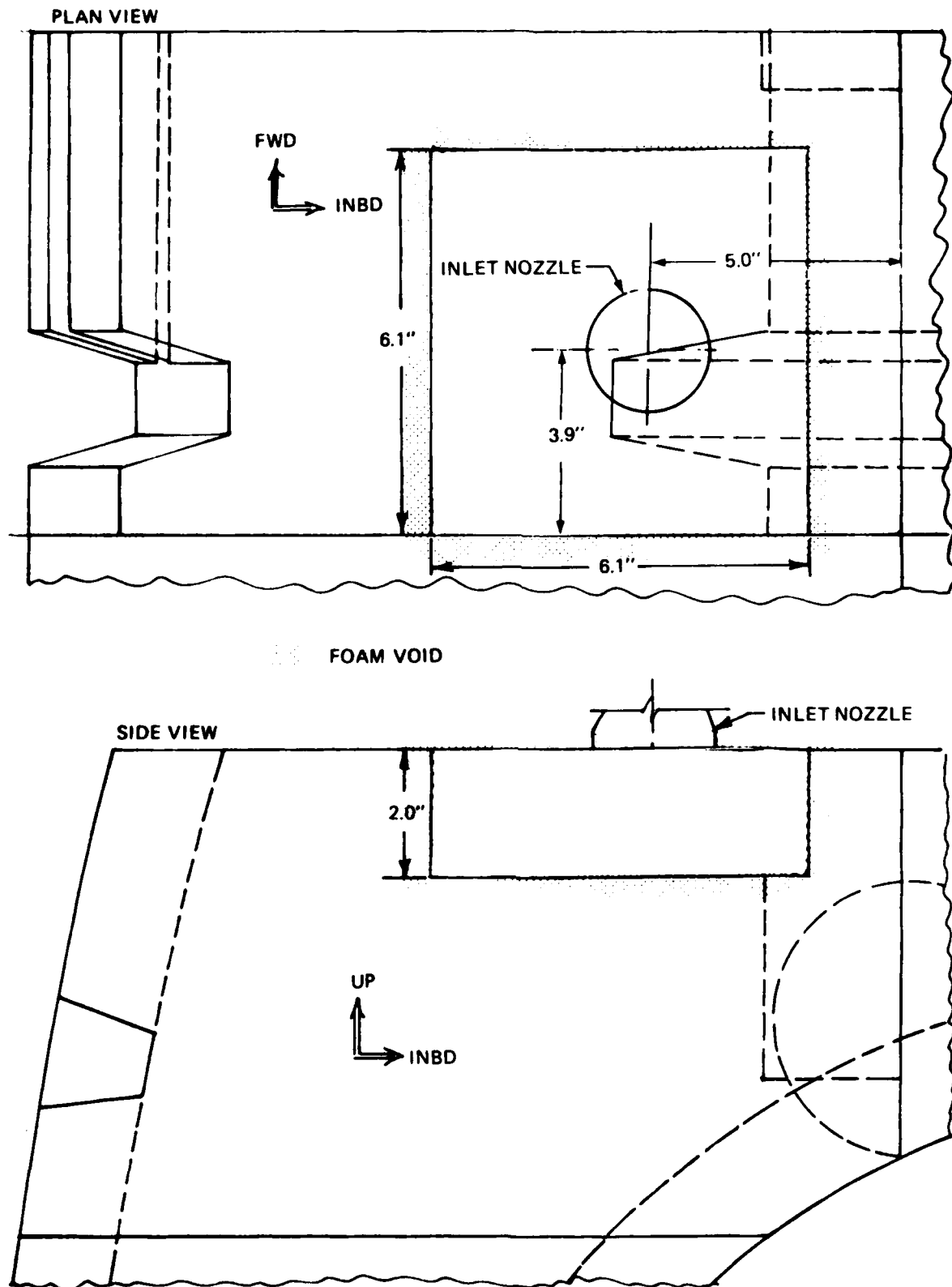
Figure 3-3. Position of A-7 Inlet Nozzle to Foam Void
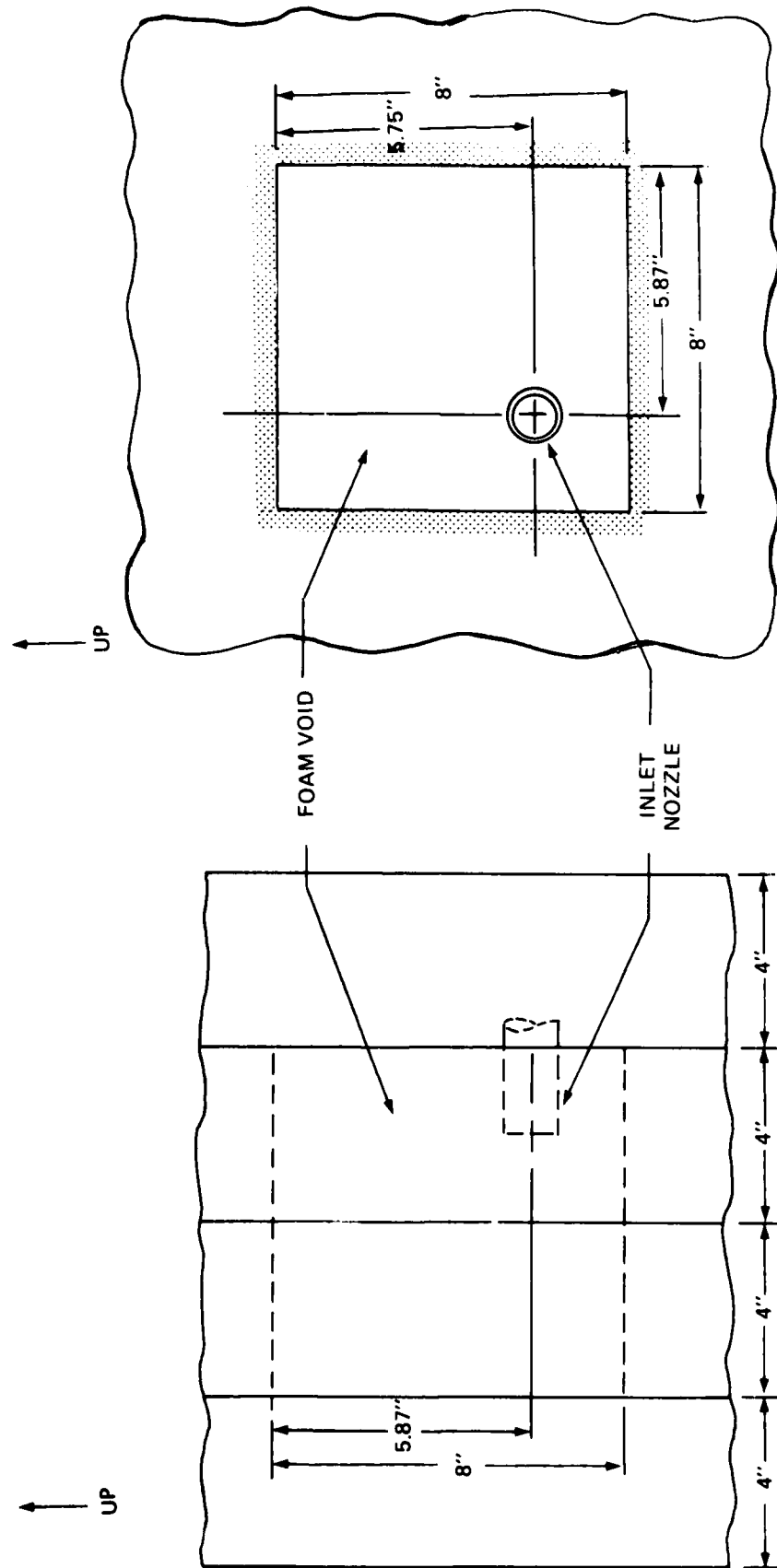
Figure 3-4. Position of the A-10 (Orifice) Inlet Nozzle in Relation to the Foam Void

FOAM

PLAN VIEW

VOID

OTHER
STRUCTURE

FUEL
OUTLET
VALVE

2½
in

FOAM

4-in MINIMUM
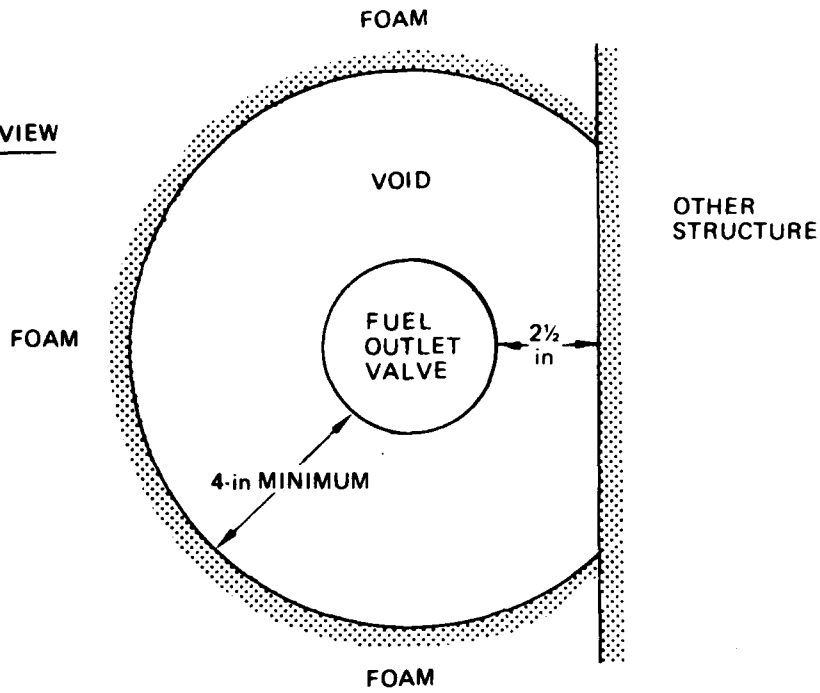
FOAM

NOTE:
CUTOUT IN FOAM HAS BEEN
ENLARGED TO 10 INCHES
SQUARE EXTENDING THE
FULL DEPTH OF THE TANK
ON SOME AIRPLANES

SIDE VIEW

FOAM

FUEL
FLOW

FUEL
FLOW

2½ in
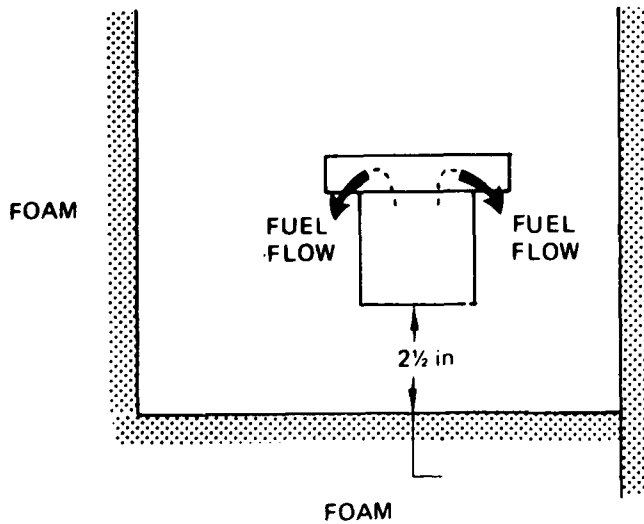
FOAM

Figure 3-5. Typical Foam/Fuel Inlet Nozzle Relationship for C-130 Airplane

PLAN VIEW

UPPER FOAM BLOCK

■ ● INLET NOZZLE
░ FOAM

5.35"

0.80"

3.75"R

2.64"

Ç
TANK

INBD

FWD

4.11"

2.5"

8.80"

6.0"

FUEL
FLOW

SIDE VIEW

2.6"

PLAN VIEW

3.75"R

MIDDLE FOAM BLOCK

2.64"

1.0"R

0.8"

8.50"

UP

4.0"

FWD

SIDE VIEW

LOWER FOAM BLOCK

PLAN VIEW

SIDE VIEW
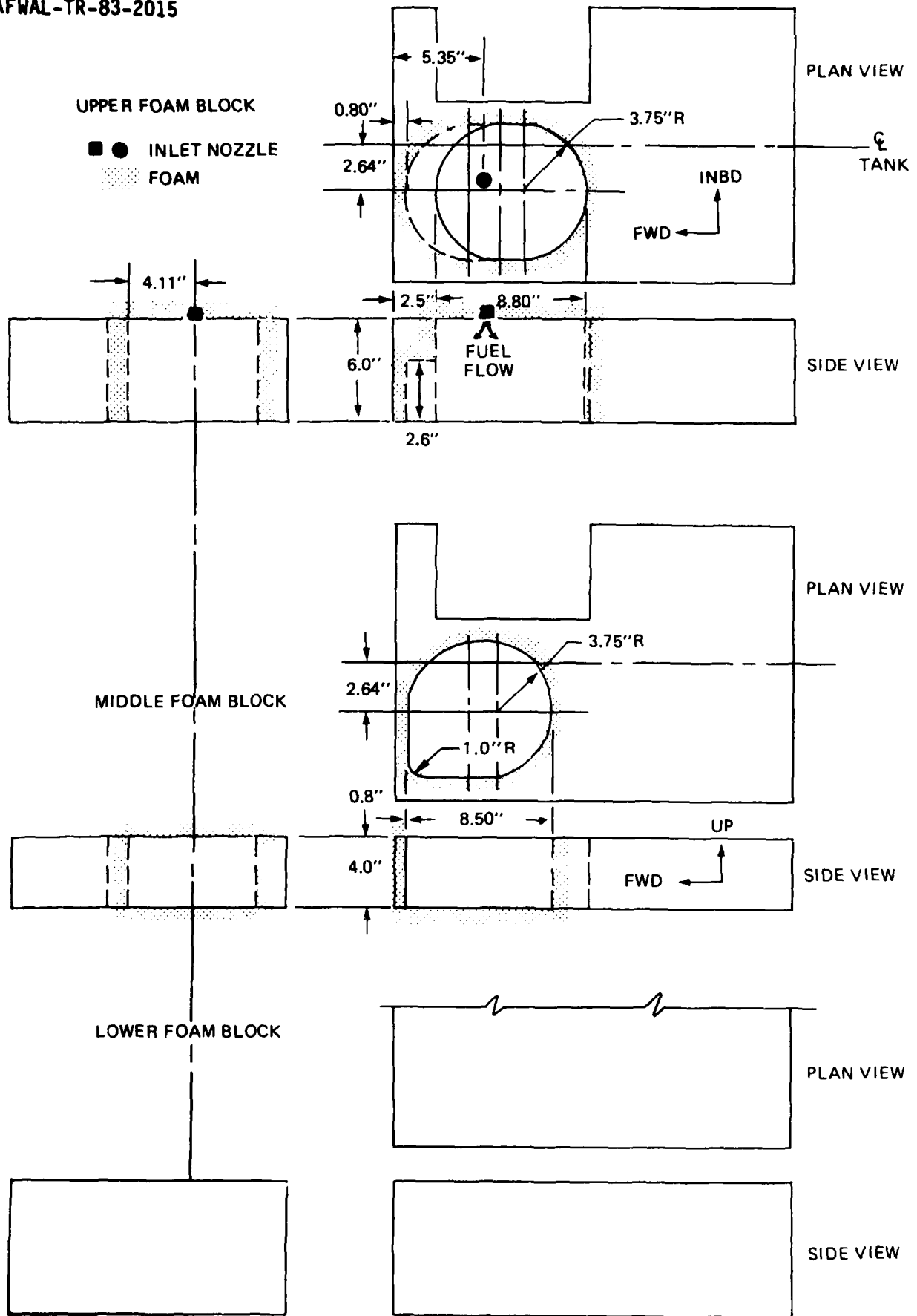
Figure 3-6. Position of F-4 Inlet Nozzle to Foam Void

PLAN VIEW

A-A
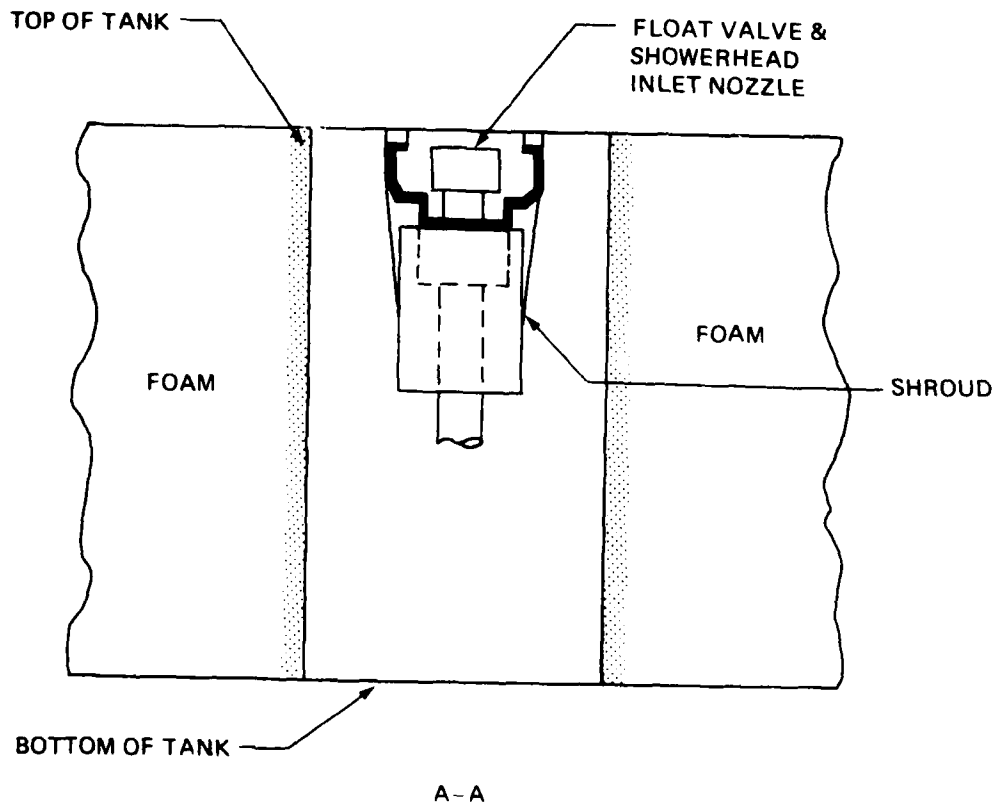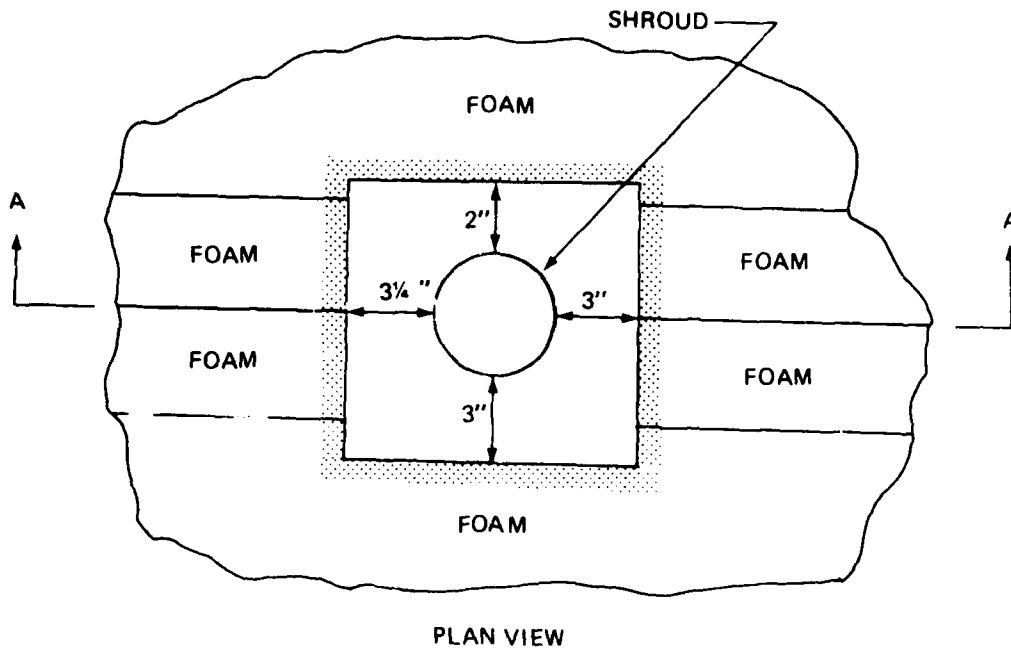
Figure 3-7. Position of F-5E Inlet Nozzle Relative to Foam Void

9.50

0.81

4.00

FOAM BLOCK –13

FOAM BLOCK–16

1.12

7.75

A

A

9.38

PLAN VIEW

INBD

FWD

FUEL FLOW

3.4

2.0

≈ 1 FT FROM TANK BOTTOM

UP

A–A

INBD
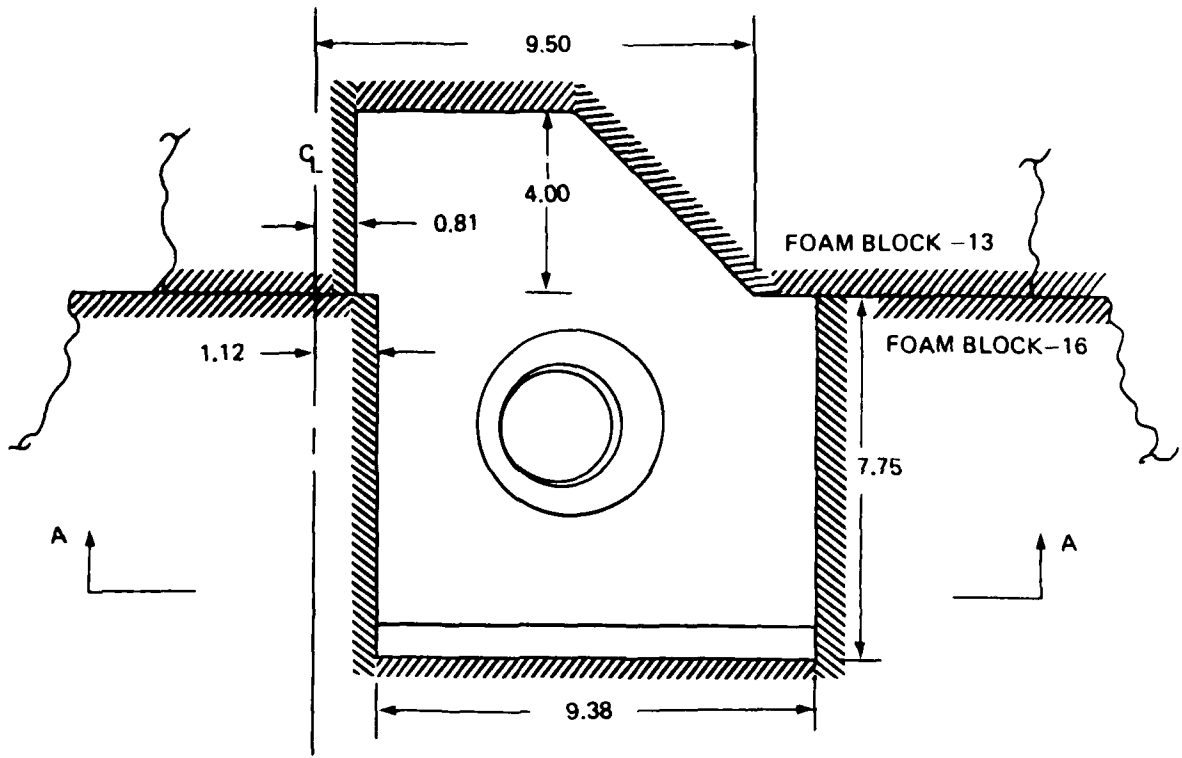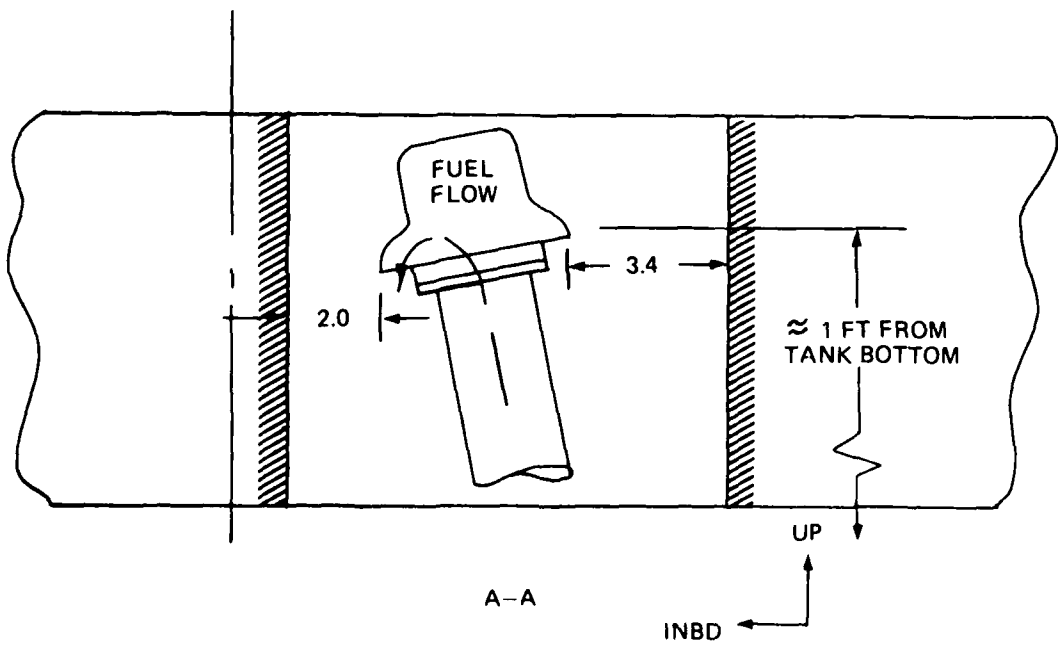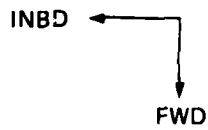
Figure 3-8. Relationship Between Foam and Fuel Inlet Nozzle for F-15 No. 1 Body Tank

31

5-26 (another polysulfide sealant) for fuel leakage control. Finally, an additional coat of epoxy primer is applied to the tank bottom members up to the top of the lower stringers. The electrical resistance of the aluminum structure itself is negligible, and since the integral tank coatings are usually quite thin, their resistances are low relative to the resistance of the fuel.

3.2.1.2 Bladder Cells

Bladder cells for USAF airplanes are supplied by Goodyear, Uniroyal and Firestone. The volume resistivity as measured by Goodyear varied from 3.1×10^{11} to 6.4×10^{12} ohm-cm. The survey did not reveal that any additional surface coatings were applied to the basic cell material, and Goodyear confirmed this for their cells. The particular materials which are used in the cells were not examined in detail because the resistivity of the total cell buildup is the factor of concern in the relaxation rate of the charge on the fuel. As discussed earlier, while the resistivity of current bladder tanks is relatively high, it is nevertheless small compared to fuel, and has been shown to have negligible effect on electrostatic charge buildup.

As a precautionary measure, it is common to use reduced fueling rates following tank maintenance or installation of a new tank for the reason that dry bladder cell tanks may be electrostatically more active.

3.2.2 Explosion Suppressant Foam Types and Installations

Five types of explosion suppressant polyurethane foams (see Figure 3-2) are or have been used in the USAF airplanes in the survey; the foam types include red, yellow and orange polyester material and the newer light blue (fine pore) and dark blue (coarse pore) polyether material. A trend toward increasing use of blue foam is evident; the A-7, A-10, and C-130 now use blue foam in all fuel cells. However the F-15 airplane presently utilizes blue foam only in its wing tanks, and there are no known plans to change to blue foam on the F-4 and F-5 airplanes.

32

The major conclusions with respect to electrostatic problems with foam filled tanks drawn from the literature survey were:

o explosion suppressant foam acts as a charge generator and accumulator

o blue foams are electrostatically more active than the other types

o incendive spark discharges during refueling can be reduced by the use of fuel conductivity additives

o spark discharges during refueling can be reduced by eliminating direct fuel impingement onto the foam

3.2.2.1 Foam Pore Size

Literature from Scott Paper Company quotes the pore size for yellow and dark blue foams as 8 to 18 pores per inch, for orange foam as 7 to 15 pores per inch, and for red and light blue foams as 20 to 30 pores per inch. The red and light blue foams are commonly called fine pore foams whereas the others are called coarse pore foams. Test results on the effect of pore size on foam charging were inconclusive. It is suspected that, other factors being equal, the fine pore foam would experience greater charging. However, unexpected events occur in practice. For instance, as mentioned previously, Mills (Ref. 3) found that fine pore foam developed a concave surface when a fuel stream impinged on the foam and much of the fuel was deflected back into the void space; the result is to produce a flammable ullage at temperatures where the ullage would otherwise be too lean. Conversely, coarse pore foam allowed all of the fuel to penetrate the foam. Test data showed that the charging was about the same for the two types of foam. The coarse pore foam has a lower charging tendency but the higher velocity of fuel flow passing through it results in a comparable charge generation.

Problems in correlating incident records and randomness of the test data makes it difficult to definitively critique the foam installations of the airplanes

in the survey. One might expect that high velocity fuel impinging on fine pore (light blue) foam at the top of the tank would be a worst case situation; happily none of the airplanes in the survey has this set of conditions. The two aircraft which currently use the fine pore light blue foam are the A-10 and F-15. The A-10 has a fully packed configuration with piccolo tubes which introduce fuel at the bottom of its tanks while the F-15 has a grossly voided configuration in the main wing tanks with shower head nozzles near the top of its tanks. Due to the gross voiding technique used in the F-15, the fuel does not impinge on the foam. Only slightly removed from the worst case situation, the C-130 has shower head nozzles near the top of its tanks and has coarse pore dark blue foam (Fig. 3-5). For some time it appeared that the C-130 would not have electrostatics problems provided the blue foam was properly installed and the fuel conductivity was at specification levels. However, as discussed in Section 1.0, there have been a number of recent incidents which suggest that this installation does produce electrostatic problems. In addition to the incidents mentioned in Section 1.0, incidents occurred in flight on a C-130 with a portion of the foam omitted from the wing and when refueling a HC-130H with a removable foam filled fuselage tank. In the latter incident, the 12,000 pound capacity fuselage tank was empty, but had been filled previously with JP-4 fuel with conductivity additive. At the time of the incident the fuselage tank was being single point refueled with JP-5 fuel without conductivity additive. The foam voiding around the nozzle was the same as in the other fuel cells as shown in Figure 3-5. The C-130 installation allows fuel to impinge directly on the foam which can cause electrostatic activity sufficient to ignite a left-over flammable JP-4 fuel-air mixture.

3.2.2.2 Foam Fuel Impingement

While one would intuitively expect the geometry of the void space around the fuel inlet nozzle to be a key parameter, the test data revealed that the major effect is whether foam impingement is allowed at all. Johnson (see Section 2.0) concluded that "systems should be designed so that high velocity fuel is not discharged directly into reticulated foam during tank filling. In tests with single orifice inlets where electrostatically 'hot' (active) fuel was

discharged into fine blue foam, some sparking still occurred at a fuel conductivity of 190 pS/m" (Ref. 11). USAF foam impingement tests by Hillman and Spencer (Ref. 17) on inlet nozzles from F-4, F-5, C-130 and A-7 aircraft reinforced Johnson's conclusions. Hillman and Spencer found that the frequency of discharging was dependent on the type of inlet nozzle and that the order from highest to lowest sparking frequency was the A-7, F-4, C-130, and F-5 inlet nozzle. They found that the frequency depended on whether the fuel struck the foam directly or impinged or splashed on the foam after striking a shroud or a wall.

Hillman and Spencer found that the JP-4 fuel tested in their program would suppress discharges on F-4, F-5 and C-130 aircraft at the approved minimum fuel conductivity level (100 pS/m). However, they found that even 100 pS/m conductivity JP-4 may not adequately protect against electrostatic sparking on the A-7 using the then existent foam voiding. Subsequently, the Air Force modified the voiding configuration around the fuel inlet in order to eliminate direct impingement on the foam. The A-10 with the piccolo type inlet should present no problems, especially if care is used to avoid foam impingement. The F-15 has limited fuel impingement in the forward fuselage tank but this tank does not use blue foam.

The F-5 airplane configuration raises some questions in this regard because of the two electrostatics incidents experienced on this airplane. The F-5 uses a metal shroud around the showerhead inlet nozzle which should cause the fuel to flow essentially straight down and impinge on the bottom of the tank since the foam void extends the full depth of the tank. The only source of fuel-foam impingement would be that resulting from splashing off of plumbing lines which come up through the void space. Reducing the fueling rate on airplanes with new tanks or tanks dried out for maintenance has apparently solved the F-5 electrostatics problem.

The findings to date indicate that direct impingement of fuel on blue foam should be avoided. This could be achieved on airplanes which now have direct

impingement by relocating inlet nozzles or modifying foam cutouts as required. Further testing could provide a basis for deciding whether airplanes which currently have fuel impingement on other types of foam should be modified.

3.2.2.3 Voiding Concept

The only airplanes surveyed which used gross-voided foam was the F-15. Foam filled tanks used in other airplanes have small voids (cutouts) in the foam for inlet nozzles and other tank hardware; no airplanes used compression filling which has been used in the past. The F-15A and B models have two foam filled body tanks, numbers 1 and 3b, whereas body tanks 2 and 3a only have foam in the top of the tank above the fuel inlet nozzles and thus use the gross-voiding concept. The F-15A and B wing tanks are about 70% gross voided and fuel foam impingement is not a consideration. The F-15C and D models have the fuel tanks described for the A and B models plus two saddle tanks behind tank number 1, wing leading and trailing edge fuel tanks, and two optional external conformal tanks located at the lower wing-body junction. The saddle tanks are filled with yellow foam and the conformal tanks use grossly voided light blue foam. The bays of the wing leading and trailing edge tanks are alternately filled with light blue foam and left empty.

The voiding adjacent to the fuel inlet nozzles varies considerably from airplane to airplane as evidenced by the sketches shown in Figures 3-3 through 3-8. Both circular and rectangular cutouts are used with impingement varying from direct to essentially no foam impingement.

3.2.3 Fuel Tank Filling

Test data for electrostatic discharges for fuel inlet nozzles in foam filled tanks were generally consistent with intuition. Lowest discharge activity was associated with nozzles with low exit velocities located at the bottom of the tank. Conversely, single orifice inlet nozzles which discharged a single stream of high velocity fuel directly into a small area of a foam surface resulted in the most frequent and highest magnitude discharges. There was general agreement that the multiple orifice (piccolo tube) inlet, which allows

the fuel to flow over a large area at low velocities and directly onto the tank floor rather than a foam surface, results in the lowest electrical discharge activity.

Now that the A-10 airplane fuel inlet nozzle has been changed from an orifice type in the middle of the tank to a piccolo tube at the bottom of the tank, airplanes with showerhead nozzles in the top of the tank would seem to be the next type of fuel inlet nozzle configuration to question. However, with the exception of the C-130 airplanes with this type of nozzle have had excellent safety records when fuel conductivity additives and proper voiding techniques were used.

3.2.3.1 Filling Rates

Results obtained by Crouch and Hillman (Ref. 18) provided the best information on fuel filling rates for airplanes for this survey. These filling rates varied from 66 to 250 gallons per minute as tabulated in Figure 3-2. As expected, the tests by Mills (Ref. 3) and Dukek, et al (Ref. 5) revealed that foam charging increases with filling rate. On this basis the F-4 should present the greatest hazard. However, no particular problems have developed in the F-4 fleet, based on a report of recent accidents. The tank geometry and the number of bays are intimately associated with the filling rate. Therefore, it is difficult to draw conclusions from the filling rate alone. Tests using actual tanks and fill rates may be the only definitive way of assessing the effects of filling rates on electrostatic charge accumulation in foam filled tanks.

3.2.3.2 Fuel Inlet Nozzle Discharge Velocities

Maximum inlet nozzle exit velocities for the airplanes in the survey are tabulated in Figure 3-2. These are calculated values based on filling rates discussed above. Most of the results are for simultaneous filling of the tanks; values for individual tank filling may be 10% to 20% higher than for simultaneous filling. Clearly the guideline value of 10 feet per second is significantly exceeded in many of the designs. However, based on Air Force experience, the inlet nozzle exit velocities are acceptable provided fuel conductivity additives and proper foam voiding techniques are used.

37

3.2.4 Conductivity Additives

The effect of fuel additives, especially conductivity improvers, was studied extensively. It was found in simulated aircraft fuelings that electrostatic discharging could be eliminated or diminished by increasing the fuel conductivity (Ref. 11). Fuels with no fuel conductivity improving additives usually range from 1 to 20 CU (pS/m) and their charging tendencies vary with the type of military specification additives and of impurities in them. The presence of fuel conductivity additive in the fuel was found to be pro-static, i.e., increased additive caused increased charge separation. However, at a certain conductivity level the increased charge separation was countered by an increase in charge relaxation. This was verified by tests that indicated more frequent sparking at moderate fuel conductivity levels than at either lower (baseline) or higher fuel conductivity levels. The fuel conductivity level necessary to eliminate sparking was found to be a function of the specific test configuration and test fuel. Generally, the required concentration of the Shell ASA-3 additive was higher than DuPont's Stadis-450 to eliminate sparking under the same fuel conditions.

Because of problems with electrostatic discharges, the USAF revised Military Specifications MIL-T-5624L and MIL-T-83133A and Technical Order 42B-1-1 on JP-4 and JP-8 fuels to require an electrical conductivity between 100 and 700 CU's at the time of delivery to the aircraft.

3.2.5 Marriage Clamps and Fuel Gauging Units

The fuel system survey included the consideration of isolated conductors such as marriage clamps which could produce a discharge with sufficient energy to ignite a combustible mixture. However, a complete survey of these conductors for the airplanes listed would have consumed excessive contract resources. The method of dealing with isolated conductors is somewhat philosophical and probably varies from contractor to contractor. The Boeing approach, which was discussed in Section 3.1.5, provides a representative technique.

Capacitance type fuel tank gauging units are quasi-isolated conductors. One plate of the capacitor is connected with a low impedance lead to ground and

the other with a high impedance lead. The high impedance value is selected such that the unit will function properly in normal operation and yet provide a current path to preclude excessive charge accumulation. If the high impedance lead should become detached, the gauging unit could be hazardous from a static electricity viewpoint.

3.2.6 The A-10 Airplane

The unusually large number of electrostatic problems experienced on the A-10 airplane raise issues that are peculiar to the design of this fuel system. Quoting from a report by Kalt (Ref. 19):

"The A-10 experienced two fuel vapor ignition incidents in 1977 with red polyester foam (explosion suppression material [ESM]). These incidents, which occurred during refueling, were determined to be due to static electricity charge generation/discharge at the refueling manifold outlets in the fuel tanks. The incidents led to the service wide incorporation of the anti-static additive (ASA) in fuel and the incorporation of a piccolo tube refueling outlet to reduce fuel velocities entering the A-10 fuel tanks. The blue polyether ESM was incorporated in production starting with aircraft 294 as an extended life replacement for the red ESM, which has a limited service life. These corrective actions appeared to resolve the A-10A static electricity discharge problem with the fuel system, until a rash of incidents began occurring in early 1981, primarily with blue ESM. This led to the formation of a special team to investigate the problem."

The latter mishaps were traced to the A-10 fuel tank foam survivability systems, line check operation and fuel purge operation. Activation of the line check operation allows the pilot to check the integrity of the fuel manifold prior to aerial refueling. This operation pressurizes the fuel lines with 65 psia bleed air for three minutes. When deactivated, the pressurized air is released into the fuel tank through the fuel inlet nozzles. When this air flows up through the foam and fuel, electrostatic charge accumulation

takes place, thereby causing discharging activity of sufficient energy to ignite combustible fuel-air mixtures within the tanks. The purge system is activated when the aerial refueling door is closed. Bleed air pressurizes the refueling line and opens a valve forcing fuel from the aerial refueling line into the forward main fuel tank. After the fuel is purged, pressurized air is forced into the forward tank which passes through the foam and fuel. At the end of the three minute cycle the residual pressurized air and fuel in the refueling manifold are released into the fuel tanks as in the line check operation, with the same potential problems as during the line check.

The remedy for the refueling problem was to change from the orifice type to a piccolo tube type inlet nozzle, as mentioned above. A final determination of the remedy for the line check/purge check problem has not been made. More detailed discussions of the A-10 electrostatics problem may be found in Ref. 7 and Ref. 19.

3.3 DISCUSSION OF COMPOSITE FUEL TANKS

Two fundamental issues surfaced in Boeing studies for composite fuel tanks.

o Fuel lines, vent lines and similar fuel tank components must have conductivities less than or equal to that of the composite structure for lightning strike safety.

o Composite buildup techniques, sealants and coatings may result in unacceptably high tank electrical resistance to bleeding off electrostatic charges.

The first point is best illustrated by considering the tank structure and a fuel line to be two parallel resistors as shown in Figure 3-9.

WING TIP ○─── R FUEL LINE ───○ **WING TIP**
R STRUCTURE
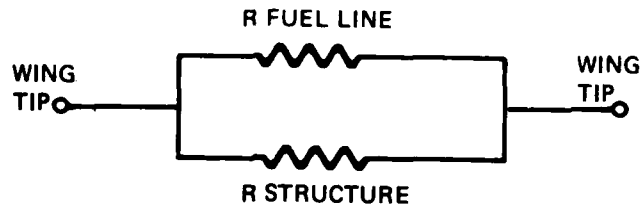
Figure 3—9. Parallel Resistor Model for Lightning Current Flow

Assuming an electrical current (I) of 200,000 amps which may occur in severe lightning strikes and an 80 to 1 cross sectional area ratio between the structure and the fuel line, the currents flowing in typical aluminum and graphite epoxy materials would be

STRUCTURE/LINE	$I_{STRUCTURE}$ (AMP)	I_{LINE} (AMP)
Aluminum/Aluminum	197,500	2,500
Graphite/Aluminum	14,600	185,400
Graphite/Graphite	197,500	2,500

The current flow through an aluminum fuel line in a graphite structure could reach 185,000 amps, which would be totally unacceptable. A design is therefore required in which the structure carries essentially all of the current.

Although low conductivity fuel lines may be satisfactory from a lightning viewpoint, they may cause electrostatics problems. Experience (Ref. 1) has shown that flowing fuel at high velocities through non-conducting lines can cause electrostatic discharges of sufficient strength to puncture holes in the lines. Farrand (Ref. 20) discussed pinhole failures which occurred in Teflon hose assemblies used in several types of jet engines. The failures were traced to electrostatic charging by JP-4 fuel. Carbon black added to improve hose conductivity extended the hose life by a factor of 4 or 5. Abbey and Upham (Ref. 21) also concluded that potentials sufficient to produce pinhole

failures could be generated by circulating JP-4 fuel containing trace amounts of asphaltic impurities through the hose. The potential at which breakdown occurred was about 50 KV and all types of Teflon examined were subject to pinhole failures. They also concluded that increasing the hose conductivity decreased its tendency to pinhole failures. The remedy of increasing electrical conductivity of the fuel lines is probably not a viable one for composite tanks since the purpose of non-conducting line is to limit current flow in the event of a lightning strike. A systematic experimental study of the effects of materials, diameters, flow rates and fuels on electrostatic charge accumulation would provide valuable design information. Another factor with respect to low conductivity fuel lines is the type of couplings which would be used and the method for connecting lines to pumps, valves and other branches of the flow network.

An inherent disadvantage of the current graphite epoxy material is that the electrical conductivity is anisotropic; electrical resistance is much greater in the transverse direction than in the longitudinal direction. Therefore, even though lightning currents are conducted without incident, static charge on the fuel may not be readily dissipated. Coatings and sealants appropriate for composite tanks are still being evaluated but they will increase the volume resistivity of the tank. A test program in which the current flow to ground during fueling of a composite tank is compared to the current flow for a metal tank would provide useful data. An unsolved problem is how to determine electric current flow patterns in the material. In these tests composite materials, candidate sealants and coatings as well as fuel types could be investigated.

Gauging systems for composite tanks may require non-conductive, non-electric tank units unless special shielding provisions are made. The capacitance gauging systems could be troublesome for two reasons. Both of these are related to the much higher voltage differences developed by lightning strikes to composite structures. The resulting voltage difference between the tank structure and the gauging unit could cause an incendive discharge. The voltage induced in the electrical leads could cause arcing at the gauge unit

or could damage the data processor. Note that since the wires from the tank units are signal leads, they do not generally have electrical overload protection.

In summary, considerable systems development work may be required prior to general implementation of wing composite fuel tanks. In some respects systems development is lagging structural development. Tests addressing issues such as those discussed above should accompany composite fuel tank development.

3.4   CONCLUSIONS ON CURRENT DESIGNS

A number of USAF airplanes using explosion suppression foam in their fuel tanks were surveyed and evaluated relative to laboratory test results and Boeing design philosophy and experience. Recognition is given to the risks inherent in extrapolating laboratory data to actual airplane installations and the fact that no current Boeing airplanes have tanks containing foam.

Based on the findings of this survey, the original A-10 design, which had an inlet nozzle near the middle of the tank with direct impingement of a high velocity fuel stream on the foam, was the worst design. With the change to the piccolo type inlet nozzle mounted at the bottom of the tank, the A-10 design should be one of the best designs of the airplanes in the survey. Test data reveal that designs using showerhead nozzles in the top of fuel tanks and direct impingement on the foam may create electrostatic problems. Several of the tank configurations surveyed have this arrangement.

Little was mentioned in the literature about temperature and humidity effects although these are clearly important factors in electrostatic discharges. Most of the accidents, according to a tabulation provided in Ref. 6, occurred at relatively low static temperatures (30 to 50°F) and low relative humidities. Note that absolute humidity may be a much more meaningful parameter than relative humidity since the significant factor is the amount of water the air will hold. Boeing small scale tests confirmed the profound

effect of humidity on foam charging characteristics. Flowing a dry fuel/air mixture through the test chamber for a few minutes changed the character of a combustible mixture from one that could not be ignited to one which was readily ignited by a spark discharge from the foam specimen.

In the Boeing small scale tests (Section 4.0), the blue foam was charged negatively, and a charge transfer of less than -70 nanocoulombs (nC) ignited a combustible mixture of JP-4S and air. With propane and air this level was less than -50 nC, which is lower than any ignition charge transfer reported in the literature. One factor may be that some of the other tests employed a stoichiometric mixture of fuel and air. In reality, the minimum ignition energy occurs in mixtures which are somewhat fuel rich. The Boeing tests used mixtures close to the minimum ignition energy point. Test data also reveal that the charge transfer required for ignition is about twice as high if the foam charges positively rather than negatively. As fate would have it, tests with flowing fuel on blue foam show that it charges negatively, increasing the probability of producing incendive electrostatic discharges.

A number of research topics were suggested by the survey to more completely understand the electrostatic hazards associated with foam filled tanks. Among these are studies of

o Fuel foam impingement to determine which voiding geometries are acceptable or whether impingement should be allowed at all. Tests should be made using fuels with and without conductivity improver.

o Secondary impingement such as fuel splashing from tank plumbing to determine if secondary impingement can cause foam charging.

o The effect of fuel chemical composition differences (impurity differences) on electrostatic charging characteristics of foam.

o Differences in bleed-off current characteristics between bladder cell and metal tanks during fueling.

o The effect of filling multibay foam filled tanks at unequal rates.

o The sensitivity of electrostatic charge accumulation to filling rate,
   inlet nozzle type and location in the tank, temperature, humidity and
   initial charge and charge polarity on the incoming fuel.

Research on composite tanks could move forward in several different areas
including:

o Studies of differences in electrostatic fields in composite tanks with
   and without foam.

o Measurements of bleed-off currents from typical composite tanks,
   coatings and sealants.

o Studies of non-conducting fuel lines as an adjunct to composite fuel
   tank studies

The capriciousness of electrostatic discharges and the lack of absolute
analytic methods leaves little alternative but to test configurations which
are questionable. Some of this kind of testing has been done. Since the
interaction of inlet nozzle, type, foam voiding, tank geometry and fuel
filling rate and velocity combine to determine whether incendive arcing will
occur, ranking of various configurations without specific test data is very
risky. On the other hand, much has been learned on how to safely use
reticulated foam in fuel tanks. Electrostatic hazards can be minimized or
eliminated completely by designs and procedures which require:

o Piccolo tube inlet nozzles to distribute the fuel evenly among bays, to
   reduce the exit velocity to less than 10 feet per second, and to
   introduce the fuel at the bottom of the fuel tank.

o Inlet nozzles which cause the fuel to impinge on tank structure rather
   than the foam.

o A fuel conductivity improver additive to increase conductivity to values above 100 CU.

o No rapid discharge of air through the fuel and/or foam

The USAF conductivity criteria of 100 CU (minimum) at the time of fueling the airplane seems adequate. Conductivity improver not only suppresses arcing due to the tendency of the foam to attain an electrostatic charge but also is beneficial in reducing the peak charge on the fuel when tank resistivity is not negligible.

4.0 SMALL SCALE ELECTROSTATICS TESTS

Quantification of the characteristics of incendiary spark for fuel-air mixtures is required in order to set design standards to obviate this hazard. These characteristics have been measured to an acceptable accuracy for metal to metal discharges; the threshold incendiary spark energy is commonly accepted to be approximately 0.2 mj, although this value may be too high according to Ref. 13. For sparks from foam, a suitable characterization is much more difficult:

o the electrostatic charge is usually generated by flowing fuel, complicating electrical measurements

o a measurement of the potential difference between the foam and a metal electrode is nearly impossible

o the extent of the charged area of foam involved in a discharge event cannot be determined

It was judged that the characterization of incendiary discharges from foam could be simplified by devising a method to charge the foam without flowing fuel, and a series of small scale experiments were outlined whose objectives were to:

o develop a method to deposit electrostatic charges on explosion suppressant foam by means other than flowing fuel

o characterize the electrostatic discharge from charged foam by determining the minimum energy or charge transfer required to ignite a fuel-air mixture

o measure the charge relaxation time for various types of foam

o measure minimum spark ignition energy in a bomb constructed using transmission line principles

4.1 ELECTROSTATIC CHARGE DEPOSITION ON DIELECTRIC SURFACES

An alternative to electrostatic charge generation by flowing fuel was developed using an ion spray technique to electrostatically charge a

dielectric surface (such as explosion suppressant foam) to levels sufficient to cause incendiary discharges. In the development of the technique, it was found easier to obtain reproducible results by charging a sheet of plexiglas than to charge explosion suppressant foam since clean-up and humidity control were simpler with plexiglas. Static discharges from plexiglas and foam were observed to be essentially identical, based on records of current rise and decay times and discharge wave form. After the charging techniques and instrumentation were well developed, the plexiglas was replaced by explosion suppressant foam for the final measurements. Testing was performed using an ion spray charging device installed in a 36x18x18 inch chamber.

4.1.1 Electrification of Dielectric Surfaces

The final form of the electrification apparatus is shown in a line drawing in Figure 4-1, and photographically in Figures 4-2a through 4-2c. In the charging process, a high voltage (0 to ±250 KV) direct current generator was connected to the ion source (a Dexter discharger, similar to the resistive precipitation static dischargers mounted on airplanes to bleed-off triboelectric charge). The ion source was supported by a hollow insulating rod extending from the rear wall of the test chamber. The hollow center of the rod contained the high voltage lead to the ion source from the high voltage generator, and a ground connection for a ball discharger also supported by the rod. The dielectric surface to be charged was supported by Teflon posts for plexiglas (Figure 4-2a) and a cage and string apparatus for foam slabs (Figures 4-3a and b). Charging of the specimen required an aluminum ground plate to be positioned immediately below the dielectric material. Stable positioning was achieved by using compressed air to hold the plate in place against the tension of a spring.

When the high voltage generator was activated, an electric field was formed between the ion source and the ground plate. At the ion source, the field had sufficient intensity to ionize the surrounding air, and the ions formed migrated toward the ground plate under the influence of the electric field between the source and ground plate. As these ions impinged on the dielectric, a surface charge was accumulated. After about 10 to 20 seconds a

48
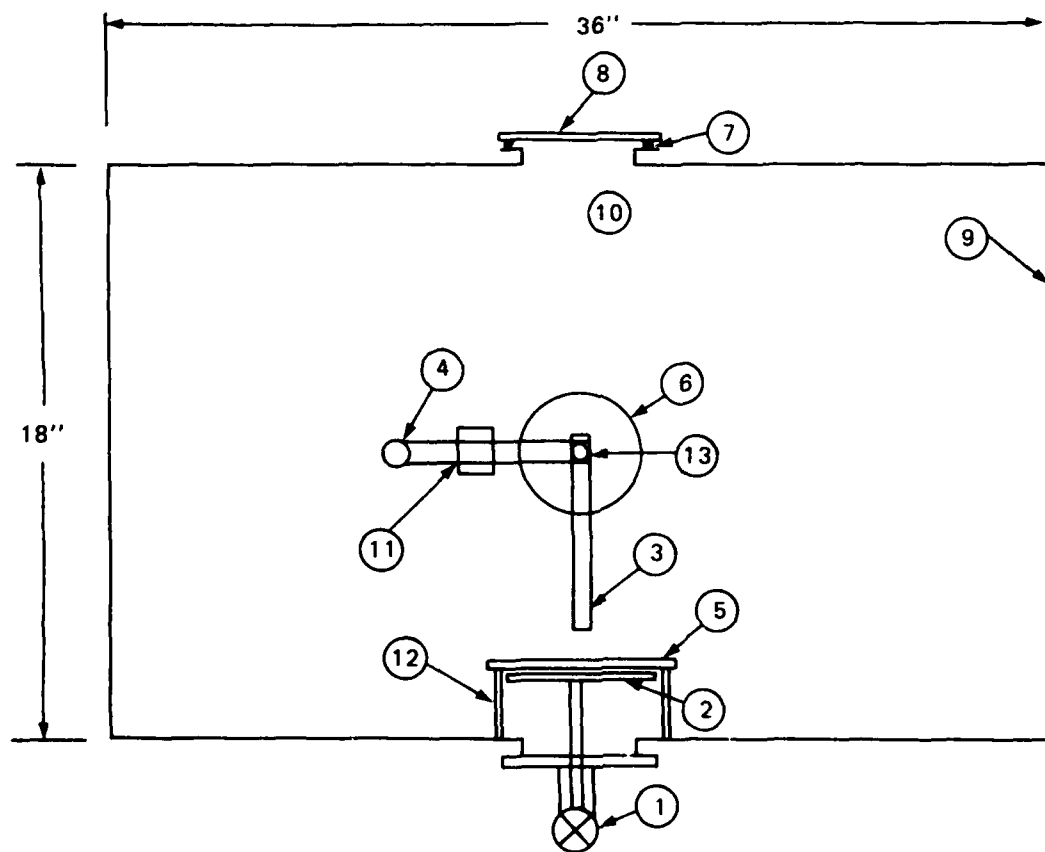
1. Air actuated piston
2. Aluminum ground plate
3. Ion source
4. Discharge ball
5. Plexiglass surface
6. Rotor
7. O-Ring
8. Blowout disc
9. Tank wall
10. Pressure relief opening
11. Adjustable length
12. Teflon posts
13. Support rod

Figure 4-1. Electrostatic Ignition Test Apparatus Schematic
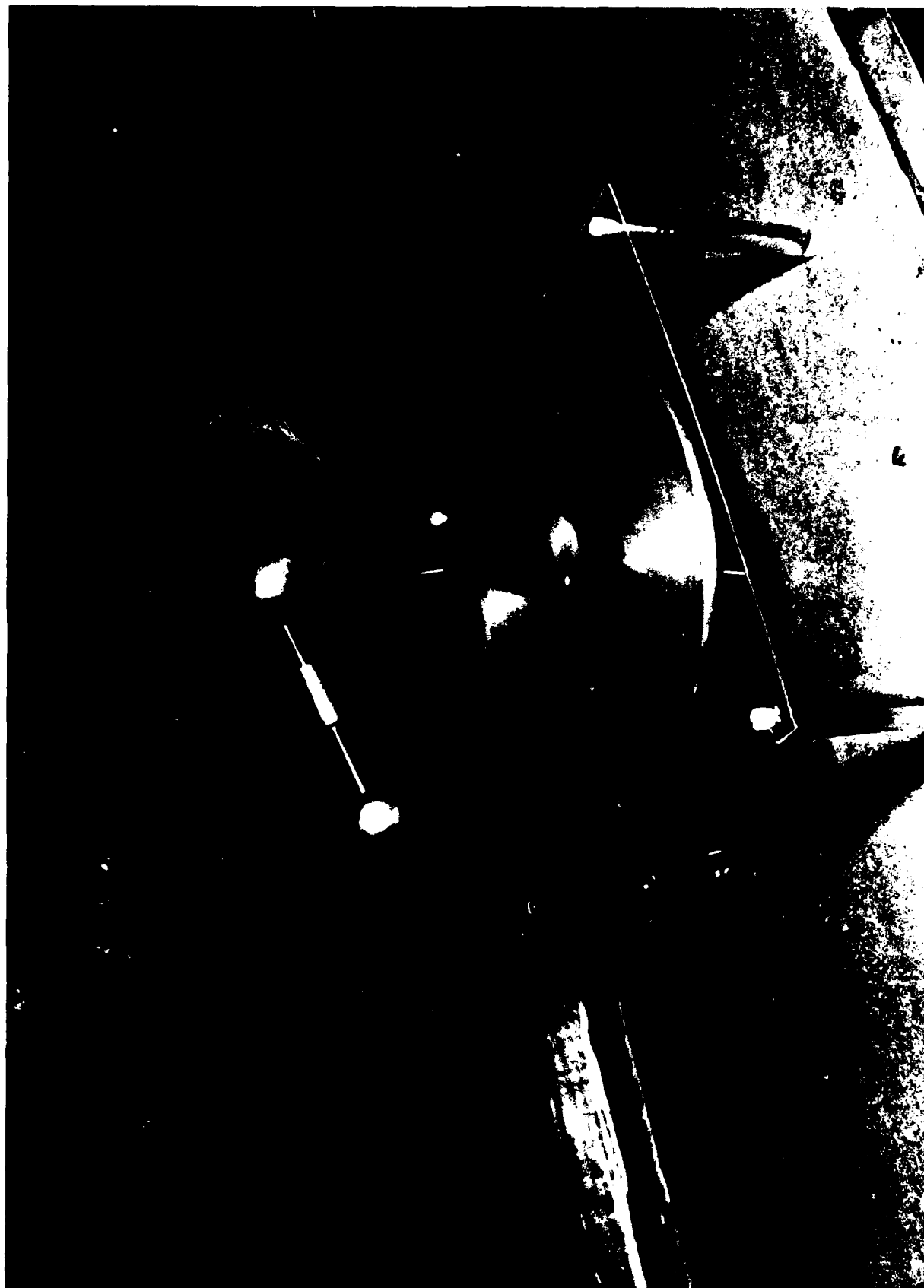
Figure 4-2a. Close-up View of Charging/Discharging Apparatus

Figure 4-2b. View of Test Chamber with Grounding Plate in Charging Position
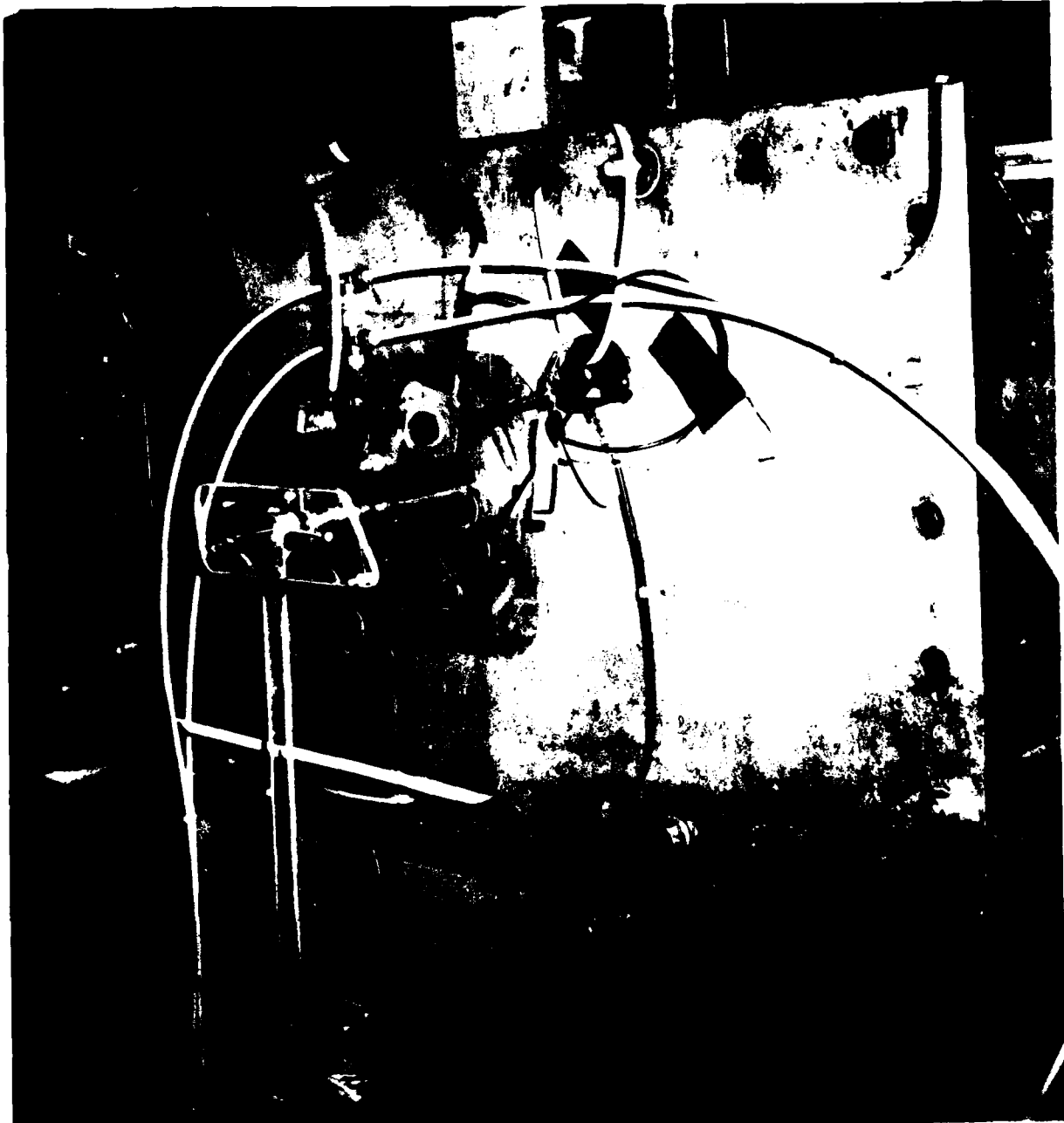
*Figure 4—2c. Rear View of Chamber Showing
Charging Device and Fuel Inlet Lines*
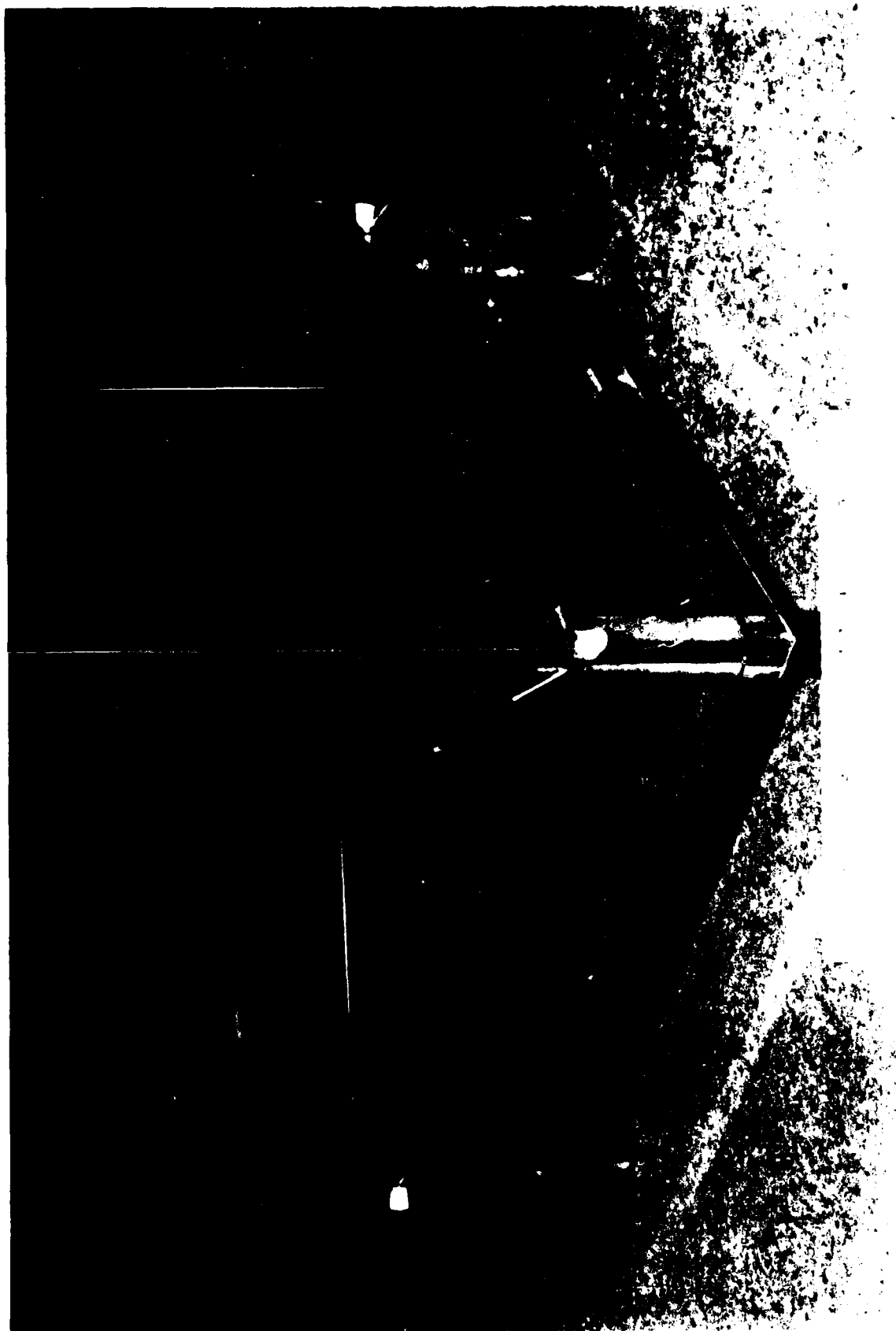
Figure 4-3a. Foam Support Cage

Figure 4-3b. Foam Support Cage with Foam Installed

steady state surface charge was obtained and subsequent migrating ions were deflected to the grounded walls of the test chamber. The final charge level and polarity accumulated by the dielectric specimen were varied by adjusting the voltage and setting the polarity of the high voltage generator.

4.1.2 Creation of Controlled Discharges

After the dielectric surface was suitably charged, a simulated fuel system component was placed near the surface to provide a discharge path. Fuel system components were simulated by a grounded sphere mounted at 90° from the ion source and supported by the same rod (Figures 4-2 and 4-3). Different diameter spheres (simulating components of differing radii of curvature) could be attached, and the length of the sphere support could be adjusted to vary the ball to dielectric gap (simulating component to foam spacing). At the completion of the charging process the voltage generator was deactivated, and the support rod was rotated 90°, removing the ion source from the vicinity of the dielectric, and positioning the ball over the dielectric. At this point the voltage difference between the ball and dielectric was normally insufficient to cause a discharge.

When a discharge was desired, the air pressure holding up the ground plate was relieved, allowing the spring to rapidly lower the ground plate, thereby reducing the capacitance of the discharger-ground plate system. Since the charge on the dielectric was essentially constant during the motion of the plate, the voltage on the dielectric surface increased until breakdown occurred. (The energy required to increase the voltage was provided by the lowering of the ground plate.) High speed photography showed that the discharge occurred while the plate was in motion; the voltage at which breakdown occurred depended on:

- o gap size
- o ball diameter
- o charge on the dielectric
- o cleanliness of the surfaces
- o humidity
- o dielectric thickness

The energy in the discharge and the charge transferred during the event depended on most, if not all, of the same factors.

4.2   CHARACTERIZATION OF INCENDIARY SPARKS

Although the charging voltage of the ion source was readily measured, specific levels of resulting voltages on the dielectric specimens could not be determined since there was no direct relationship between specimen voltage and subsequent charge transfer. Determination of the incendiary threshold was performed by starting with a sufficiently low charging voltage (about 10KV) which, based on previous experience, would not result in ignition of the combustible mixture. The experiment was then repeated as the charging voltage was increased by small increments until ignition occurred. A charging voltage of 20-30KV usually deposited sufficient charge for ignition. However, in some cases discharges with charging voltages up to 40-50KV failed to produce combustion. The absence of a direct link between charging voltage and charge transfer required for ignition is probably due to the vagaries of the discharge phenomenon and other factors such as those listed in the preceeding section.

In the early experiments both negative and positive charges were deposited on the dielectric specimens. Studies were made of the time to reach a steady state charge and to discharge a specimen and on various charging techniques. Once a suitable apparatus was developed, negatively charged specimens were used in most of the tests to measure charge transfer required for ignition of combustible mixtures. The decision to concentrate on negatively charged test specimens was based on findings by Johnson (Ref. 11) and Leonard and Affens (Ref. 4). Johnson found that a charge transfer of +140 nC or -70 nC from explosion suppressant foam was needed to ignite a hydrocarbon and air mixture. Based on these results ignition may be expected with lower charge transfers when the foam specimen is negatively charged. Leonard and Affens found that "although the signs of the charges of the untreated fuels or the polyester foams were both positive and negative, the charges on the polyether foams were almost always negative. In the case of the ASA-3 treated fuels,

AFWAL-TR-83-2015

the charges on the polyester foams were almost always positive, but the
charges on the polyether foams were always negative." Whereas these findings
clearly point to using negatively charged polyether specimens for ignition
tests, one might argue that positively charged specimens should have been used
for polyester tests. However, the evidence allows the possibility of
negatively charged polyester foams and if negative charging does occur the
charge transfer required for ignition would be lower.

4.2.1 Ignition Criteria for Sparks Originating from a Dielectric Surface
When a discharge occurs between a dielectric surface and the grounded ball,
its incendivity can be observed directly when the gas around the discharge is
flammable. The discharge intensity may be measured in terms of spark energy,
(the usual and historical measure), or in terms of charge transfer during the
event.

4.2.1.1 Energy Criterion - Metal Electrodes
From an electrostatic safety standpoint, it has been conventional to measure
the minimum discharge energy in a gap which can ignite various fuel vapor/air
mixtures. Such measurements have been made using metal electrodes in a
fuel-air bomb; the electrical energy deposited in the gap is assumed to be
that stored in a lumped capacitor which discharges across the gap (Figure 4-4).
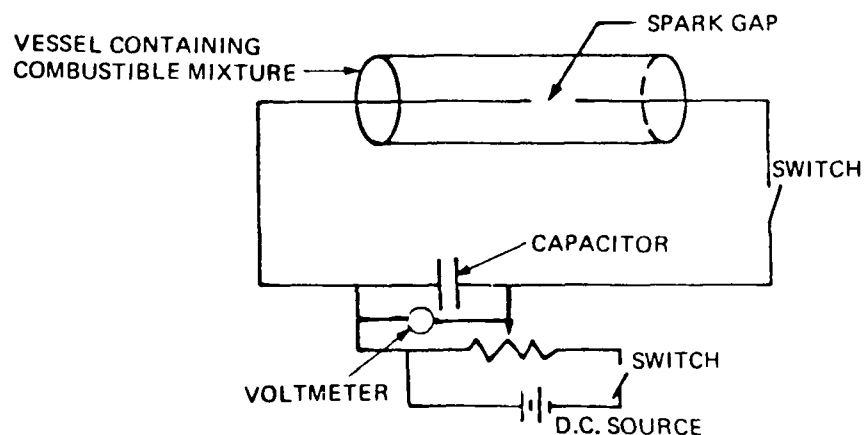
Figure 4-4. Schematic of Standard Minimum Energy Measurement Apparatus

57

The energy (E) in the capacitor depends on its capacitance (C) and the voltage (V) to which it is charged at time of discharge

$$E_{capacitor} = \frac{1}{2} CV^2$$

Note that with metal electrodes all the energy is concentrated in a single arc. However, if the impedance of the capacitor and associated wiring is sufficiently high, as will be the case at the frequencies involved in sparks, estimates are that less than 1/2 of the stored energy in the capacitor will be dissipated across the gap. Bridges, Zalewski and Nanda (Ref. 13) recommend computing the energy in the gap by integrating the product of voltage and current measured over the time of the discharge (Δt)

$$E_{gap} = \int_{0}^{\Delta t} I(t) \, V(t) \, dt$$

The measurement of current [$I(t)$] is readily made, but voltage [$V(t)$] is a difficult measurement, even when both electrodes are metal.

4.2.1.2 Energy Criterion -- Dielectric Discharges

When the discharge occurs from a dielectric surface to a metal conductor, there is no lumped capacitor and one electrode is a dielectric. While current is readily measured, there was no means to measure voltage, and the discharge energy cannot be computed. Alternative optical energy measurement techniques were attempted, based on the relationship between gap energy and gap temperature, and electrode separation. This effort also failed because the sparks were too faint even for the ultra-sensitive optical spectrometers and photo diodes used in plasma research. Further consideration of gap energy as an ignition criterion for discharges from dielectric surfaces was therefore abandoned. However, a related effort was made to improve the accuracy of measurement for discharges between metal electrodes, as reported in Section 4.4.

4.2.1.3 Charge Transfer Criterion -- Dielectric Discharges

Attention was next turned toward the use of total charge transfer, Q_{gap}, as a criterion of incendivity of sparks where

$$Q_{gap} = \int_{o}^{\Lambda t} I(t)\, dt$$

The current measurement, $I(t)$, was accomplished by sensing the current flowing from the ball discharger to ground (Figure 4-5). Data acquired by the current probe was stored and photographed using a storage oscilloscope. The traces on the photographs were digitized, and the necessary integration was performed by computer (Figure 4-6).

The initial series of measurements were made to determine the mixture ratio of fuel vapor and air which required minimum charge transfer to cause ignition. As earlier noted a plexiglas dielectric was used, since it eliminated cleanup associated with combustion over a foam dielectric (Figure 4-7) and the shape of the discharge current pulse is essentially identical to that of foam. It was observed that there was a region of certain ignition, a region of no ignition, and a zone of overlap in which ignition might or might not occur (Table 4-1). The fuel/air mixture ratios were based on previous studies (See Figure 4-8 which was extracted from Ref. 22) of minimum charge transfers required for ignition. Experiments with propane were usually made with a 5.3% mixture which was equivalent to 1.3 times the stochiometric ratio. Similarly experiments with JP-4S utilized mixtures which were 2.0 times stoichiometric.

4.2.2 Characterization Experiments

To characterize the discharges which occur from dielectric materials, tests were made to determine the nature of the arcing from the dielectric specimen to the discharge ball and the charge transfer required for ignition of combustible mixtures.

4.2.2.1 Nature of Discharge

Close-up high speed photography (4000 frames/sec) of the sparks using a plexiglas specimen with the front face of the chamber removed showed a dim,
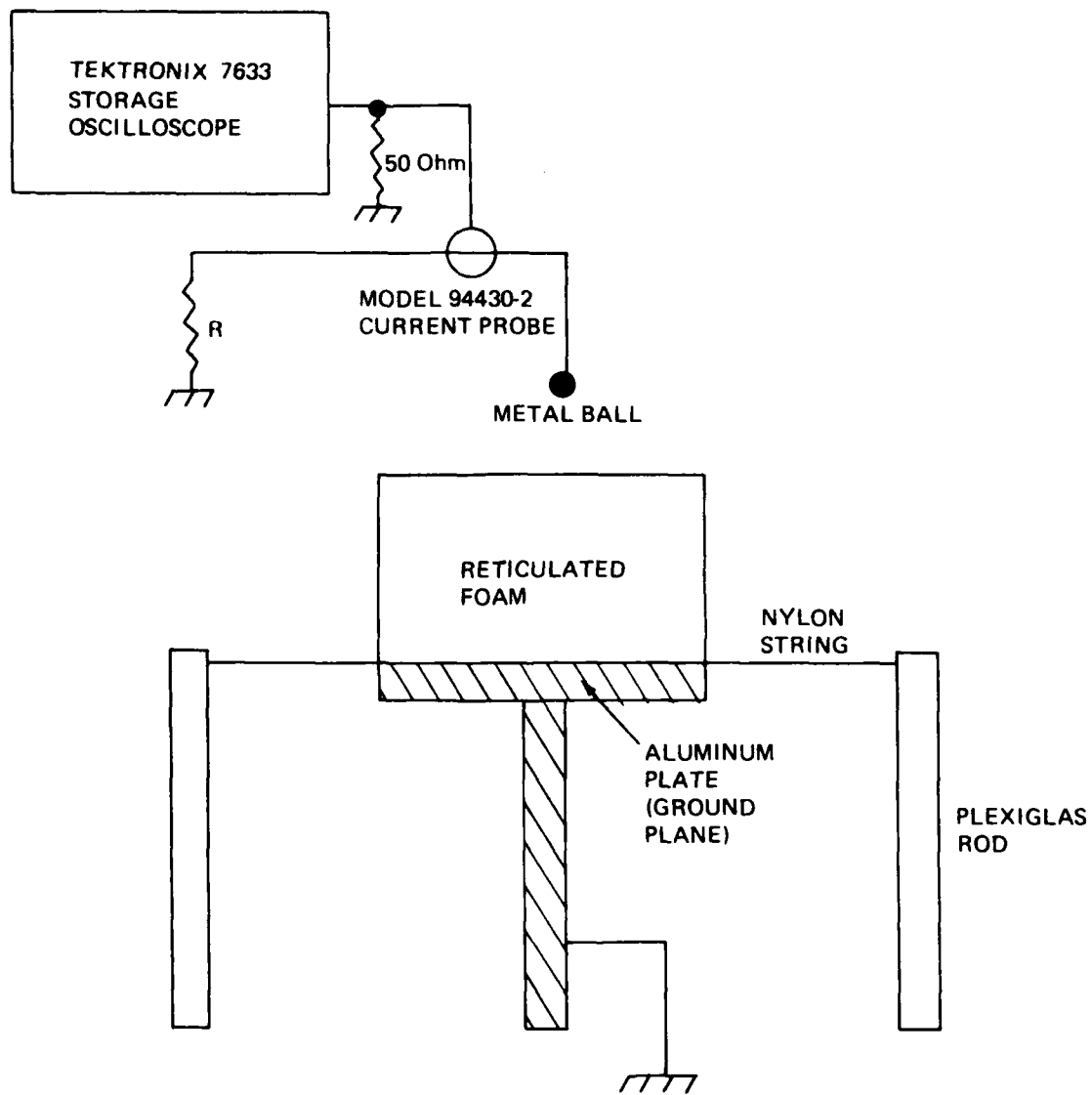
Figure 4-5. Test Configuration for Charge Transfer Measurement
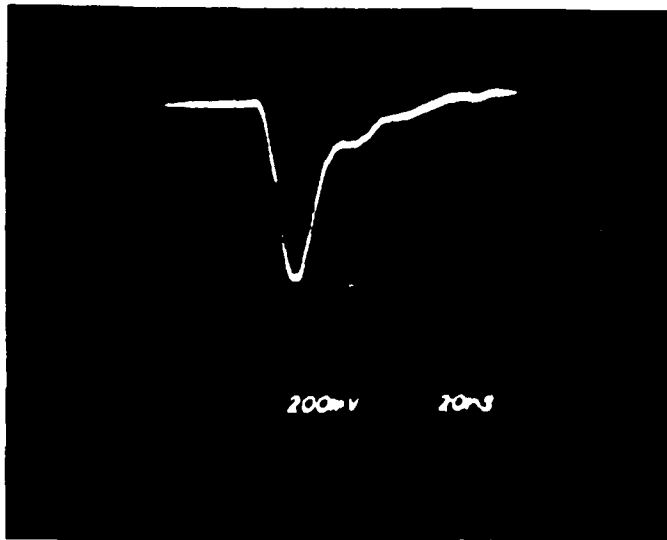
TEST CONDITIONS:

- 4.2% Propene by Volume
- 1 Inch Ball
- 0.7 Inch Gap
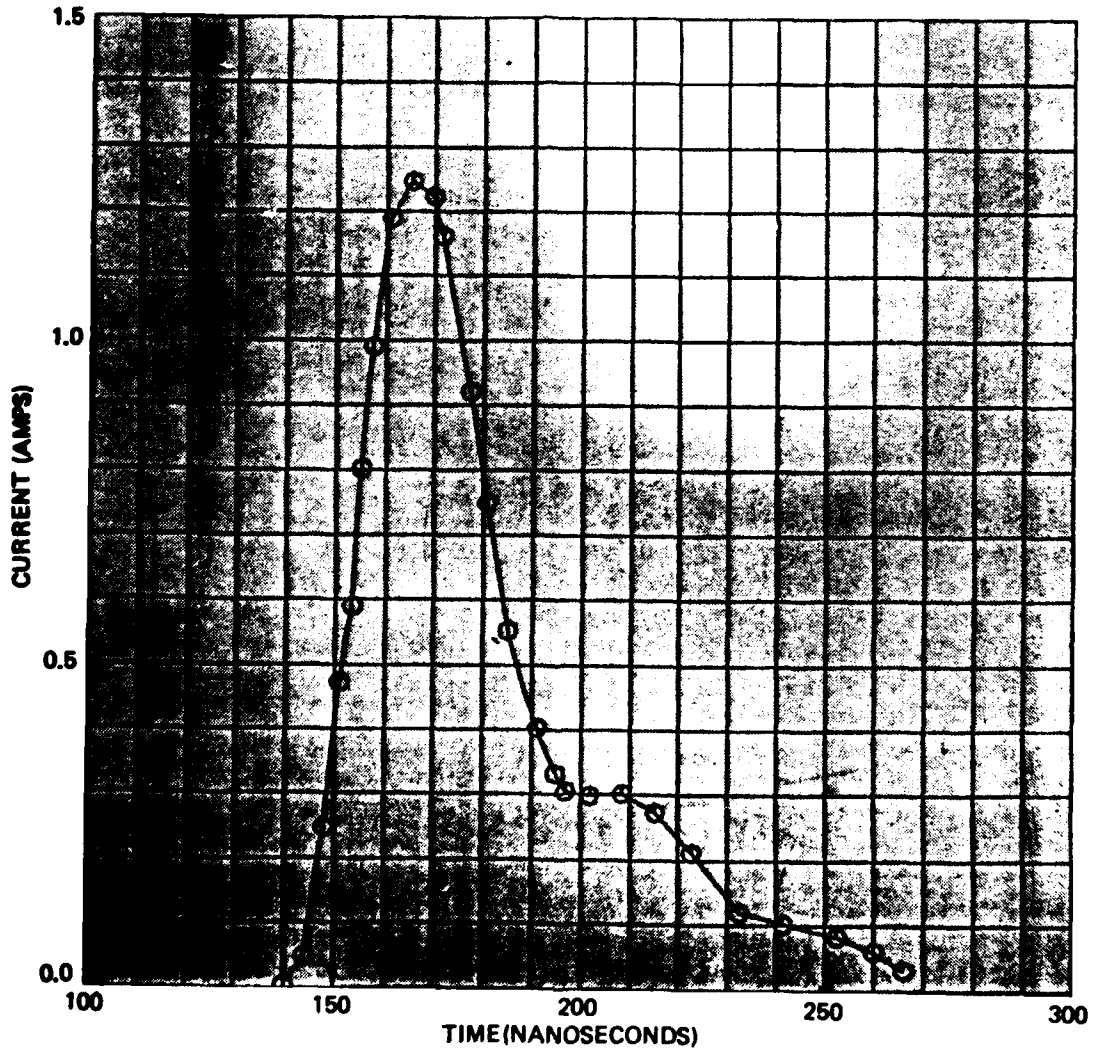
Figure 4-6. Typical Oscillograph Trace and the Corresponding Digitized Waveform

61
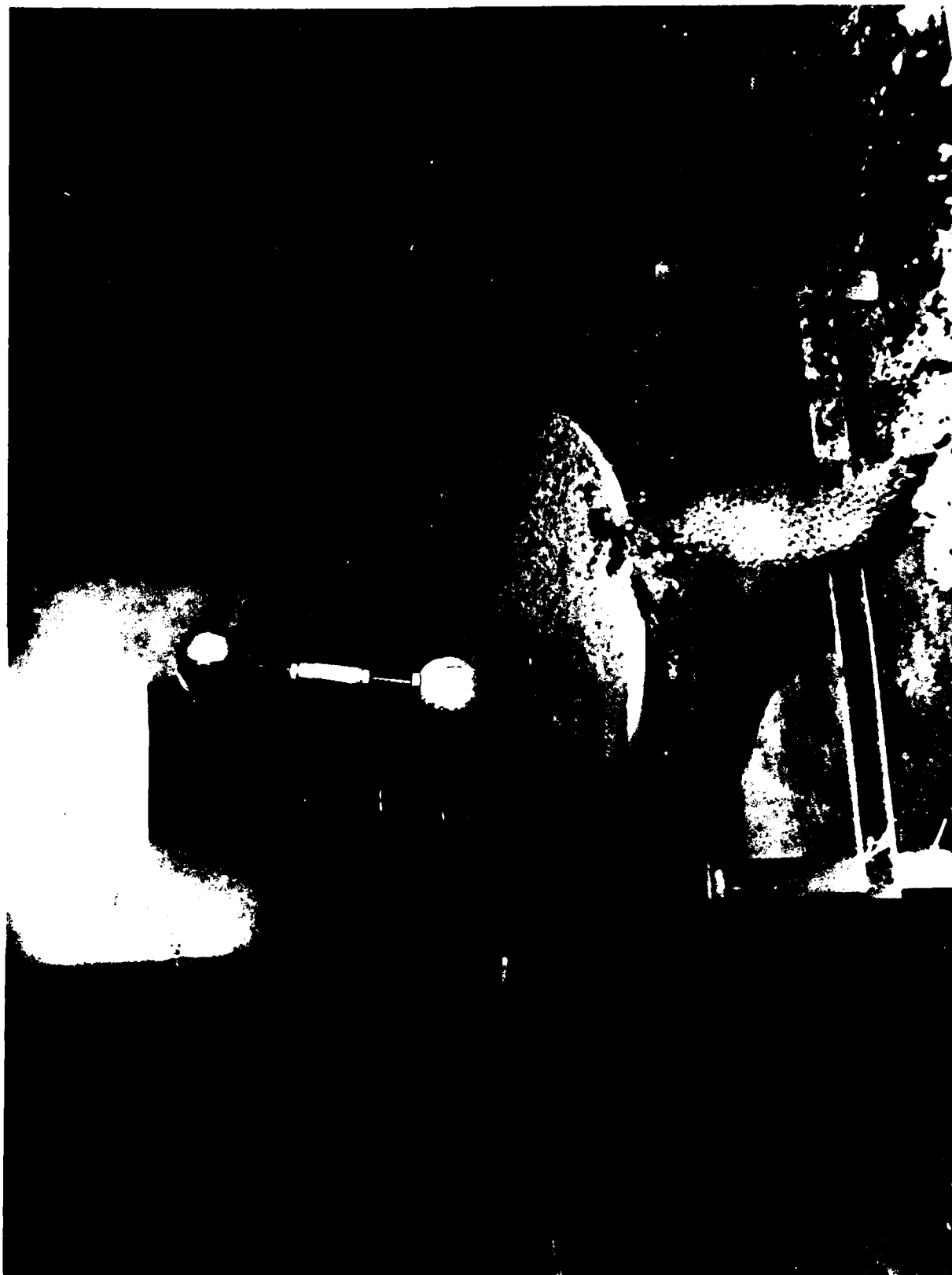
Figure 4-7. Charred and Melted Foam After an Incendiary Discharge

TABLE 4 – 1.
CHARGE TRANSFER AND IGNITABILITY RESULTS USING
PLEXIGLAS AND PROPANE FUEL WITH 0.7 INCH SPARK GAP AND
1 INCH DISCHARGE BALL

NEGATIVE CHARGE POLARITY

VOL. % OF PROPANE in AIR	2.8		4.2		6.3	
IGNITION?	YES	NO	YES	NO	YES	NO
TOTAL CHARGE TRANSFER (nC)	90.1	152.5	51.3	45.6	67.7	59.3
	95.2	152.5	62.0	51.2	76.6	61.6
	136.4	153.6	68.4	55.8	80.2	62.1
	179.0	154.9	71.3	60.5		79.2
				62.1		
				63.0		
				65.2		
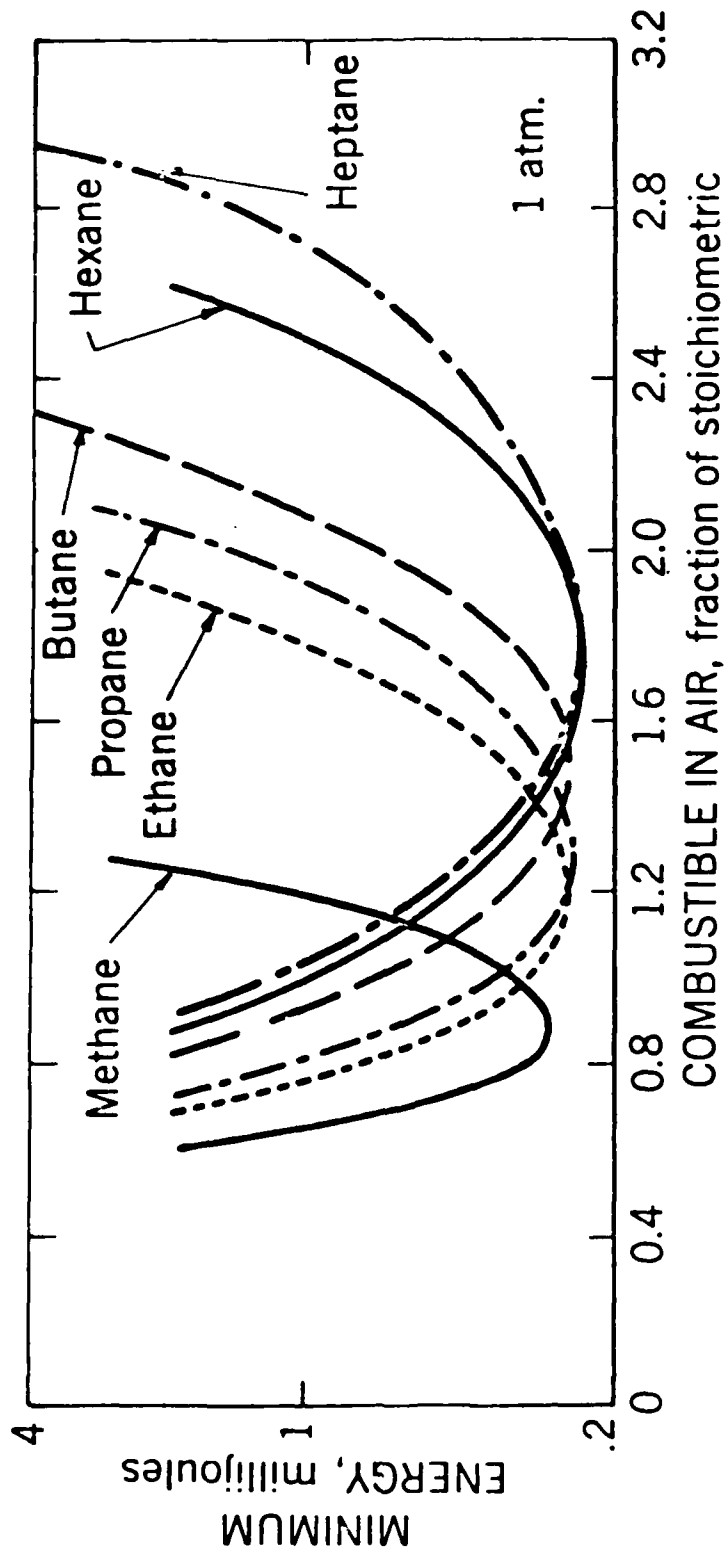
Figure 4-8. Spark Ignition Energy vs Mixture Composition for Mixture of Various Straight Chain Saturated Hydrocarbons With Air at 1 Atmosphere

AFWAL-TR-83-2015

diffuse discharge at the dielectric surface, which coalesced into a bright arc at the discharge ball. Figure 4-9 shows that the discharge may consist of single or multiple branches (as opposed to single discharges between metal electrodes). Other photographs of ignition events show that the bright arc region is the ignition zone (Figure 4-10). The incendivity of the arc apparently hinges on the rate of energy release in the bright zone, and the rate of energy removal from this zone.

4.2.2.2 Threshold Charge Transfer Tests

To conduct a test of minimum ignition charge transfer, the ground plate was positioned under the dielectric specimen and the ion source positioned above the specimen. If desired for the test at hand, the relative humidity was reduced to less than 20% by blowing dry plant air through the test tank for several minutes using air inlet and outlet valves, which were then closed. Propane was added to the tank by reducing the tank pressure by 2 inches Hg (5 cm Hg) and then bleeding in propane until the tank pressure returned to one atmosphere. The amount of JP-4S was controlled by injecting a predetermined volume in the liquid phase using a syringe. As noted earlier the mixtures were about 2 times the stoichiometric value to minimize ignition energy requirements. Two small spark-proof fans mounted on the bottom of the test chamber were then turned on for several minutes to ensure uniform mixing. The selected charging voltage was applied to the ion source for 10 seconds. The support arm was rotated 90^0, placing the discharge sphere over the dielectric specimen, and instrumentation and recorders activated. At this point the air valve attached to the ground plate was opened, causing the ground plate to retract and the voltage on the dielectric specimen to increase. When breakdown voltage was reached, a spark formed, and ignition occurred if the charge transfer was of sufficient magnitude. As discussed above, the initial charging voltage was sufficiently low to prevent ignition. The experiment was then repeated while gradually increasing the charging voltage until ignition occurred. Data from both ignition and non-ignition experiments were recorded. The data show a threshold charge transfer below which, for a given geometry, ignition will not occur and also show a linear correlation between maximum current and total charge transfer. Above this

65
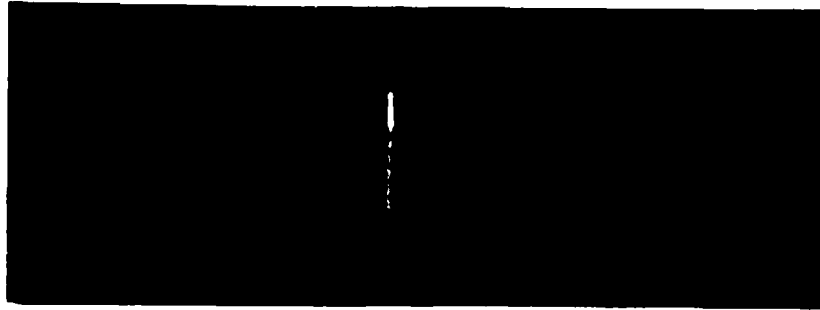
a. SINGLE DISCHARGE

b. MULTIPLE DISCHARGE
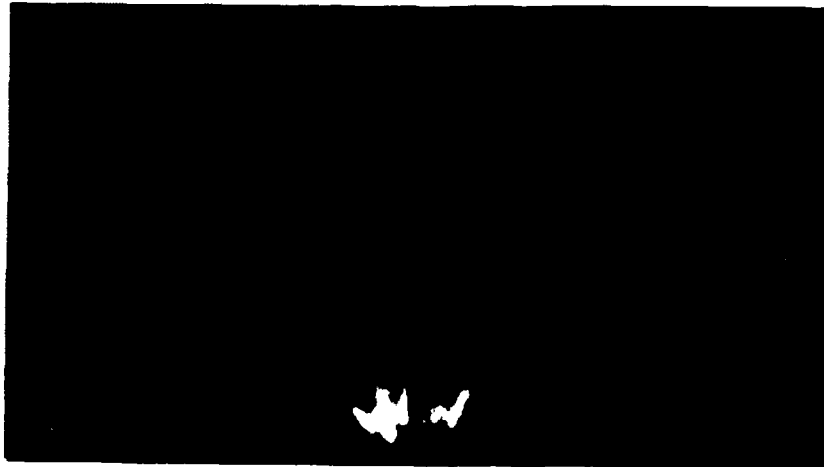
c. MULTIPLE DISCHARGE

NOTE DIFFUSE ORIGIN OF SPARKS

Figure 4-9. Types of Discharges Observed

NOTE POSITION
OF GROUND PLANE
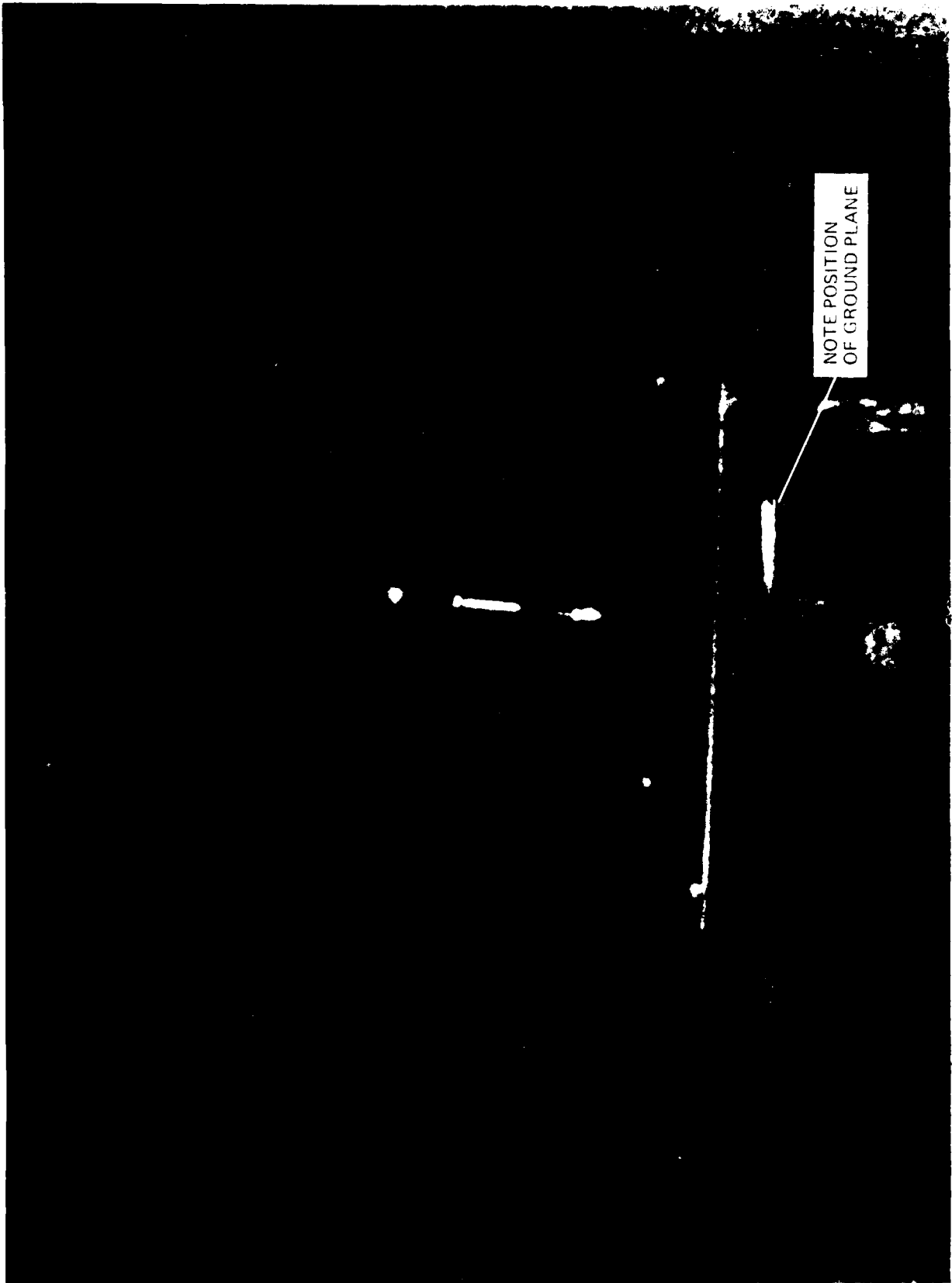
Figure 4-10a. Initiation of Ignition
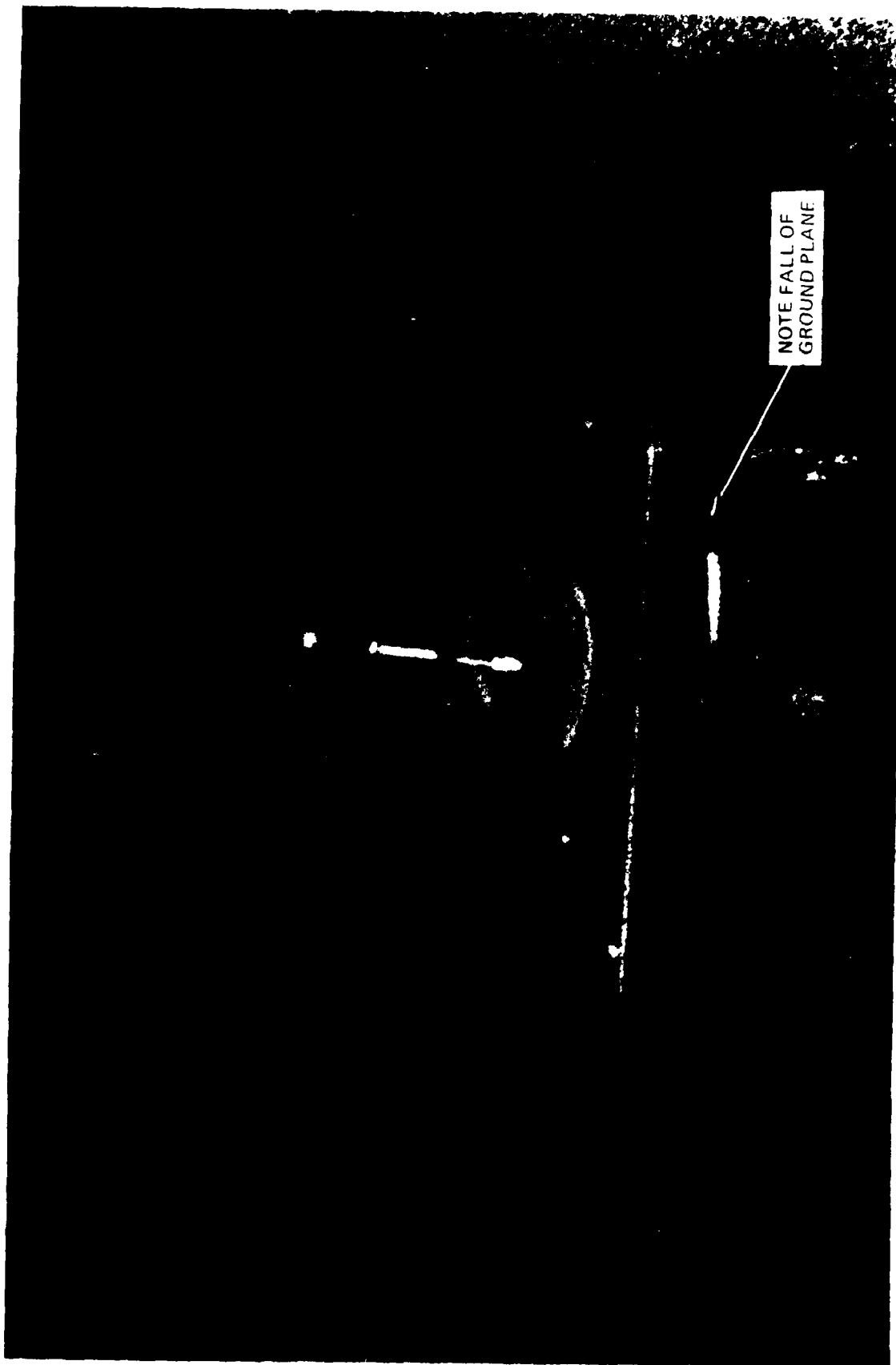
Figure 4-10b. Spreading Combustion Zone

NOTE FALL OF
GROUND PLANE
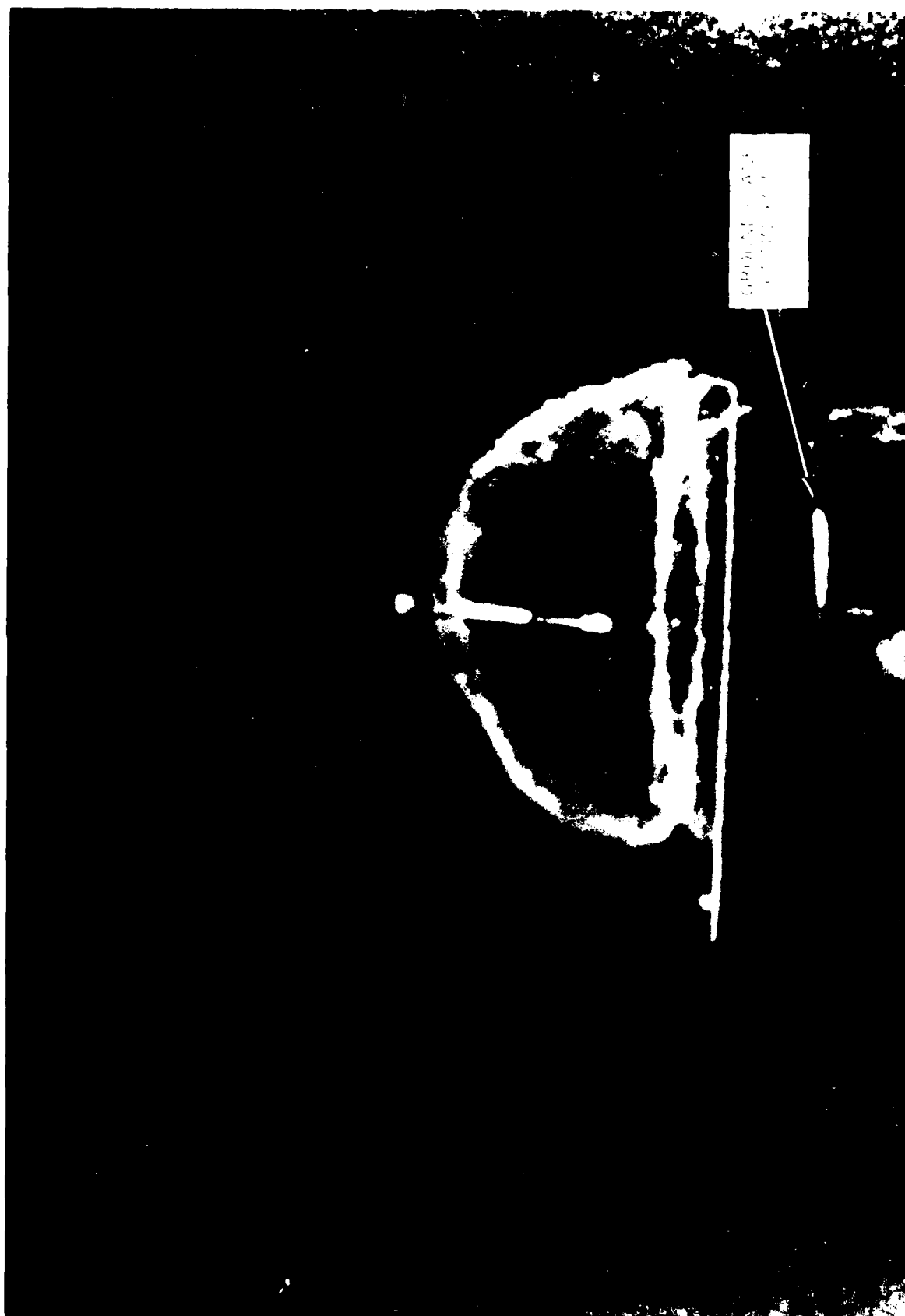
Figure 4-10c. Further Spread of Combustion Zone

threshold charge transfer, ignition becomes increasingly probable. As mentioned above and noted on tables of results, ignition tests were made using negatively charged specimens.

Varying the gap distance and discharger ball diameter produced a variety of results:

o With a plexiglas dielectric, a 0.5 inch diameter discharger, and a gap setting of 0.7, minimum charge transfer for ignition was 77.6 nC; the region of overlap in which ignition might or might not occur was ~ 20 nC (Table 4-2). When the gap setting was increased to 1.2 inches, the minimum observed charge transfer for ignition was 60.9 nC and the region of uncertainty increased to 160 nC (Table 4-2). In an effort to understand the cause of the zone of uncertainty, recall that more than one arc may occur in a given discharge. It is speculated that the cause of the uncertainty is related to the number of discrete arcs that occur in any given event. For a given level of charge transfer, the greater the number of arcs per event, the less the charge transfer per arc, and the weaker the associated bright arcs at the discharge ball. Multiple weak arcs probably have less likelihood of igniting a flammable mixture than one or two strong arcs, even though the total charge transferred may be the same. The minimum observed incendiary charge transfer would, following this line of reasoning, be associated with a single arc event.

o In plexiglas dielectric tests, with a one inch diameter discharger and a 0.7 inch gap setting, arcing of unknown intensity occurred as the discharger was rotated into position, prior to movement of the ground plate and setting the charge transfer measurement device. Because of the premature discharging with the 0.7 gap, the gap distance was doubled to 1.4 inches. However, little usable data was generated at this gap setting (Table 4-3). Intermediate gap settings of 1.0 and 1.2 inches proved to yield more meaningful data, as shown in Table 4-3. The minimum charge transfer for ignition was 47.9 nC, again with the possibility that a single arc was involved.

TABLE 4 – 2.

CHARGE TRANSFER AND IGNITABILITY RESULTS USING
PLEXIGLAS AND PROPANE FUEL WITH 1/2 INCH DISCHARGE BALL

NEGATIVE CHARGE POLARITY

GAP DISTANCE (IN)	0.7		1.2	
IGNITION?	YES	NO	YES	NO
TOTAL CHARGE TRANSFER (nC)	77.5	71.5	60.9	69.0
	88.0	72.7	67.2	69.9
	101.3	75.9	81.3	72.0
	113.9	77.6	91.3	75.7
	124.6	78.6	94.2	78.8
		87.6	97.3	80.1
		89.8	102.9	81.3
		96.9	106.5	81.3
			128.6	83.9
			128.9	86.9
			135.4	89.1
			141.3	93.0
			156.2	95.0
			158.7	107.4
			170.3	109.2
			191.1	136.3
			204.1	142.?
				150.0
				154.0
				156.9
				172.8
				188.9
				221.3

TABLE 4 – 3.
CHARGE TRANSFER AND IGNITABILITY RESULTS USING PLEXIGLAS AND PROPANE FUEL WITH 1 INCH DISCHARGE BALL

NEGATIVE CHARGE POLARITY

GAP DISTANCE (IN)	1.0		1.2		1.4	
IGNITION?	YES	NO	YES	NO	YES	NO
TOTAL CHARGE TRANSFER (nC)	47.9	52.5	53.8	50.8	55.8	55.2
	52.1	54.4	58.2	53.7	67.0	
	63.4	57.0	64.4	54.6		
	64.7	58.0	66.8	56.6		
	67.4	59.5	72.4	57.3		
			80.0			

o Preliminary testing with explosion suppression foam revealed that smaller gap distances (than with plexiglas) could be used without premature discharging. A gap distance of 0.5 inches was found to be near optimum for ignition testing with foam, based on results of preliminary tests.

o With explosion suppressant foam dielectric, a one inch diameter discharger and a 0.5 inch gap, the minimum charge transfer for ignition *of propane was very close to the 47.9 nC value for plexiglas* dielectrics (Table 4-4 and Figure 4-11). Sufficient data were obtained to conclude that the threshold ignition charge transfer with propane fuel is 46.5 nC, with an error estimated as ± 1 nC, independent of dielectric. The lowest measured charge transfer for ignition of JP-4S was about 65 nC (Table 4-5). However, absence of data between 43 nC, the maximum for non-ignition, and 65 nC, the minimum for ignition, indicates that the minimum charge transfer for ignition of JP-4 vapor may be less than 65 nC.

4.2.2.3 Summary of Tests on Incendiary Sparks

An experimental apparatus was developed which could electrically charge the surface of a dielectric material to a level sufficient to ignite combustible gas mixtures when discharged rapidly to ground. The studies were intended primarily to demonstrate that electrostatic studies could be conducted on explosion suppression foam specimens without using flowing fuel to charge the foam. The most significant finding was that the minimum charge transfer from a dielectric surface required to ignite an optimum propane/air mixture was less than 50 nC. This was first observed in tests with plexiglas and duplicated in tests on foam. Another significant finding was the range of uncertainty of the charge transfer that produced ignition -- some 30 nC. The uncertainty may be explained by photographs which reveal that the total charge transfer may result from either one high intensity arc, or from several lower intensity arcs. The test data indicate that the charge transfer required for ignition is lower for propane than JP-4S fuel. However, this is a preliminary conclusion since insufficient data were obtained to precisely determine the

TABLE 4 – 4.
CHARGE TRANSFER AND IGNITABILITY USING EXPLOSION
SUPPRESSANT FOAM AND PROPANE FUEL

TEST CONDITIONS : 1 ″ DIAMETER DISCHARGER BALL
1/2 ″ GAP BETWEEN BALL AND FOAM
1/4 ″ AND 1/2 ″ THICK BLUE FOAM AND
1/2 ″ THICK YELLOW FOAM SPECIMENS

IGNITION ?	YES	NO
TOTAL CHARGE TRANSFER (nC)	46.5	20.5
	49.4	27.1
	64.3	27.2
	74.4	29.5
		32.0
		32.9
		33.8
		35.0
		37.6
		42.5
		42.6
		46.5
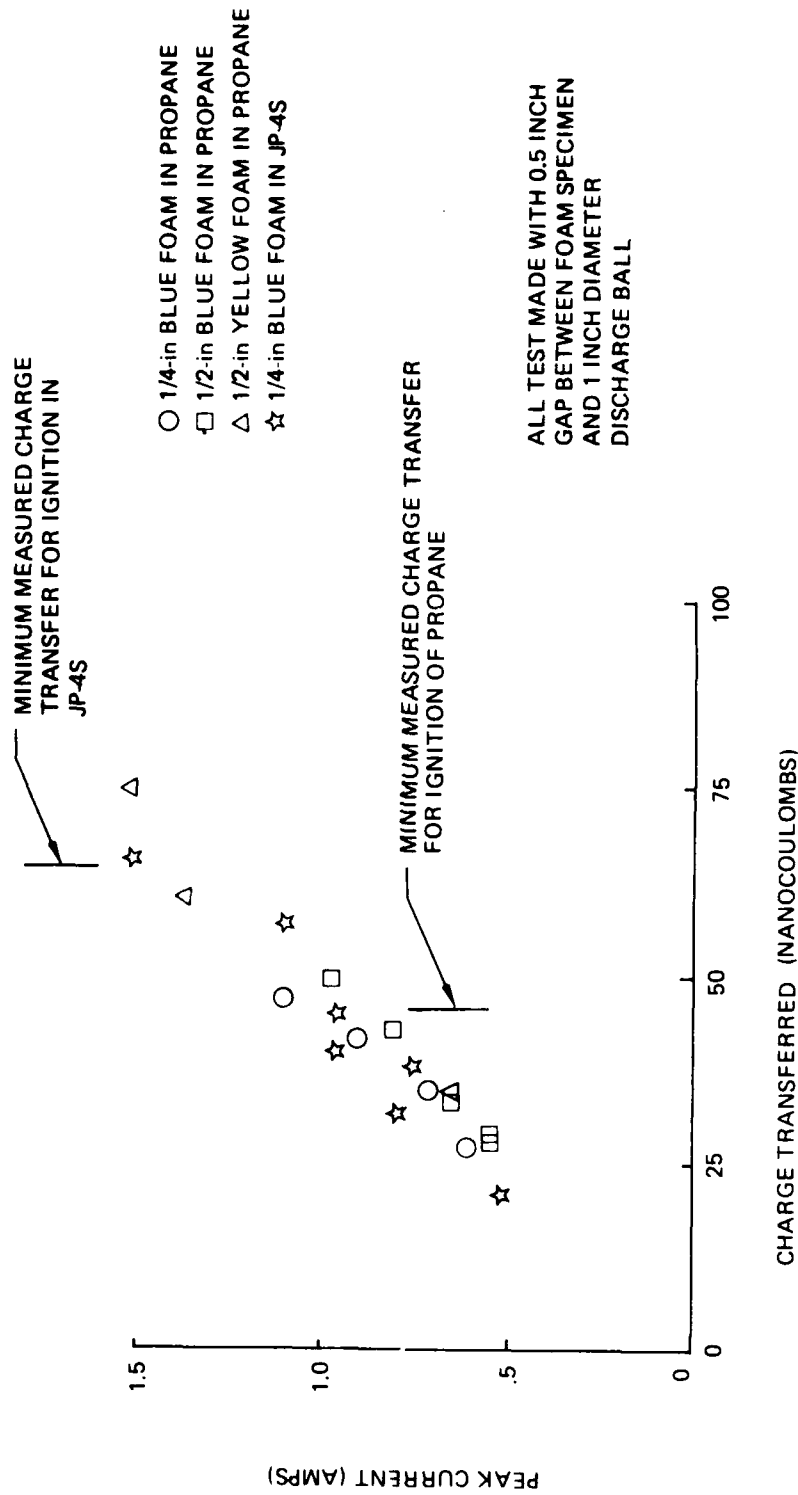
Figure 4-11. Ignition of Flammable Mixtures by Electrostatic
Discharges From Fire Suppressant Foams

75

TABLE 4 – 5.
CHARGE TRANSFER AND IGNITABILITY RESULTS USING
EXPLOSION SUPPRESSANT FOAM AND JP – 4S FUEL

TEST CONDITIONS : 1" DIAMETER DISCHARGER BALL
1/2" GAP BETWEEN BALL AND FOAM
1/4 " THICK BLUE FOAM SPECIMENS

IGNITION ?	YES	NO
TOTAL CHARGE TRANSFER (nC)	65.4	20.5
		24.3
		24.6
		29.8
		30.4
		32.0
		32.3
		33.4
		33.8
		34.5
		34.6
		35.2
		37.6
		43.0
		43.2

minimum charge transfer for JP-4S fuel; neither was the optimum JP-4S/air mixture ratio clearly established. An optimum propane/air mixture was relatively easy to load in the test chamber, but JP-4S was injected as a liquid and small variations in mixture ratio were difficult to control.

Other observations were that the minimum charge transfer for ignition decreased with the larger diameter discharger balls but the data on the effect of gap width were inconclusive. The results for the different diameter discharge balls may be interpreted by the well known inverse relationship between radius of curvature and voltage level required to produce arcing; sharp points require the lowest discharge voltages. The effect of radius of curvature of the discharge surface on the electrostatic ignition hazard is a contentious issue. Although sharp points result in arcing at lower voltages, the discharge intensity may be harmlessly low. In fact, some have suggested deliberately utilizing sharp pointed objects to neutralize charges before high voltage, high intensity discharges occur. (See Section 2.1.3 for additional discussion of sharp pointed electrodes.) The scope of the current study did not allow a systematic study of radius of curvature of the discharge surface. Since the one inch diameter ball was considered representative of realistic fuel tank components and resulted in lower charge transfer for ignition than the 1/2 inch ball, the one inch ball was used for the ignition tests on the explosion suppression foams. An explanation of the sensitivity of the gap width to charge transfer for ignition would have required extensive experiments on the sparking phenomena and was also beyond the scope of this study.

4.3   CHARGE RELAXATION TIMES OF VARIOUS EXPLOSION SUPPRESSANT FOAM MATERIALS

The ability of charges to migrate through explosion suppressant foam to ground determines the time required to bleed off accumulated charge, and determines the minimum charging rate necessary for charge accumulation. Three characteristic times were measured during a series of experiments:

o   rise time -- the time required for the charge migrating into the foam to reach 90% of the final attained value of voltage

o   decay time -- the migration time required for the charge on the foam to
    decrease to 10% of the initial charging voltage

o   relaxation time -- the time required for the charge on the foam to
    decrease to 1/e (37%) of its value

The charge was measured indirectly by observing the foam potential as sensed
by an electrostatic voltmeter. The preponderance of charge migration time
tests were conducted in an uncontrolled relative humidity environment (43% to
70%).

4.3.1 Test Setup

The test configuration used to measure the characteristic times of the
different foams is shown in Figure 4-12. A two-inch thick layer of
reticulated foam was placed on an aluminum charging plate which was isolated
from ground by a one-inch thick sheet of Teflon and a 24-inch thick piece of
styrofoam. An electrostatic field sensor (Monroe probe model 1015A mounted
inside a gradient adapter K1009A/22D) was located 2 inches above the foam
surface. Digital multimeters were used to monitor the input and output of the
Monroe 166 electrostatic voltmeter. A Gould model 110 recorder was used to
obtain stripline recordings of the foam surface potential.

The D.C. potential to the aluminum plate was supplied by a Voltronics D.C.
voltage supply. To ensure that the voltage supply was stable and precisely
measured, the voltage to the plate was monitored with a Keithley Model 1600
high voltage probe and a digital multimeter.

4.3.2 Procedure

The electrostatic field sensor was zeroed by placing a thin sheet of grounded
aluminum on the top surface of the reticulated foam. After careful adjustment
of the balance and zero controls, the aluminum plate was removed from the foam
surface. Figure 4-13 shows the stability of the zero line after the aluminum
sheet was removed from the foam surface, and indicates that, during typical
measurement times, the sensor was not influenced by the external environment.
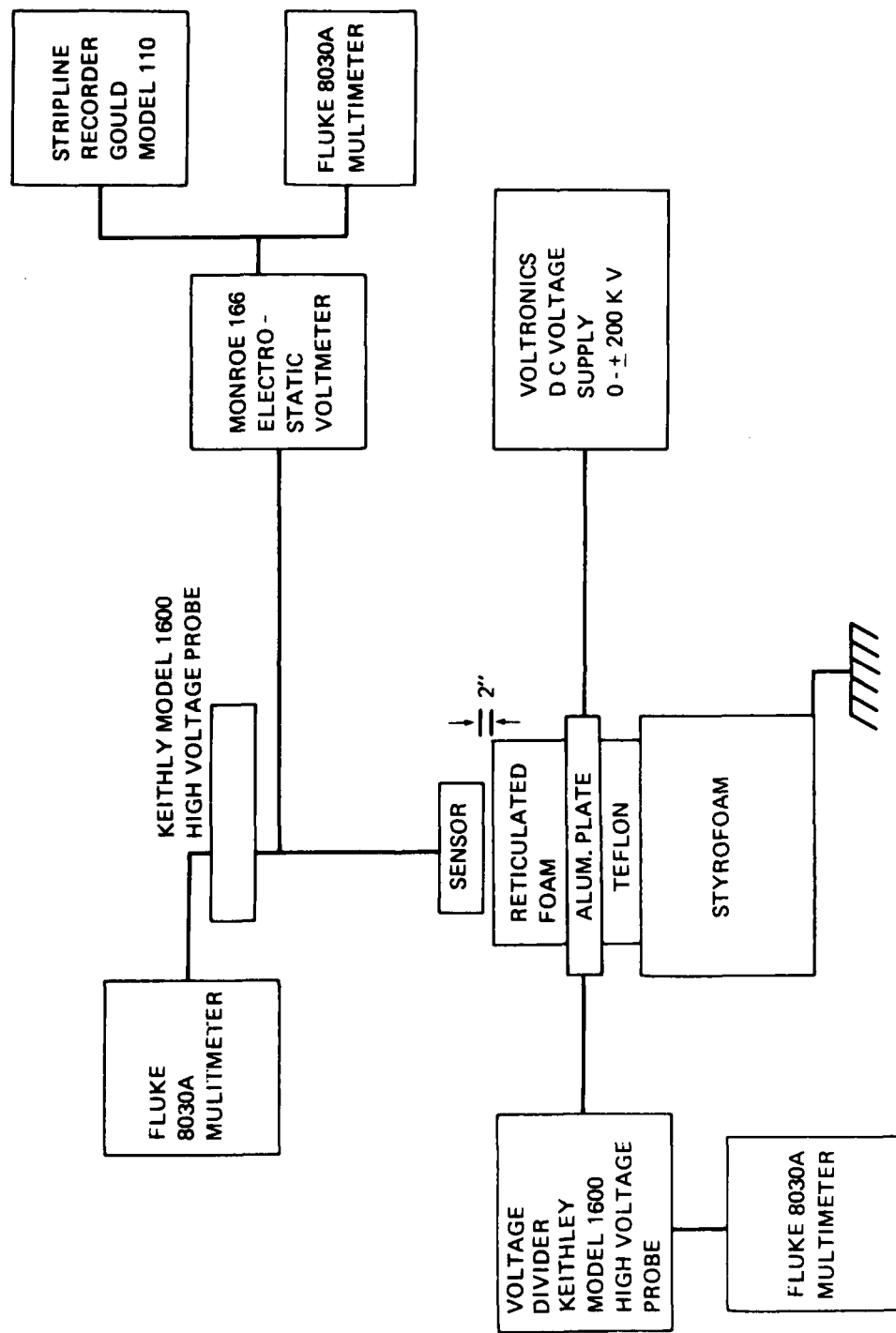
Figure 4-12. Test Configuration for Measuring Relaxation Rate of Foam

Relative Humidity = 56%
Sensor Height = 2 Inches

TIME (MINUTES)

ZERO
LINE
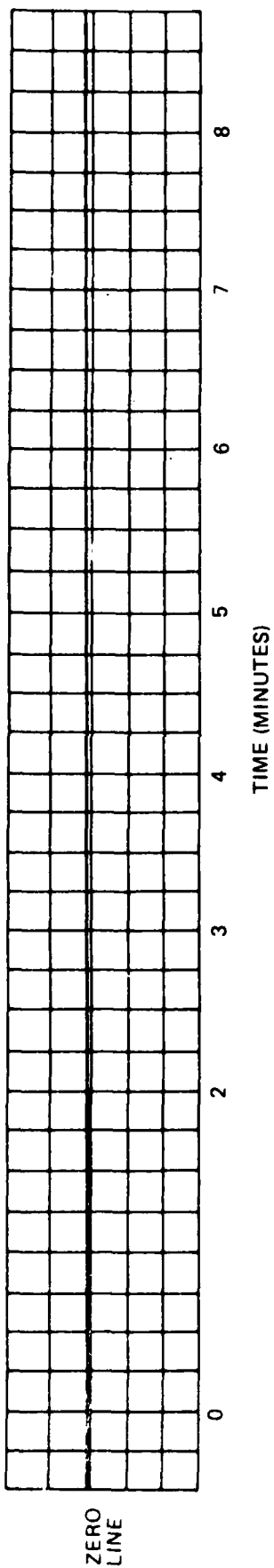
Figure 4-13. Stability of Instrumentation

Tests were conducted by applying a constant potential to the aluminum plate and monitoring the surface potential of the foam. When the surface potential stabilized at its maximum value, the power supply was turned off and the aluminum plate was grounded. The surface potential was then monitored until it returned to zero.

4.3.3. Results

Figure 4-14 is a typical stripline recording of potential variation with time when a charging voltage was applied to the aluminum plate. The curve depicting the rise of potential shows two rates of rise:

o the initial steep rate which represents the charging rate of the aluminum plate-insulator capacitor system

o a slower rate, which represents the migration of charge into the explosion suppressant foam.

The decay measurements displays a similar variation:

o an initial rapid decrease of voltage, due to the discharge of the aluminum plate-insulator capacitor

o a slower rate of decrease, which represents the migration of charge from within the foam to ground.

Since the migration times are sought, only the slowly varying voltage data was studied.

Table 4-6 gives the results of computations based on the observed rates of charge and discharge of the foam. As the charging voltage is changed from positive to negative, the data show that the migration rates change. The differences in the characteristic times from foam to foam reflect the variations in conductivity which have been measured between different types of foam; evidently, blue foam has the lowest conductivity. Assuming a fuel with very low conductivity, and given equal charging rates during fueling of an airplane, the airplane with blue foam in its fuel tanks would charge most

TEST CONDITIONS:

RELATIVE HUMIDITY = 56%
SAMPLE THICKNESS = 2 INCHES
CHARGING VOLTAGE = -20 KV
SENSOR HEIGHT = 2 INCHES
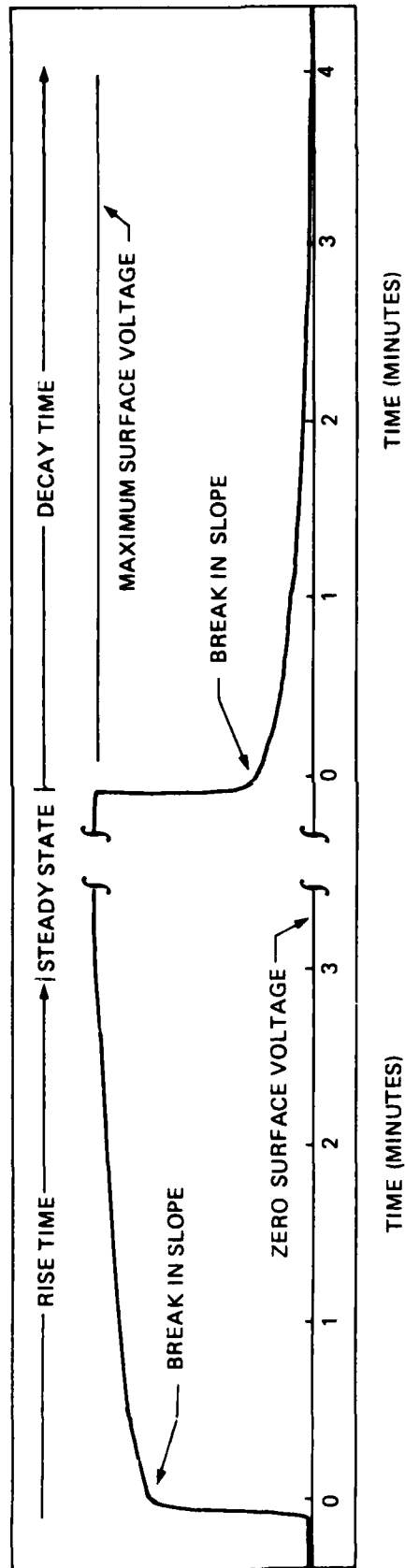
Figure 4-14. Charging and Discharging Characteristics of Blue Foam

TABLE 4 – 6.
APPROXIMATE RISE, DECAY, AND RELAXATION
TIMES OF RETICULATED FOAMS

FOAM TYPE	POTENTIAL ON PLATE	RISE TIME (SEC)	DECAY TIME (SEC)	RELAXATION TIME (SEC)
BLUE	-20 KV	150	210	50
BLUE	+20 KV	240	150	45
ORANGE	-20 KV	4	4	1
ORANGE	+20 KV	15	15	2
RED	-20 KV	6	6	1
RED	+20 KV	14	10	1.5

rapidly to high voltage, presenting a greater electrostatic hazard. The problem is compounded if fuel impinging on blue foam has a greater charging tendency, as appears to be the case.

4.4   MEASUREMENT OF IGNITION ENERGY, METALLIC ELECTRODES

The accuracy of measurement of the minimum ignition energy for the single arc which forms between metal electrodes was discussed in Section 4.2.1.1. The problem centers on the assessment of the energy actually dissipated in the arc, given a knowledge of the energy stored in an external lumped capacitor (see Figure 4-4). The concern is that, given the usually accepted criterion of 0.2 millijoules for ignition, designers usually limit the capacitance of isolated conductors in fuel tanks such that the maximum stored energy is 0.02 mj at breakdown voltage, providing a supposed tenfold safety margin. If, as has been suggested, the minimum ignition energy is actually 0.1 mj (or worse, 0.05 mj) the design margin of safety is much reduced.

The best measure of minimum energy for an incendiary spark involves the simultaneous measurement of the time varying voltage V(t) voltage across and current I(t) through the gap, and the computation of gap energy by integrating the voltage-current product over the event time (Δt):

$$E_{GAP} = \int_{\Delta t} I(t)\ V(t)\ dt$$

It appeared that the use of matched transmission lines might permit simultaneous current and voltage measurement, and an apparatus was designed and manufactured in pursuit of this goal. A schematic drawing of the final form of the test layout is shown in Figure 4-15. The impulse generator transmitted a double exponential voltage waveform (Figure 4-16) of 2 nanoseconds risetime and 60 nanoseconds duration through a 50 foot long, 50 ohm transmission line. The voltage pulse then entered a tapered 50 ohm transition section, leading into a 3-inch diameter section of 50 ohm rigid brass transmission line (Figure 4-17). The inner conductor of the 3-inch transmission line was interrupted to form a gap over which a spark could be

Figure 4-15. Minimum Ignition Energy Test Apparatus
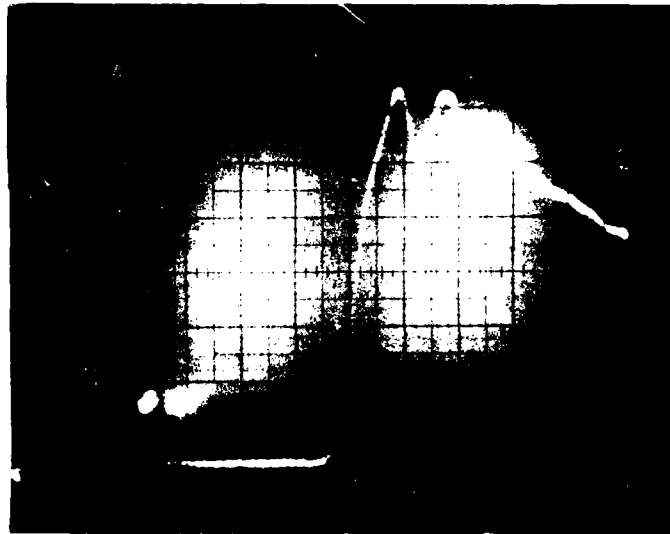
2 nsec/div
5 volt/div
(REDUCED SCAN MODE)

a. EXPONENTIAL VOLTAGE RISE

10 nsec/dev
5 volt/div
(REDUCED SCAN MODE)

b. EXPONENTIAL DECAY

Figure 4-16. Voltage Output Waveform From Pulser

86
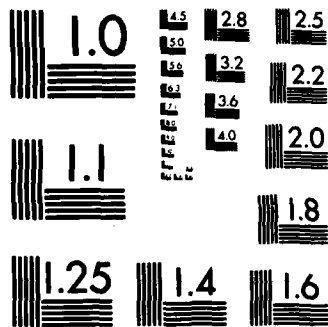
MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A
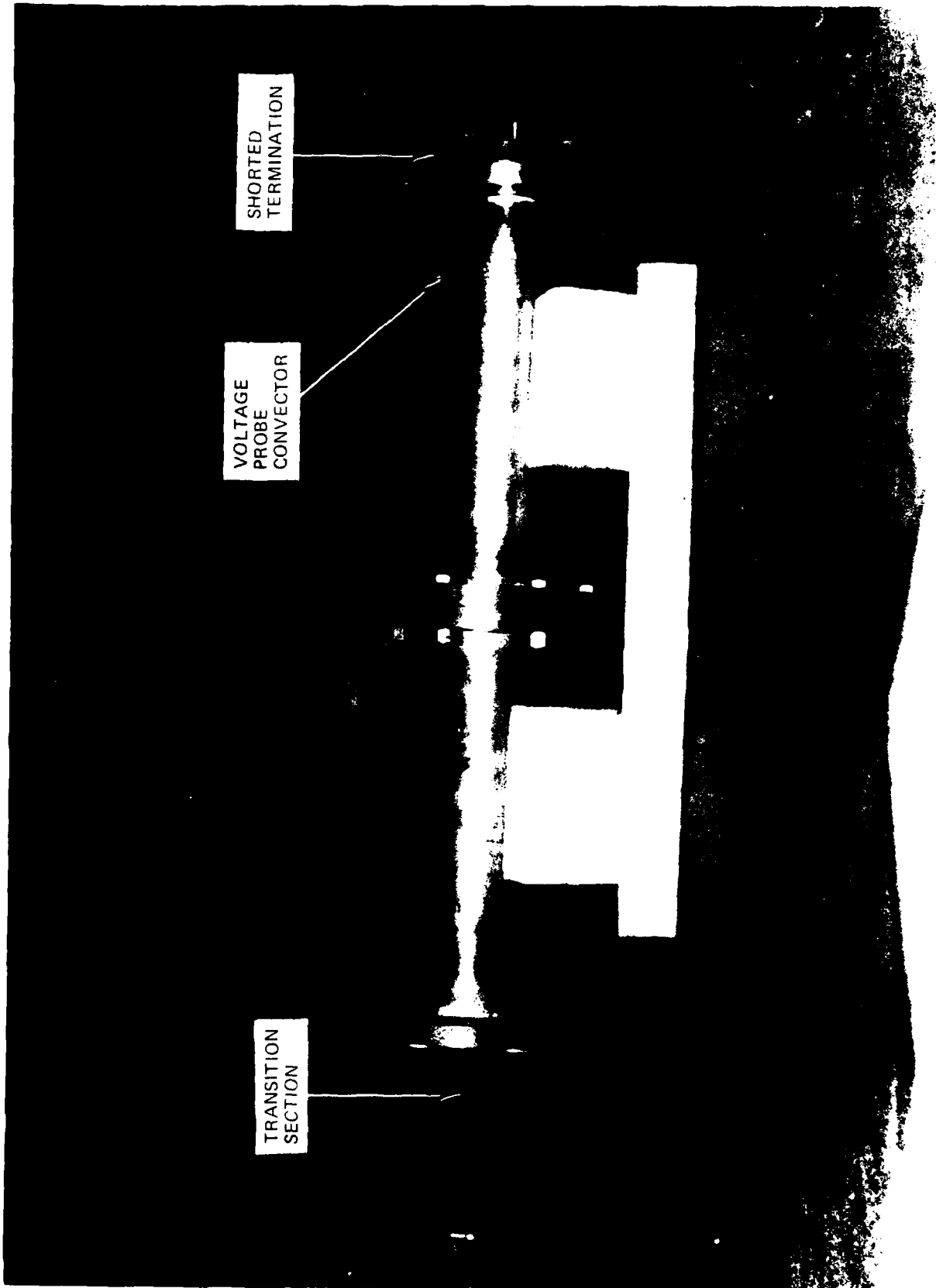
Figure 4-17. Ignition Test Section Fabricated From Transmission Line

formed. The downline inner conductor was shorted to the outer conductor and threaded into the terminal shorting section to permit adjustment of the gap width. The rigid section, when filled with a combustible mixture, formed a bomb for the minimum ignition energy experiment. In the developmental version of the device used for checking out instrumentation, the gap was bridged by a one ohm resistor to simulate the resistance of the gap after the arc was formed.

4.4.1 Gap Current Measurement

The actual current waveform across the gap was measured by sensing the time varying magnetic field induced by the gap current. The $\dot{B}$ sensor consisted of a 10 mm diameter loop whose output was integrated and stored as current vs time in a storage oscilloscope. Figure 4-18 shows the $\dot{B}$ sensor output in its original (Figure 4-18a) and integrated (Figure 4-18b) versions. It can be seen that the integrated current waveform corresponds well to the pulser waveform of Figure 4-16; the negative spike to the far right of Figure 4-18b is spurious, and is due to pulser shut-off characteristics.

4.4.2 Gap Voltage Measurement

Two methods were proposed to measure voltage across the gap. In the first, a direct connection was made to the inner electrode using the center conductor of a coaxial cable; the voltage difference to ground was attenuated and then recorded on an oscilloscope. Figure 4-19 shows the measured voltage waveform using the direct connection technique. Analysis on an equivalent transmission line shows that the exponentially decaying waveform is predominantly the time varying voltage across the one ohm resistor. The high frequency oscillations which overlay the first wave packet were analyzed as due to a complex coupling of the electric field in the chamber and the conduction current through the resistor bridging the gap. The second wave packet is a damped reflection from the shorted end of the transmission line. This damped reflection could have been eliminated by inserting a delay line between the downstream gap electrode and the shorting section, but the voltage measurement would then have required a connection to both sides of the gap, possibly aggravating the oscillation problem.

ONE OHM BRIDGING RESISTANCE
Loop Dia. = 10 mm (Sensor Uncalibrated)
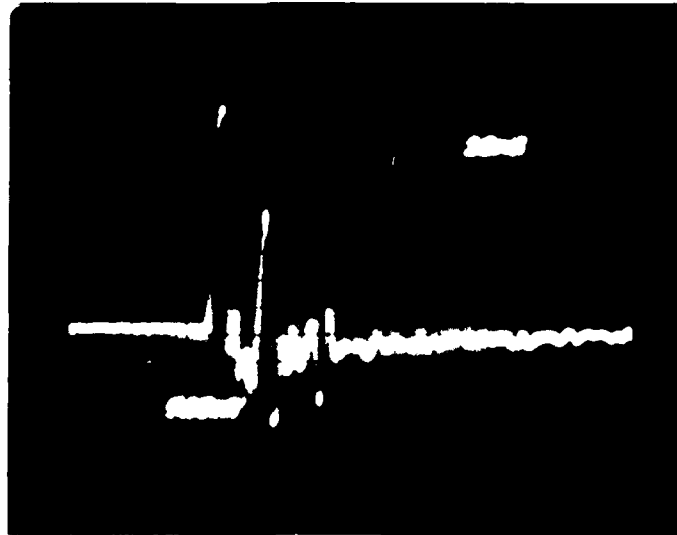
10 nsec/div
500mV/div

(a.) Ḃ. RECORDING

10 sec/div
5 mV/div

(b.) INTEGRATED Ḃ MEASUREMENT

Figure 4-18. Waveform From Ḃ Current Probe

MEASURED THROUGH A 40 db ATTENUATING NETWORK
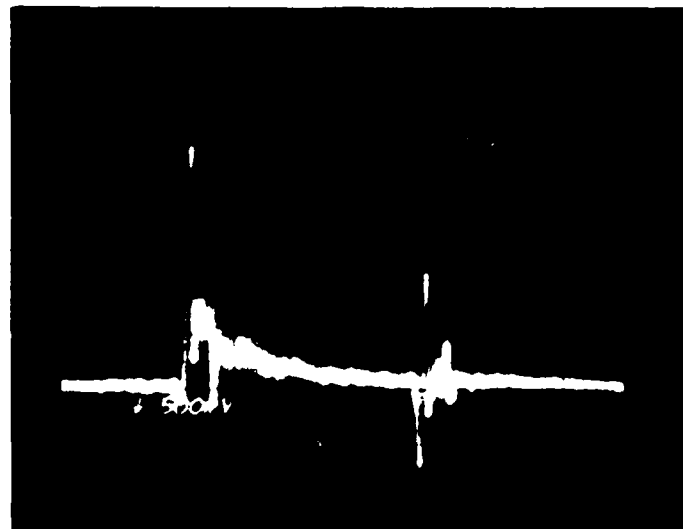
20 nsec/div
500 mV/div

*Figure 4-19. Voltage Across a One Ohm Bridging Resistance Using
the Direct Connection Technique*

The E-field sensor waveform recorded is shown in Figure 4-20. Unfortunately, the recorded voltage waveform does not provide sufficient resolution for determining the gap voltage versus time.

4.4.3 Interruption of Experiment

Although the measurement of current appeared practical, there was no clear indication that near term success was likely in the measurement of voltage. The direct connection voltage measurement appeared to have the most promise, but because of the perceived difficulties, the experiment was terminated. However, it appears that a technique such as proposed offers the best method for an actual accurate measure of minimum ignition energy in arcs between metal electrodes.

NOTES:
- Disk Dia. = 1.5 inches
- Reduced Scan
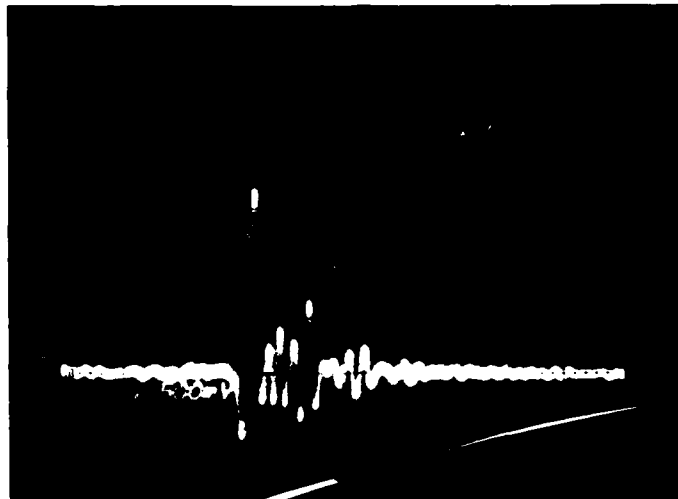
10 nsec/div
500mV/div
(a.) E FIELD RECORDING
(DIFFERENTIATED VOLTAGE WAVEFORM)
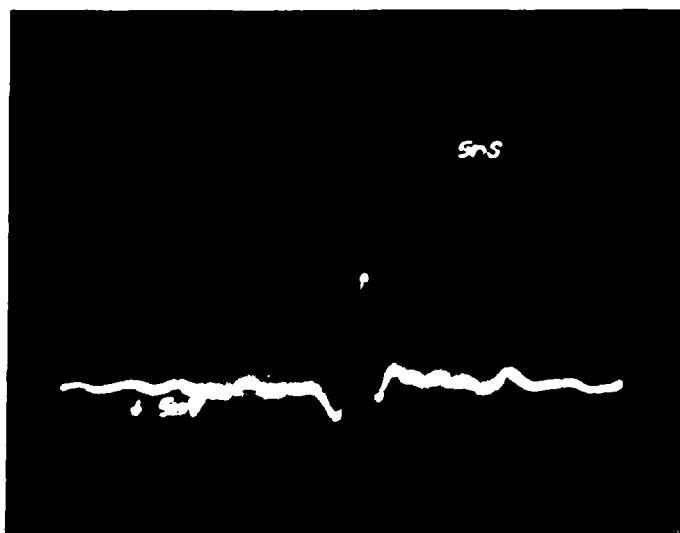
5 nsec/div
5mV/div
(b.) INTEGRATED VOLTAGE WAVEFORM

Figure 4—20. Voltage Across a One Ohm Bridging Resistance Using an E—Field Sensor

5.0 FUEL INLET NOZZLE DESIGNS

Ample evidence exists to prove that the electrostatic charging of explosion suppressant foam is heavily influenced by the method of discharging fuel into the tank. The worst design is a high velocity jet which impinges directly on the foam at the top of the tank. Conversely, discharging the fuel with low velocity at the bottom of the tank with no foam impingement is the best design. One task of this contract was to design and build inlet nozzles which the Air Force could test in their Fuel Tank Electrostatic Simulator (FTES) facility. Originally, three conducting and three non-conducting nozzles were specified. Later, it was decided to reduce the effort to include just two conducting nozzles.

The two inlet nozzles selected for design and manufacture were a piccolo tube type and a diffuser type. The piccolo tube concept is in practical use in a number of military and commercial airplanes. The type of diffuser nozzle developed has not been used in aircraft to the author's knowledge. The piccolo tube nozzle had eight oulets cut in the side of the supply tube whose diameters were about half the supply tube diameter. This resulted in a velocity reduction of roughly a factor of two from the supply tube velocity. The diffuser type inlet nozzle is a device which turns the flow 90° in order to take advantage of the large flow area increase which accompanies an increase in radius. This nozzle had a geometrical area increase of about 4 but viscous effects reduced the actual flow area increase to about a factor of 3.

5.1   PICCOLO TUBE INLET NOZZLE

The design presented for the piccolo tube inlet nozzle is based on a combination of solutions from a Boeing fuel system analysis program (P178) and hand calculations. The P178 program solves flow rates and pressure losses in a flow network by simultaneous solution of the governing flow equations.

93

However, the program does not include loss coefficients for "side branch" orifices inherent in a piccolo tube design. User defined loss coefficients are allowed but an iteration on hole sizes was still required. Specifying side branch orifice loss coefficients is complicated by the absence of directly applicable experimental data.

The first design step was to establish the tubing diameter. Tubing diameters considered were restricted to sizes commonly found in aircraft fuel systems. Initially, a 2-inch diameter was considered because it is a widely used size. However, the resulting flow rates were considered excessive, since the filling time for a 500 gallon tank would have been about 2 minutes. The next smaller size which is fairly standard is a 1-1/2 inch diameter tube. This size was selected as the best compromise between flow rate and commonality with aircraft systems. Note that the flow rate in the 1-1/2 inch diameter tube would be about half that in a 2-inch diameter tube for the same velocity.

The next step was to select the number of outlets in the piccolo nozzle. In this process it was assumed that the piccolo tube diameter was constant and that the hole diameter should not be greater than about 50% of the tube diameter. Since the area changes as the diameter squared, at least 4 holes would be required to equalize inflow and outflow velocities. On this basis, 8 holes were selected to achieve a factor of 2 decrease in velocity, and match the ratio of maximum network velocity to maximum exit velocity established in the ground rules discussed above.

Other design features included (1) a 13-inch long vertical tube terminated by a standard AN coupling to connect to the fuel line in the AFWAL electrostatics test facility, (2) a 90° bend with a bend radius to tube diameter ratio of 2 to turn the flow from vertical to horizontal and (3) a 26-inch long horizontal piccolo section containing the outlet holes spaced on 3-inch centers. The length of the horizontal segment was dictated by the length available in a composite tank to be used for electrostatic tests.

94

Since loss coefficients for side branch orifices were not known precisely, several approximate approaches were tried. One assumed that each piccolo hole could be treated as a tee fitting with a zero length 90° leg which was terminated by an orifice plate. Since the computer program treats tee losses and wye losses slightly differently, this approach was repeated assuming wye fittings at each hole. A third approach assumed that each hole could be treated as an in-line orifice at the end of a tube. In each approach the set of hole diameters was adjusted by iteration such that the flow rate from each outlet was similar and the maximum exit velocity was less than 10 feet per second.

These solutions provided useful information on approximate hole diameters and pressure losses through the network. However, none of the solutions yielded totally satisfactory results and hand calculations were used to finalize the set of hole diameters for the piccolo tube design.

The in-line orifice approximation yielded the most credible results from the P178 program and is the approach which has been used for Boeing piccolo tube inlet nozzles. Hence, this technique was selected for the final piccolo tube design. The logic for this selection follows. The ratios of hole diameters to tube diameter lie between the corresponding ratios for two limiting cases. If the hole diameters are much smaller than the tube, the tube becomes analogous to a large reservoir supplying several small outlets. In this case, the momentum in the tube is negligible and the total pressure at each outlet would be about the same. The converse is the situation where the hole diameters are comparable to the tube diameter. Here the upstream momentum is very significant and substitution of an in-line orifice for a side branch orifice would probably be invalid. Although the ratio of internal flow to outflow decreases at each successive hole in the current design, there is a corresponding decrease in upstream momentum. Hence, the in-line orifice approximation was judged best.

Data for in-line orifice flow coefficients are often given in terms of Reynolds number and the ratio of orifice diameter to pipe diameter. However, since the in-line orifice model is only an approximation, a constant flow coefficient of 0.61 was used. This is consistent with other Boeing piccc'o tube designs. Furthermore, the Reynolds number and diameter ratio are only second order effects. The loss coefficient, which is the proportionality constant between pressure loss and dynamic pressure, is the inverse of the flow coefficient squared.

A hand calculation was used to establish the set of hole diameters for the final design. The flow rate upstream of the first hole in the piccolo tube was assumed to be 110 gallons per minute which corresponds roughly to 20 feet per second. Another goal was equal flow rates from each hole. The pressure loss as a function of flow rate between each pair of holes was determined from the P178 program. The calculation procedure was begun at the last hole. A hole diameter was assumed and the orifice pressure loss for 1/8 of the total flow in the supply tube was computed. Subsequently, the pressure at each preceding upstream location was found by adding the friction loss between holes to the pressure at the downstream hole. With the pressure known and the flow rate specified, the area for each orifice was found from

$$A_o = \dot{m}(k/2\rho\Delta p)^{1/2}$$

where

A_o = orifice area
$\dot{m}$ = mass flow rate
k = loss coefficient (2.69)
ρ = density
Δp = tube pressure minus atmospheric pressure

When the area for the most upstream hole (the hole with the highest velocity) was determined, the corresponding average velocity was computed. If this

velocity was not approximately 10 feet per second, a new area for the most downstream hole was assumed and the calculation procedure repeated. The final piccolo tube inlet nozzle design is shown in Figure 5-1.

5.2   DIFFUSER INLET NOZZLE

The diffuser inlet nozzle was designed to mount vertically in a fuel tank as shown in Figure 5-2. The nozzle consists of an upper and lower flow guiding surface. The upper surface is similar in shape to a bell-mouth or trumpet type inlet. However, the direction of flow is reversed from that common in these inlets. The bottom surface serves to provide a relatively linear growth in flow area and uniform internal velocity profiles. A primary advantage of this type of inlet is that the flow area increases as the square of the diameter, which offers a large potential for velocity diffusion. The diffuser design details are shown in Figure 5-3.

The upstream section of the diffuser was made from a length of standard 1-1/2 inch diameter aircraft aluminum tubing and was terminated with a standard AN coupling. This provided commonality with the piccolo tube inlet nozzle.

The design was based on results from the Boeing flow field solution program P318. This program predicts surface and flow field pressure coefficients for two-dimensional and axisymmetric flows in such devices as inlets, nozzles and ducts. The solution is obtained by dividing the flow field into a curvilinear network composed of lines of constant velocity potential and stream function. The flow field is then solved numerically using a successive line relaxation process. The program also includes a boundary layer solution which solves a set of momentum, energy and continuity equations by a finite difference method. Both laminar and turbulent boundary layers can be analyzed with transition at a predefined or a calculated location. The boundary layer displacement effect is incorporated by bleeding flow at the walls such that the mass flow defect is simulated.

FUEL IN

STANDARD AIRCRAFT
TUBE FITTING

1 ½ " DIA TUBE

13"

3" SPACING
TYPICAL

END CAP

90° BEND
BEND RADIUS =
TUBE DIA. X 2

0.747   0.764   0.777   0.787   0.794   0.798   0.800   0.801

EXIT HOLE DIAMETERS

26"
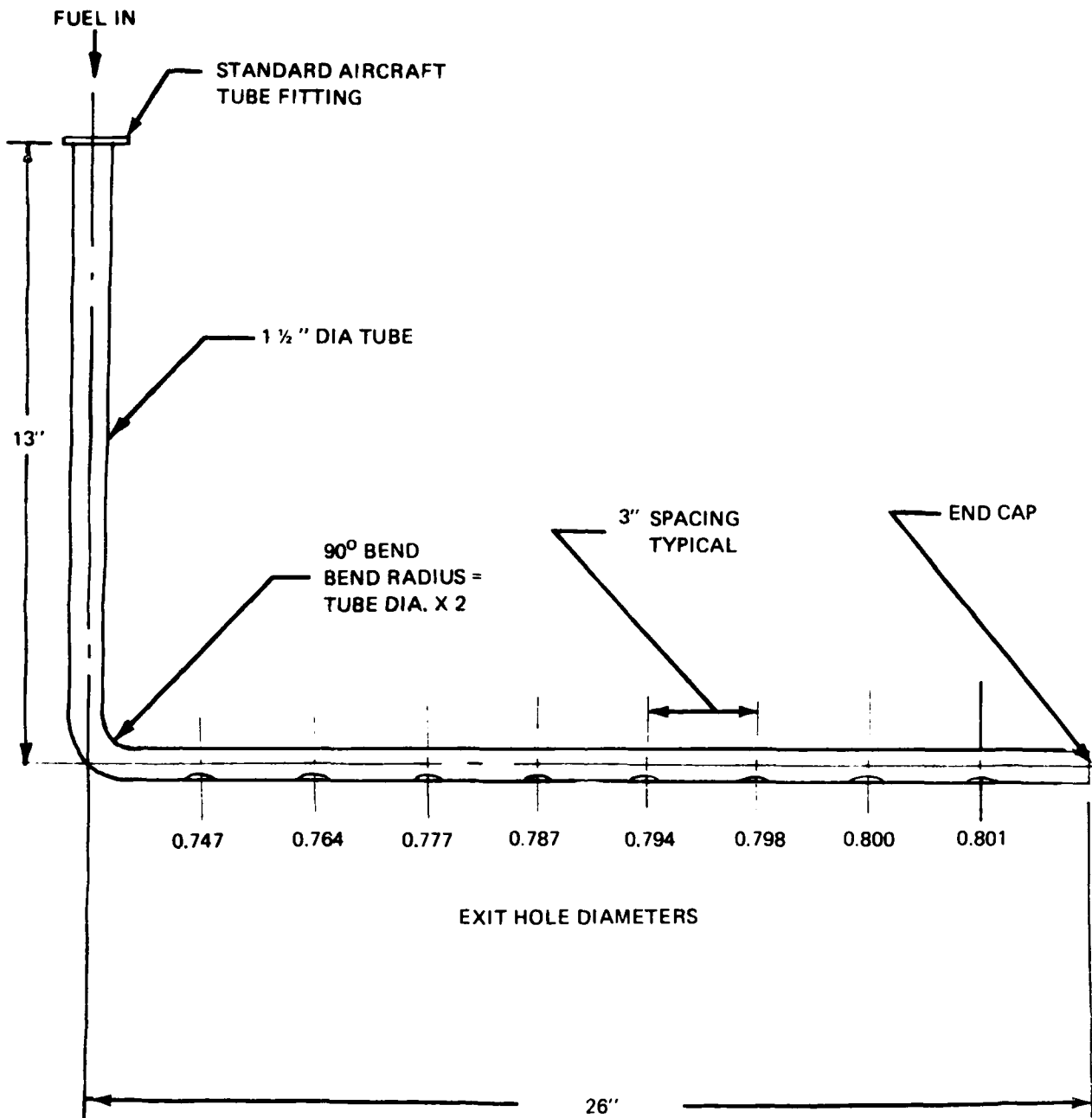
Figure 5-1. Piccolo Tube Inlet Nozzle Design

FUEL IN

TEST TANK

AN STANDARD
FITTING

DIFFUSER INLET NOZZLE

FUEL OUT
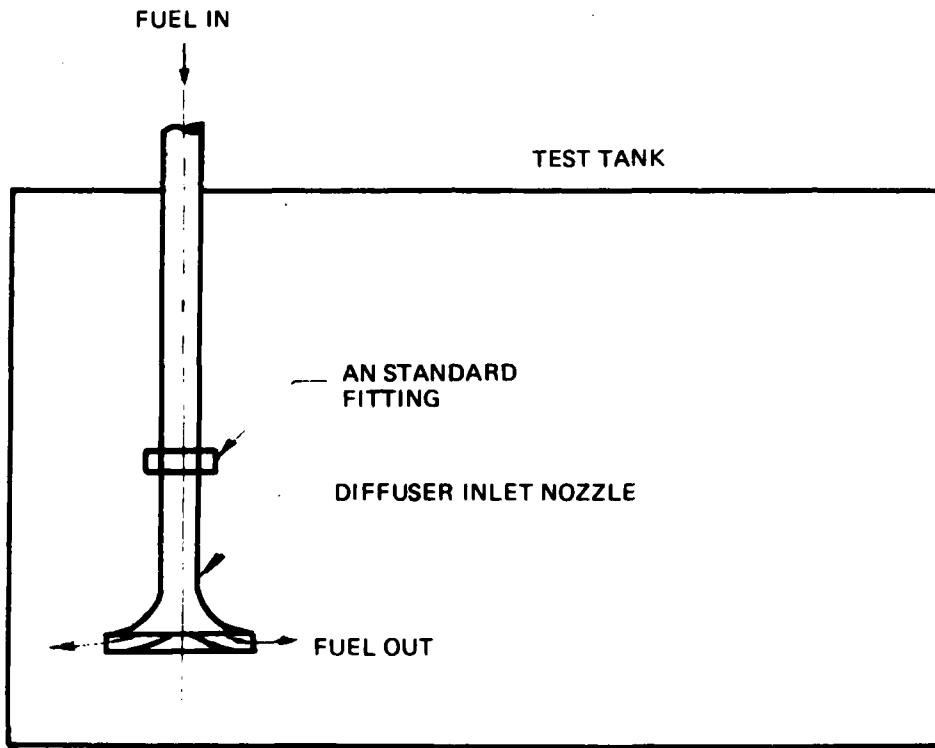
Figure 5-2. Diffuser Inlet Nozzle Installation

99

NOZZLE WALL COORDINATES

LOWER (CONCAVE) SURFACE

X	R
0	0
12.175	0
12.555	0.176
12.768	0.634
12.861	0.932
12.897	1.233
12.916	1.397
12.935	1.559
12.953	1.714
12.976	1.925
13.000	2.250

UPPER (CONVEX) SURFACE

X	R	X	R
0	0.701	11.393	1.047
10.156	0.701	11.510	1.127
10.300	0.704	11.630	1.219
10.445	0.720	11.745	1.322
10.583	0.734	11.853	1.438
10.727	0.767	11.935	1.534
10.864	0.803	12.032	1.668
11.002	0.853	12.082	1.750
11.138	0.910	12.156	1.870
11.265	0.972	12.264	2.079
		12.340	2.232

NOTE: UPPER SURFACE COORDINATES ARE INSIDE DIMENSIONS FOR A 1 ½ INCH DIAMETER TUBE WITH A 0.049 INCH THICK WALL

CALCULATED POINT FROM POTENTIAL FLOW PROGRAM (TYP)

NOZZLE EXIT

AN STD FITTING FOR 1 ½ INCH DIAMETER ALUMINUM TUBING

FLOW

AXIAL DISTANCE, X ~ INCHES

RADIAL DISTANCE, R ~ INCHES

3.0   2.0   1.0   0

9.0   10.0   11.0   12.0   13.0

Figure 5-3. Diffuser Inlet Nozzle Design

The initial approximation in the design process was to specify circular arcs for the convex portion of the upper wall and for the lower wall contour, producing a fairly linear area growth. The resulting flow field solutions revealed unacceptable large velocity non-uniformities. The next step was to improve the uniformity of the potential flow by changing the curvature on the upper and lower surfaces. The convex portion of the upper wall was changed from a circular arc to a surface which had an increasing radius of curvature with distance. Conversely, the radius of curvature on the lower surface was decreased. The flow uniformity improvement achieved was significant and sufficient to justify proceeding with boundary layer analyses.

Preventing or minimizing boundary layer separation is a very difficult aspect of diffuser design. Since adverse pressure gradients are inherent in the velocity diffusion process, the tendency for boundary layer separation is strong. In some cases vortex generators are required to avoid large scale separation. The inside or convex surface of a curved flow channel is especially susceptible to separation because of centrifugal forces combined with adverse pressure gradients. For this reason the flow area often is held constant in bends. In the present diffuser design, allowance was made for a degree of flow separation by making the geometrical area larger than required to obtain the required velocity decrease.

The boundary layer calculations were based on a Reynolds number of 500,000 per foot. Fuel flowing in a channel at room temperature at 20 feet per second would have a Reynolds number per foot of about 1 million. Choosing a lower value provides a conservative prediction of separation, i.e., the predicted separation point tends to move upstream with decreasing Reynolds number.

With the second design, attached flow was predicted on the lower surface all the way to the nozzle exit. However, separation was predicted on the upper surface about half way around the convex surface. Further contour modification was not attempted as the probability of completely avoiding analytically predicted separation was considered quite low. Furthermore, the

101

actual separation point is often downstream of the predicted point. The likelihood of separation did cause a reduction of the exit diameter, since the occurrence of separation would render the upper guiding surface ineffectual; the diameter was reduced from 6 inches in the original design to 4-1/2 inches in the final design.

5.3   RESULTS

Designs for piccolo tube and diffuser fuel inlet nozzles were completed. Both nozzles were designed to couple with a standard 1-1/2 inch diameter fuel fill line by means of a standard AN fitting. The piccolo tube nozzle design was based on an in-line orifice model to simulate the side branch orifices in the actual piccolo tube. The piccolo tube section has 8 holes, each designed to have the same flow rate. The diffuser inlet nozzle was designed to turn the flow 90° while reducing the velocity by more than a factor of 2. The design was developed from potential flow and boundary layer solutions.

Design ground rules prescribed a maximum exit velocity of 10 feet per second for a 20 feet per second velocity in the 1-1/2 inch diameter supply tube. Since the designs were based on analytical considerations alone, the actual velocities and flow rates may differ from predicted values. A modest experimental program would provide valuable data for confirming the design, and these data should be obtained if possible.

6.0 CONCLUSIONS

Much has been learned on design practices for minimizing electrostatic hazards in aircraft fuel systems which use explosion suppressant foam. Design guidelines for such airplanes may be summarized as follows:

o   Introduce the fuel at low velocity near the bottom of the tank in a manner that avoids direct impingement of fuel on the foam. The most practical method of achieving this is with a piccolo-tube inlet nozzle whose outlets direct the fuel against the bottom of the tank.

o   Vent pressurized air used in line check operations directly overboard through a flame arrestor rather than through the fuel system.

o   Restrict fuel tank material volume resistivities to about 10^{12} ohm-cm which is typical for bladder cell fuel tanks. Any combinations of materials, sealants, and coatings which result in higher resistivities should be carefully checked for suitability.

o   Ensure that all isolated conductors in the fuel tank are incapable of producing a discharge with an energy of more than 0.2 milli-joules. If doubt exists, the discharge energy may be calculated by measuring the capacitance and the breakdown voltage of the isolated conductor in its installed condition.

o   Continue indefinitely the requirement for additives to increase the conductivity of the fuel to 200 to 600 pS/m at the point of purchase and 100 to 700 at delivery to the aircraft.

o   Consider using reduced fueling rates when foam conductivity is low, and when the ullage fuel-air ratio is likely to enter the flammable range. Foam conductivity will be lower when humidity is low, or when a dry tank (new or after maintenance) is being fueled for the first time, and JP-4 ullages tend to be flammable at comparatively lower temperatures.

o Design the fuel system for a maximum internal velocity of 20 feet per second in the piping network and an inlet nozzle maximum exit velocity of 10 feet per second.

o Require cutouts in foam bl ks around fuel inlet nozzles to be large enough to prevent high velocity fuel/foam impingement. In some installations piccolo tube inlet nozzles may be impractical and other types of inlet nozzles may be required. If so, their fuel spray pattern should be experimentally evaluated including spray from fuel splashing off adjacent hardware.

o Permit switch loading operations only to fuels which contain conductivity improver. Specifically this would require that the specification on JP-5 fuel be changed to include a conductivity improver additive.

7.0 RECOMMENDATIONS

The first recommendation is that electrostatics research should continue because of the number of questions which remain unanswered. Included in this category are issues involving fuel composition, fueling rates and inlet nozzles and fuel system materials.

It has been well established (Ref. 23) that there is no relationship between fuel conductivity and charging tendency, at least in fuels without conductivity improver additive. Studies should be made using fuel samples representative of those used in the fleet to ensure that the current specification on conductivity improver additive is adequate.

Intuitively, one would expect that a higher inlet nozzle exit velocity could be tolerated if the fuel was directed at the bottom of the tank and the nozzle was below the fuel surface for most or all of the filling process. Since rapid refueling is an operational requirement on most airplanes, measurements should be made of charging tendencies in foam as a function of the type of inlet nozzle and its location in the tank.

Probably the greatest lack of information is related to fuel systems which use composite materials. A fundamental, systematic research program should be carried out to validate composite tank fuel systems in terms of electrostatic safety. Among the issues which should receive attention are tank construction, including sealants and coatings, non-conducting fuel lines and inlet nozzles and fuel charging characteristics compared with metal tanks.

Considerable attention has been given to the longitudinal conductivity characteristics of composite materials, because of the importance of conductivity in lightning strike studies. However, conductivity in the transverse direction, which is the important direction for dissipating electrostatic charges, has received much less attention. A systematic study of bleed off currents from typical composite tank buildups is recommended.

As discussed in Section 3.0, metal fuel lines in composite tanks may be incompatible with elimination of lightning hazards. However, with low- or non-conducting fuel lines the charge on the fuel can reach a level which allows subsequent discharges to create pinhole failures in the lines. Studies are recommended which evaluate charge accumulation as a function of line diameter, flow rate and fuel composition for a number of candidate non-conducting fuel line materials. Similar studies involving fuel couplings, valves and pumps would also be useful.

Studies are also recommended to measure electric field intensities during filling of foam filled composite tanks. It is further recommended that filling of a metal foam filled tank with the same geoetry and representative of an aluminum aircraft tank be conducted simultaneously. By this approach, variables such as fuel composition, atmospheric conditions and time of day would be eliminated. Any differences in charging characteristics would be attributable to the tank itself.

APPENDIX A

Characteristics of JP-4S

Introduction

Over the past decade, the U.S. Armed Forces have conducted many fuel tank vulnerability/survivability test programs. One of the major stumbling blocks in these programs has been the difficulty in obtaining a repeatable flammable ullage, the volume above the fuel in the tank, with jet fuels. This is primarily because JP fuels are comprised of a mixture of hydrocarbons. JP-4 for example, has an equilibrium flammability curve as shown in Figure 4-8. As can be seen, there is a rather wide deviation over the range due primarily to the allowable broad Mil-Spec requirement for vapor pressure. If JP-4 is used in a testing program, the entire test article should be temperature conditioned from approximately 20 - 50°F to obtain a near optimum flammable mixture, however, this is only an approximation at best for determining where the test point is on the flammability curve and what the constituents of the ullage are. Detailed studies cannot be conducted because exact fuel/air (F/A) ratios are not known, therefore, only approximations can be made. To simplify the difficulties associated when testing with JP-4, a single or neat hydrocarbon has been substituted for the JP-4 mixture. These have included propane, pentane, and hexane. When using these compounds, exact F/A ratios can be obtained by mixing either partial pressure or by controlling the mass of the liquids injected into a tank of known volume. However, when these neat hydrocarbons are used, some total realism is lost.

A better approach would be a mixture of hydrocarbons that could be used for testing in the same manner that a neat hydrocarbon is utilized but which would simulate JP-4 vapors.

JP-4S

To accomplish the above task, a number of JP-4 samples were obtained from different fuel lots across the U.S. The vapor emitted from each sample of JP-4 at 70^OF was collected and analyzed by gas chromatography. From this analysis, the 15 most prevalent hydrocarbons were selected and averaged to obtain a standard JP-4 mixture that could be handled similar to pentane. This JP-4 vapor simulant has been designated JP-4S.

Table A-1 lists the components by mass percentage of the material.

From the above data and combining like molecular weight compounds, a balanced chemical equation can be written as follows:

$$.0872 \ C_4H_{10} + .4008 \ C_5H_{12} + .2962 \ C_6H_{14} + .1195 \ C_6H_{12} + .0345 \ C_6H_6$$
$$+ .0056 \ C_8H_{18} + .0178 \ C_7H_{16} + 8.5780 \ O_2 + 32.2254 \ N_2 \rightarrow$$
$$5.4915 \ CO_2 + 6.1731 \ H_2O + 32.2254 \ N_2$$
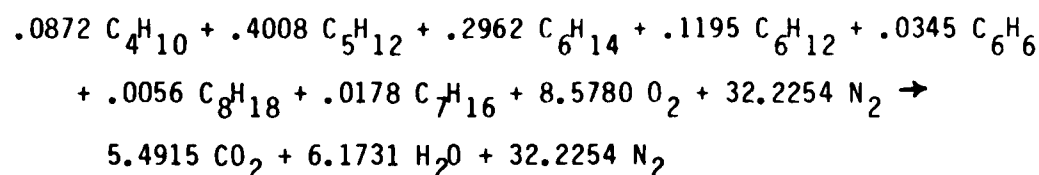
Therefore the stoichiometric concentration is $\frac{1}{41.877}$ = 2.3877% fuel by volume

Because the JP-4S has a high vapor pressure, the mixture is delivered in a K-bottle with 50 psi nitrogen pressure applied. A system was developed to handle the fluid at 50 psi so that the light hydrocarbons do not separate from the mixture.

The needle valve is operated such that the liquid in the syringe remains at 50 psi throughout the injection process.

To calculate the amount of liquid JP-4S required to obtain a certain fuel vapor concentration, the following equation is used:

Table A1. Mixture Composition by Mass

		MASS PERCENT
1.	Isobutane	0.56
2.	n - Butane	5.90
3.	Isopentane	15.50
4.	n - Pentane	21.36
5.	2,3 - Dimethylbutane	7.54
6.	2 - Methylpentane	6.66
7.	3 - Methylpentane	6.15
8.	n - Hexane	12.18
9.	Methylcyclopentane	6.41
10.	Benzene	3.44
11.	Cyclohexane	6.41
12.	Mixture of Dimethylcyclopentanes	2.73
13.	3 - Methylhexane	2.28
14.	Methylcyclohexane	2.06
15.	Mixture of Dimethylhexane	0.82
		100.00

$$V_L = \frac{(\%)\, P_T VM}{\mathcal{P} RT}$$

where

V_L = Volume of Liquid to be Injected

% = Volume Percent Desired

P_T = Initial Pressure of Test

V = Volume of Tank

M = Molecular Weight

$\mathcal{P}$ = Density of Liquid

R = Gas Constant

T = Absolute Temperature at Initial Mixture Conditions

Reference:

"Simulated JP-4 Vapors for Fuel Tank Explosion Testing," AFAPL-SFH-TM-77-10, Wright-Patterson Air Force Base, Ohio, February 1977.

APPENDIX B

Annotated Bibliography

B.1 Kirklin, P.W., "Factors Affecting Electrostatic Hazards," Mobil Research and Development Corporation, Technical Report AFAPL-TR-78-89, December 1978.

The effect of various fuel additives on electrostatic charge generation and accumulation in fuel systems of Air Force aircraft was studied. Fuel is often delivered at high velocity into fuel tanks lined with low conductivity bladder material and filled with reticulated plastic (explosion suppression) foam. The study considered additives such as icing inhibitor, corrosion inhibitors, antioxidants and metal deactivators which are presently approved for use, as well as the conductivity improvers ASA-3 (Shell) and Stadis 450 (DuPont). The effects of combining presently approved additives with the proposed conductivity improvers was also investigated.

The primary test apparatus was the Small Scale Electrification Test (SSET) rig developed by Mobil. The rig consists of a pump, filter/separator, coalescer, and five gallon receiver vessel. The coalescer and the separator were used as fuel charging devices and the fuel flow configurations include flow:
- o through the coalescer only
- o through the separator only
- o through the coalescer and separator in series
- o bypassing both coalescer and separator

The following conclusions were reached on the basis of these SSET results:
- o Conductivity improver additives (Shell ASA-3 or DuPont Stadis 450) at conductivity levels of nominal 100 conductivity units (CU) or higher, effectively reduce JP-4 charge accumulations generated by coalescer and filter/separator elements (or by piping and inlet nozzle restrictions) regardless of the presence of other additives (fuel system icing inhibitors, corrosion inhibitors, antioxidants, or metal deactivator) or their combinations.

111

o At conductivity levels less than about 30 CU, Stadis 450 increased charge accumulation (i.e. was prostatic) in SSET coalescer generated, negatively charged fuel; conversely, ASA-3 increased charge accumulation in SSET separator generated, positively charged fuel.

o Without conductivity additives, DuPont DCI-4A had significant pro-static characteristics in both negatively and positively charged fuel; Hitec E-515 and its combinations with Ethyl 733 or MDA, and Petrolite Tolad 246 + Ethyl 733 with and without MDA, were significantly pro-static with positively charged fuels. The use of these additives by the USAF may have contributed to the reported static charge ignited aircraft fires. Other additives or combinations examined either had little significant effect on charging or were anti-static.

o With a bladder lined foam-filled SSET receiver vessel, electrostatic charges in the incoming fuel transferred rapidly to the foam surface. Red foam appeared to accept fuel charges more readily than blue foam but the charges were more rapidly relaxed.

o Unusually high concentrations of conductivity additives may be required to obtain a minimum fuel conductivity of 100 CU because synergistic effects with some military approved additives (i.e. corrosion inhibitors, anti-oxidants, or metal deactivators) reduce the fuel response to conductivity additives.

o The Exxon Mini-Static Tester did not predict the charging performance of fuels in the SSET.

On the basis of these conclusions, the following recommendations were made:
   o Because conductivity improver additives significantly reduced charging regardless of other additive effects, consideration should be given to the early introduction of conductivity improver additives Shell ASA-3 or DuPont Stadis 450 into USAF JP-4 fuel system at a minimum of 100 CU at the place and temperature of refueling.

o Electrostatic effects from charged reticulated foam surfaces during introduction of charged fuel into bladder-lined, foam-filled receivers were noted but not investigated. These effects should be the subject of future studies.

o Because some additive-fuel combinations required unusually high concentrations of conductivity improver additives to insure static hazard protection of 100 CU at low temperatures, it was recommended that fuel-water separability of fuels with conductivities of 300-450 CU at temperatures of about 70°F be the subject of future investigations.

Other observations made in the report include:

o No change in fuel conductivity was noted after bladder material was soaked in fuel for two weeks or after soaking seven different foam samples for four weeks.

o The tendency for charge generation of the different fuel flow configurations was found to increase with decreasing fuel temperature: however, in a coalescer and separator in combination, generation remained essentially independent of temperature.

o Various fuel and additive combinations were tested in Exxon's Mini-Static Tester, but none of the results showed trends similar to either SSET coalescer or separator charging.

B.2 Johnson, J. K., "The Effect of Stadis 450 and ASA-3 on Sparking in Foam-Filled Tanks," Shell Research Limited, Thornton Research Center, Final Report, September 1977.

In an experimental foam-filled tank, similar to an aircraft tank, charge generation and sparking were examined during the few seconds after start of tank filling at a flow rate of 5 liters/sec through a .9 inch diameter inlet. The foam type was Scott orange Type I and red Type III polyester polyurethane foams for the majority of his testing. Another foam type was tested, however, it was not clear what type of foam this was. A fuel of low electrostatic activity with a conductivity of 0.8 pS/m caused incendive sparks between a

simulated coupling and a pipe. A more active fuel with a conductivity of 6 pS/m (made active by the addition of the pro-static additive, 1-decene polysulphone) caused incendive sparks between the charged foam and the pipe. When no pipe was near the inlet, the fuel of low activity caused incendive sparking between the foam and the inlet nozzle. The incendivity of all three types of sparks was confirmed by ignition of propane/air mixtures.

The progressive addition of Stadis 450 to any of these fuels increased the charging as the conductivity rose to 40 pS/m. Above that concentration, the hazard declined and was negligible at 150 pS/m for any mode of sparking. The addition of ASA-3 to these fuels reduced the hazard and at 150 pS/m it was again negligible.

The conclusions drawn from this investigation were:

o If a pipe coupling is located near the incoming stream of fuel in a foam-filled aircraft tank and is more than 2 mm clear of the pipe, then a fuel of low electrostatic activity will probably cause an incendive spark between coupling and pipe. If no coupling is present, a fuel of moderate activity (hotter fuel) will draw incendive sparks between the pipe and the charged region of foam. If no pipework is near the inlet, a fuel of low activity will draw sparks between the foam and the inlet nozzle.

o The progressive addition of Stadis 450 to such fuels increases the hazard as the conductivity rises to about 40 pS/m but the hazard declines to a negligible level at 150 pS/m, for any mode of sparking.

o The addition of ASA-3 to these fuels reduced rather than increased the hazard, and at conductivities of 150 pS/m the hazard was again negligible. The minimum conductivities that prevent incendive sparking for the three modes of sparking are listed in the following table:

Conductivity Necessary to Prevent Incendive
Sparking Due to an Active Fuel (pS/m)

Mode of Sparking	Additive Type	
	Stadis 450	ASA-3
Charged foam to tube	140	30
Sleeve to tube	160	100
Charged foam to nozzle	140	80

Additional observations made in the report were:

o For spark discharges from a fuel or foam surface to a grounded inlet nozzle a total charge transfer of +140nC or -70nC was needed to ignite a hydrocarbon vapour and air mixture. (These values were not determined during this effort, but in a previous test effort.)

o For a metal to metal spark with a spark gap of 2mm the incendiary energy threshold was .25mj.

o The risk of incendive sparking was influenced by:
   o geometry of the inlet nozzle
   o geometry of the void in the foam
   o foam pore size
   o the mode of sparking

B.3 Mills, J. S., "Electrostatic Charging in Reticulated Foams," Shell Research Limited, AFWAL-TR-81-2015, March 1981.
"A number of fires have occurred during the refueling of aircraft tanks filled with reticulated foam. These incidents were almost certainly caused by electrostatic discharges, resulting from the foam acquiring an electrical charge owing to the passage of fuel. A series of tests have been carried out

to examine the effect on charging of a variety of parameters, including foam type, inlet nozzle type, filling rate and discharge velocity, fuel type, additive content, water content and fuel temperature. Furthermore, the minimum conductivity required (produced by the addition of an antistatic additive) to suppress all sparking was determined for a variety of tank configurations and filling conditions. Two additives were evaluated, Shell ASA-3 and DuPont Stadis 450. Most of the tests were carried out on a large-scale rig which incorporated a 400 litre simulated aircraft tank.

Polyether urethane foam (designated blue) was found to be intrinsically more hazardous than polyester urethane foam (designated red or orange). Under identical test conditions the polyether foam gave charging currents up to 18 times greater than those from the polyester foam. Furthermore, the blue foam has a conductivity an order of magnitude lower than that of the red and the orange foams.

The rate of charge generation was found to increase with both filling rate and discharge velocity, and results showed that systems should be designed so that fuel with high discharge velocity is not directed into reticulated foam. In tests with a single-orifice, high-velocity inlet and electrostatically active fuel, some sparking still occurred at a conductivity of 190 pS/m when the fuel was discharged into blue foam. The piccolo multi-orifice inlet was intrinsically the safest nozzle evaluated. Only in a very small number of tests with this device were hazardous discharges recorded, demonstrating further the importance of minimizing discharge velocity.

Of the various additives evaluated, the corrosion inhibitor Hitec E-515 was found to be the most electrostatically active and capable of significantly increasing charging.

In tests with electrostatically "hot" fuel and fine pore blue foam, a conductivity of 20 pS/m, produced by progressive additions of ASA-3, was sufficient to suppress all sparking with the piccolo inlet and also with a

116

showerhead nozzle of the type found on F5-E aircraft. With the single-orifice inlet, where fuel was discharged against the tank wall, a conductivity of 39 pS/m was required. In tests with the showerhead nozzle and Stadis 450, a conductivity of 37 pS/m was needed to suppress all sparking. These results indicate that if a system is correctly designed, a minimum conductivity of 50 pS/m (at ambient temperature) will provide adequate protection against electrostatically produced explosions. Finally, results from tests with the piccolo inlet indicated that a 'hot' fuel, made safe at ambient temperature by the addition of ASA-3, will not constitute a hazard at temperatures at least as low as -15^0C."

<div align="right">(Author's Abstract)</div>

The conclusions were separated into categories of foam type, nozzles and filling rates, fuels and additives, antistatic additives and fuel temperature.

Foam type

o   Blue polyether urethane foam is intrinsically more hazardous than red and orange polyester urethane foams.

   o   The conductivity of the former is an order of magnitude lower than that of the latter.

   o   Comparing foams of equal porosity, under identical test conditions, fine blue foam produced charging currents between 2 and 18 times greater than those produced by red foam.

   o   In some instances, the test fuel absorbed a pro-charger from the blue foam.

o   New foam can be a significantly more active charge generator than used foam.

o   For both foam types, the rate of charge generation increases with the number of pores per inch.

<div align="center">117</div>

o   ICI Promel is intrinsically less hazardous than blue polyether foam. Promel has a charging tendency between that of red and coarse blue foam and a conductivity of the same order as that of the former material.

Nozzle Type and Filling Conditions

o   The rate of charge generation increases with filling rate and inlet velocity.

o   Systems should be designed so that high velocity fuel is not discharged directly into reticulated foam during tank filling. In tests with the single orifice inlet where electrostatically "hot" fuel was discharged into fine blue foam, some sparking still occurred at a fuel conducitivty of 190 pS/m.

o   The piccolo nozzle was the intrinsically safest nozzle tested. Hazardous discharges were observed in only a very small number of tests with this inlet.

Base Fuel and Additive Content

o   Hitec E-515 was the most electrostatically active additive evaluated. Unicor-J and Apollo PRI-9 were the least active and did not significantly increase charging.

o   The charging tendency of Jet A-1 was significantly higher than that of clay-treated odorless kerosene.

o   In tests with the piccolo inlet, the presence of free water did not significantly increase charging.

Anti-Static Additives

Tests were conducted with ASA-3 and Stadis 450 using single orifice, showerhead and piccolo nozzles and both clean and "hot" base fuels to find the minimum fuel conductivity level required to suppress all sparking. Measured

minimum conductivity values ranged from 8 to 39 pS/m for all three nozzles. The major difference between these results and the 190 pS/m quoted above is that direct high velocity fuel impingement onto the foam was not allowed in the latter tests.

Fuel Temperature

o   In the tests with the piccolo inlet, reducing the temperature of the fuel to -15°C did not give a significantly increased hazard.

o   Results indicated that an electrostatically hazardous fuel made safe at ambient temperature by the addition of ASA-3 will not present a hazard at temperatures down to at least -15°C.

B.4 Dukek, W. G., Ferraro, J. M. and Taylor, W. F., "Static Electricity Hazards in Aircraft Fuel Systems," Exxon Research and Engineering Company, Technical Report AFAPL-TR-78-56, August 1978.

Static electrification and spark discharges which occur when fueling aircraft tanks containing reticulated plastic foam were studied using two small-scale test tanks, a 208 liter (55 gallon) bladder-lined drum and a 341 liter (90 gallon) bladder cell. The dielectric properties and static charging tendencies of several foams were also investigated. The role of anti-static additive (ASA-3) added to fuel to improve conductivity as a means of eliminating spark discharges was assessed.

Inlet conditions for delivery of fuel into the foam filled tank in terms of fluid velocity and number of exit orifices proved to be crucial for minimizing spark discharges. When delivering fuel at maximum flow rates into foam through a single orifice, spark discharges were observed on a radio and by current measurements, as well as visually and photographically. The number and energy of sparks were a function of the type of foam, the quantity of foam, the amount of charge carried by incoming fuel, the velocity of the fluid, the distribution of fluid into foam, and the conductivity of the fuel.

Spark frequency could be reduced or eliminated by using a multiple orifice (piccolo) type inlet to deliver fuel into the foam. The maximum velocity of fuel exiting each orifice also proved to be critical for eliminating spark discharges; a maximum value of 3 meters per second (m/s) was recommended for sizing each orifice.

Polyether polyurethane (blue) foam is 10-100 times more active than polyester polyurethane (orange, yellow or red) foam in terms of charge generation, spark intensity, etc. Even with a multiple orifice inlet, the polyether foam will cause sparks unless the conductivity of the fuel is increased to a minimum value of 50 pS/m. However, the spark energy measurements show that the multiple orifice inlet is contributed to inlet spark energies of only 2-5% as high as those resulting from a single orifice (high velocity) type inlet.

Polyester foam, on the other hand, does not produce sparks if fuel is introduced through a multiple orifice inlet below 3 m/s velocity. For this reason, it is not necessary to establish a minimum fuel conductivity level if a multiple orifice inlet is provided. Use of a single orifice high velocity inlet, on the other hand, requires a minimum fuel conductivity of 50 pS/m.

Design criteria for fuel systems and fuel quality suggested by these tests in small-scale rigs include the avoidance of blue foam and the establishment of a minimum conductivity level of 50 pS/m in JP-4 fuel by the use of conductivity improver additive. The test data also support the modification of aircraft tank inlets to use a multiple orifice type to distribute fuel into a tank at a maximum exit velocity of 3 m/s. If the multiple orifice inlet is installed, the more electrostatically active blue foam can be used in place of red foam.

Test results with the bladder liner indicate that the presence of a non-metallic bladder in a tank does not significantly effect static charge generation or discharge. Tests with an aluminum mesh foam show that it is effective in minimizing static buildup but produces unacceptable metal fragments which can act as charge collectors.

The conclusions supporting these design criteria were based on data specific to the test materials and facilities used during this project. In some cases, data were limited in scope or incomplete for particular configurations. As with most static electricity studies, a high degree of data scatter sometimes occurred. This was expected since the desired end result was the frequency and energy content of static spark discharges. Although the test rigs were designed to realistically simulate actual aircraft fueling operations, an extrapolation of these data to a full-scale aircraft tank must be done with caution.

The investigators concluded that considerable progress was made in understanding the complex problem of static charge generation and spark discharge in foam-filled aircraft fuel tanks, but that certain technical questions remained unanswered. Additional experimental work was recommended to adequately fill the technical gaps remaining. Specifically, the areas of spark incendivity, scale up effects, inlet type, fuel system design, and fuel quality criteria were recommended for further study. The work effort on this project strongly suggested that the static problems associated with these areas were amenable to solution, and that additional study was warranted.

The interactions among foam type, fuel quality, and inlet fueling velocity significantly influenced charge generation and static discharge. The synergistic effects of these variables on charge generation and accumulation could, if not properly considered, lead to potentially serious static electrification problems.

The conclusions presented below, supported by experimental results, point out several foam/fuel/inlet interactions and identify certain conditions where the static problems could possibly be minimized.

o Polyurethane open-pore foam provides a surface for static charge generation and retention when installed in an aircraft tank.

o Blue polyether foam is a much more active material for charge generation and retention than red polyester foam.

o Transient localized pockets or zones of high charge may develop in the foam and discharge as sparks depending critically on fuel properties and velocity of the fuel impingement jet into the foam.

o A multiple orifice low velocity inlet (i.e. piccolo) eliminates sparks in red foam except at unrealistically high input charge levels and reduces spark energies in blue foam to low values with fuel containing only corrosion inhibitor and anti-icing additives.

o A multiple orifice inlet produces fewer sparks if the entering fuel spreads over a large tank floor (or wall surface) at exit velocities not greater than 3 m/s.

o With a single orifice (high velocity) inlet, fuel conductivity additive was needed to eliminate sparks in red foam; the minimum conductivity required was 30 pS/m. With blue foam, sparks could not be eliminated even at impractically high conductivity levels, i.e. greater than 500 pS/m.

o With a multiple orifice (piccolo) inlet, fuel conductivity additive was not needed to eliminate sparks in red foam unless the input charge was extremely high. With blue foam, the threshold fuel conductivity for no sparks was 250 pS/m for a 10 m/s velocity piccolo but only 30 pS/m for a 3 m/s velocity piccolo. With non-additive fuel, sparks in blue foam appeared to be very low in energy.

o Spark energy (charge transfer) measurements made with an oscilloscope on the inlet show blue foam discharges were 10-100 times greater in energy than red foam discharges. In a multiple orifice (piccolo) inlet only 1/10 to 1/100 as much charge was transferred in a spark compared

with a single (high velocity) orifice inlet. The spark energy levels appeared to be incendive for the single orifice but appeared to be non-incendive for the multiple orifices.

o A bladder liner showed no significant difference in static charge generation or retention compared with an empty drum. Initial charge relaxation was equivalent to charged fuel in the metal drum but the rate of decay of field strength became slower at low voltage levels.

o Substitution of an expanded metal mesh for reticulated foam produced much lower field strengths with both single and multiple orifice inlets. However, the development of broken fragments of aluminum mesh which acted as charge collectors militates against use of metal instead of plastic foam.

This project was limited in scope, and the conclusions and the data from which they were derived were specific to the test materials and facilities used during this project. Although an attempt was made to realistically simulate actual aircraft refueling operations the direct extension of these limited data to full scale aircraft facilities was discouraged. Further work was recommended to adequately define the effects of scale-up (tank geometry, internal plumbing configurations, foam volume, inlet location, fuel quality, etc.).

B.5 Radgowski, E., and Albrect, R., "Investigation of Electrostatic Discharge in Aircraft Fuel tanks During Refueling," Fairchild Repulic Co., Journal of Aircraft, pp. 506-512, Vol. 16, No. 7, July 1979.

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 was 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.

The following conclusions were drawn from the data obtained during the test program:

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, contributed to the electrostatic charge buildup within the tank. The potential for static discharges was 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 main fuel tank 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 increased the fuel conductivity and decreased 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 95 pS/m) eliminated static discharges when the forward inlet was used

in conjunction with blue foam, which was the worst-case configuration. A 200 pS/m fuel conductivity was also tested, and no static discharges occurred.

B.6 Radgowski, E., "Final Report for Fuel Foam Charging/Fuel Vent System Investigation for A-10A Aircraft," Fairchild Republic Company, Report GT160R0274, 31 August 1982.

A test program was conducted to evaluate design changes proposed for the A-10 fuel and vent systems. These changes were designed to prevent (or to reduce to an acceptable level) static electricity discharges generated as a result of the line check or purge operations which subsequently resulted in foam charring. Initial testing was conducted with the then current A-10 fuel system configuration to verify that the most probable cause of the static electricity generation was the release of substantial quantities of air/fuel/vapor through the fuel tank and/or vent tank foam as occurs during line check/purge operations. The primary objective was to demonstrate by tests on the A-10 full scale fuel system simulator that the corrective fixes proposed for the aircraft fuel and vent systems either eliminated static electricity discharges or reduced them to an acceptable level. The secondary objective was to perform baseline tests without the corrective fixes installed in the simulator, and thereby to determine which fuel system operation presented the greatest potential for causing static discharges. The resultant test data were evaluated and used to design the optimum corrective fix.

Some of the conclusions reached on the basis of the test results were:

o With the then current aircraft configuration, the line check operation presented the greatest potential for generating charges in the fuel system. The static charges occurred when the refueling manifold pressurized air was exhausted through the fuel shut-off valves into the fuel tanks. Fuel in the wing vent lines at the time of the pressure release appeared to contribute to static charge formation in the vent collector tank.

o The purge operation using the then current configuration also posed the possibility of generating static charges when the pressurized aerial refueling manifold was vented into the forward main fuel tank, but to a lesser degree than the line check.

o Aerial refueling indicated the least electrostatic activity of the three operations. Static generation was maximum when air was simultaneously in the tanker boom and the refueling manifold.

o The manifold pressure rise and decay during the line check at 50 psig with the corrective fixes installed appeared to alleviate electrostatic activity.

o The fuel purge of the aerial refueling manifold at 50 psig with the corrective fixes installed appeared to alleviate electrostatic activity.

Recommendations arising from the study were to:

o Reroute the line check and purge operations' air flow directly into the vent system.

o Retain blue foam in the vent tank.

o Reinstate the line check and purge operation which had been discontinued.

o Advise operators that white vapor will be evident, especially during the purge operation.

5./ Leonard, J.F. and Affrens, W.A., "Electrostatic Charging of JP-4 Fuel on Polyurethane Foam," Naval Research Laboratory Report, 3 March 1979.
The electrostatic charge generating characteristics of JP-4 fuel were determined on both polyester- and polyether-type polyurethane foams. Fiver samples of JP-4 fuel, covering a range in electrical conductivity of 0.55 :

10.27 pS/m were tested. The conductivity of one sample was increased incrementally to 200 pS/m by use of a static dissipator additive (ASA-3). The charging tendency of the fuels was determined by measuring the filter current developed by the passage of 50 ml of fuel through a cylindrical section of foam held in an electrically isolated filter holder (standard Exxon charge tendency test). The charging tendencies of all fuel was then determined using a reference paper filter. It was found that JP-4 fuels can become charged electrostatically by passing through polyurethane foam. However, the magnitude of the charge cannot be predicted from the electrical conductivity of the fuel nor on the basis of its charging tendency on the reference paper filter. The charging tendencies on the polyether foam was about six times greater than on the polyester foams.

Of the two generic types of polyurethane foam tested (polyester and polyether), the polyether was found to be the more electrostatically active surface. For both untreated and ASA-3 treated fuels, the charge densities on the polyether foams were, on the average, about six times greater than on the polyester foams at the flow velocities used in this study. Although the signs of the charges of the untreated fuels passing through the polyester foams were both positive and negative, the charges of the fuel passing through the polyether foams were almost always negative. In the case of the ASA-3 treated fuels, the charges of the fuel passing through the polyester foams were almost always positive, but the charges of the fuel passing through the polyether foams were always negative.

The maximum charge density for a given ASA-3 treated fuel was found to occur when the fuel conductivity was less than about 100 pS/m. Therefore, if a static dissipator additive was to be used to protect an aircraft fuel system with foam-filled fuel tanks, it was recommended that the fuel conductivity be maintained well above 100 pS/m instead of the 50 pS/m value, which is the internationally accepted lower level for fuels containing static dissipator additive. Finally, the charging tendency of SGT (Silica Gel Treatment) n-heptane on both types of foams was found to be negligible.

Four samples of reticulated polyurethane foam, representative of materials used in aircraft fuel tanks, were analyzed for extractable substances. This work was conducted in support of an effort by the AFWAL Aero Propulsion Laboratory's Fire Protection Branch to determine the reason(s) for fuel ignition that has occurred occasionally during the fueling of aircraft. Buildup of static electricity, followed by discharge, was the presumed cause of the ignition.

The two most significant compositional changes that occur upon flow-through of JP-4 through the polyether-based polyurethane foam are: (1) extraction of diethylhexyl phthalate from the foam, and (2) sorption of alkylphenol type substances, present as oxidation inhibitors in the fuel, by the foam.

It had been previously reported that the propensity of the polyether-based polyurethane foam for static electrification diminished upon repetitive flow-through of JP-4. The reduction of the propensity of the foam for buildup of static electricity, upon flow-through of JP-4, was presumed to be mainly due to sorption of the polar, alkylphenol type substances.

The use of antistatic ingredients in the reticulated polyurethane foam was suggested as a means of minimizing static electrification.

It was determined by instrumental analysis that the two most significant compositional changes that occur during the extraction of the foam with JP-4 are:
    o   Removal of diethylhexyl phthalate from the foam.
    o   Sorption of alkylphenol type compounds by the foam.

The latter of these two compositional changes was believed to have a relatively larger effect on the polarization characteristics of the surface and its conductivity.

The analysis results, in conjunction with static electrification experiments, indicated that very small amounts of materials on the surface of the

polyether-based polyurethane foam cause significant changes in its propensity which could contribute to buildup and discharge of static electricity. Incorporation of antistatic agents into the foam appeared to be a feasible and cost-effective means of minimizing fire hazards associated with such a discharge. A literature search was conducted for anti-static agents used in polyurethane compositions.

B.8 Hillman, T. C., and Spencer, G. A., "Electrostatic Evaluation of Aircraft Fuel Tank Inlets," AFWAL-TR-82-2091, September 1982

Tests were conducted on the inlet nozzles from five different aircraft (F-4, F-15, F-5, C-130, A-7). Blue polyether coarse pore foam (Type IV) was used to pack the test tank, and JP-4 fuel with and without ASA-3 conductivity additive was the test fuel. The total charge transfer during the discharges was calculated based on the assumptions of a triangular waveform and a transfer time of 0.3 microseconds. Shell found that the minimum charge transfer that was required to ignite JP-4 fuel/air mixture was approximately +140 and -70 nanocoulombs.

Tests showed that at low fuel conductivities sparking was produced by all five inlet nozzles. The frequency of the discharging was, however, different for the individual inlet nozzles, with the approximate order from highest to lowest frequency being:

  o A-7 inlet nozzle
  o F-4 inlet nozzle
  o C-130 inlet nozzle
  o F-15 inlet nozzle
  o F-5 inlet nozzle

This variance appeared to be a function of fuel foam impingement, with those nozzles which discharged all the fuel directly into the foam having the highest frequency of discharging and those nozzles which avoided discharging fuel directly into the foam having the lowest frequency of discharging.

Increasing the conductivity of the fuel by adding ASA-3 reduced the amount and intensity of discharging. Conductivity levels which suppressed all sparking were approximately:

o 47 pS/m for the F-4 inlet nozzle

o 40 pS/m for the C-130 inlet nozzle

o 48 pS/m for the F-5 inlet nozzle

o inconclusive for A-7, as consecutive tests at 97 pS/m produced discharges in one case but not the other.

o inconclusive for F-15, since higher conductivity fuel was not tested.

These values do not represent the absolute lower limit of fuel conductivity necessary to suppress sparking since intermediate values for fuel conductivity were not tested.

It was concluded that the F-4, F-5, F-15, and C-130 could use Type IV blue foam with fuel having a conductivity of 100 pS/m as required by the Air Force. The A-7 may not be adequately protected against electrostatic spark discharging when the Type IV blue foam is used in conjunction with JP-4 fuel having a conductivity of 100 pS/m. The Air Force A-7's, however, are currently using Type IV blue foam.

B.9 Dunnam, B. C. (Chairman), "Proceedings of Mini-Symposium on Static Electricity Hazards During Aircraft Fueling," Air Force Aero Propulsion Laboratory, WPAFB, Ohio, 18 November 1977.

Interim reports on several research programs were presented at this Symposium. Among these the following are covered elsewhere in this report:

o Mobil (B.1)

o Exxon (B.4)

o Naval Research Laboratory (B.7)

o Fairchild (B.5)

o AFWAL (B.8)

The other presentations made at this Mini-Symposium are summarized in the following paragraphs.

The USAF electrostatic aircraft fueling history since December 1974 includes two A-10, two F-105, two F-5, two UH-1N, two B-52, and one TH-1F accidents. In all cases the fuel tank had bladder liners and all except the TH-1F and the B-52's contained fire suppression foam. The ambient temperature at the time of the accidents ranged from 18-40°F.

There have been three commercial accidents; one involving a Bristol Britannia airplane while the other two involved Boeing 727 airplanes. All airplanes had bladder liners, ambient temperature ranged from 8-54°F, and the fuel temperatures ranged from 31-57°F.

The fuel supply network is very large and complex, which results in the scope of the electrostatics problem being very large. Significant factors of the aircraft static problem include:

- o Initial fuel state
- o Charge generation
- o Charge relaxation
- o Charge accumulation
- o Discharge energy
- o Usage conditions

The risk probability of aircraft fuel tank fire/explosion can be defined as

$$PR = PEM \times PI \times PDR$$

where:

- o PR = Risk probability
- o PEM = Probability of combustible fuel/air mixture within tank.
- o PI = Probability of ignition source being applied to mixture.
- o PDR = Probability of destructive reaction when ignition source is applied.

Risk probabilities for several aircraft fueling hazards were calculated by evaluating the ignition energy of the fuels at different temperatures but the probability of the ignition being applied was left as a variable. The calculated risk probability was compared to actual accidents which fit the same hazard scenario. It was found that the scenarios for which the accidents occured generally had a high calculated risk probability.

The volume resistivities of different foams were tested and it was found that blue polyether foam had a resistivity about an order of magnitude greater than the other polyester foams. The resistivity of the foams varied very little over an applied voltage range of 0-25KV. The relaxation time of blue foam was calculated to be 1233 sec which compares to 99 sec for red foam. Facilities to be used for large scale refueling simulation tests and small-scale spark discharge tests were outlined.

Service tests of ASA-3 and Stadis 450 were being conducted. The effect of the additives on fueling handling equipment was to be evaluated. Also it was to be determined whether or not depletion of the additives occurs to such an extent that safe fuel conductivity levels cannot be maintained.

The National Bureau of Standards provided technical assistance to the Air Force in the following areas, and conclusions drawn in each area at the time of the Symposium are summarized below.

o Static charge buildup within the fuel itself.

Based on the investigations by Royal Dutch Shell and the Canadian government, and also on the favorable results of the Canadian and UK use over the past 8 to 12 years, NBS recommended the use of conductive additive in all flightline fuels. The one qualification to this concerned investigation of undesirable side effects, but unless these side effects were obvious, immediate, and serious, the reduced accident potential weighed heavily toward an early adoption of a conductive additive.

o Electromagnetic interference from nearby man-made sources such as radars and communication transmitters. (Work was incomplete.)

There were many reports by different workers in this area. They gave very contradictory results, and NBS committed to resolve this issue. The then current AF Technical Order TO 31Z-10-4, p3-21, stated a limit of power density of 5 watts/cm2 (or 4340 volts/meter). This would probably have to be reduced downward drastically.

The suggestion was to separate fueling operations from radar or transmitter operation by 1000 meters until this problem was resolved.

o Static charge buildup on clothing and insulating surfaces.

There were two areas of concern, charge generation and charge dissipation.

In the first area, a NBS effort plus a previous AF effort, showed that washed 50-50 cotton polyester blend fatigues generated less charge than 100% cotton, 100% nylon, or 100% polyester materials. This was true particularly at lower temperatures such as would be encountered at Northern tier bases.

In the second area, a NBS effort showed that footwear and ground surfaces need additional attention in order that they would provide an adequate discharge path. The criteria were that neither footwear nor ground surfaces of flightlines should have a resistance exceeding 109 ohms. Composition soles (e.g., Neolite) and cold weather footwear far exceeded this upper limit. Leather soles and composition soles with an added conductive material did meet these criteria. Footwear with resistance less than 106 ohms could create a personnel shock or electrocution hazard. Therefore, the desired range was 106 to 109 ohms.

Ground surfaces such as concrete, bare dirt, and ice or snow had resistances less than 109 ohms. Asphalt did not meet this requirement, and therefore should not be used as a flightline surface.

Most leather gloves provided an adequate discharge path without removal of the gloves. Synthetic material gloves or leather gloves with synthetic liners might not provide an adequate discharge path. Data were too limited on this point to provide definitive guidelines.

o Lightning and static discharge of metallic frames.

Due to the severe requirements placed on all equipment in case of direct or nearby lightning strike, and due to the uncertainty in predicting lightning, all bonding and grounding requirements for aircraft on flightlines must be continued or strengthened.

o Equipment failure and personnel error.

Based on review of past work of others, JP-8 is an inherently safer fuel than JP-4, and the planned Air Force change to JP-8 should reduce the bad effects of all accidents, including flightline fueling accidents.

Based on review of many AF accident reports in which personnel error or equipment failure is the most probable cause, the practice of bonding and grounding aircraft during all servicing operations on flightlines must be continued.

Simulated refueling tests of the YF-16 were conducted using both a graphite-epoxy and an aluminum tank. Conclusions of this testing include:

o Sparking in all tanks is primarily a function of detail design.
o Use of insulating materials impacts detail design.

o   Insulative properties much greater than those demonstrated by this graphite-epoxy tank would be necessary before a composite tank became more critical than a similar metal tank.

B.10   Dunnam, B. C. (Chairman), "Sixth Meeting of AD HOC Committee on Aircraft Fuel Static Electricity Hazards," Air Force Aero Propulsion Laboratory, WPAFB, Ohio, 19 January 1978.

Presentations were made on the research programs being conducted by Fairchild, Exxon, Mobil, AFWAL, and Southhampton University. Most of the results are summarized elsewhere in this Bibliography (See B.9)

Resistivity testing of various foams was conducted and the following conclusions were drawn:

o   Foams show a reduction in resistivity when wetted with baseline (10 CU) JP-4 fuel.

o   Foams wetted with JP-4 fuel doped with shell ASA-3 (100 CU and 1000 CU) do not show any significant reduction in resistivity compared to the baseline wetted foams.

o   A tenfold reduction is noticed when the blue foam is wetted with baseline JP-4 fuel.

o   Pigments show little effect on resistivity.

o   The foams charging and relaxation times were reduced when wetted with baseline JP-4 fuel.

o   The blue foam's charging/relaxation time was significantly reduced when wetted with baseline JP-4 fuel.

Simulated aircraft refueling tests were also conducted. To this point only limited testing had been conducted with only blue foam tested. It was found that blue foam produced a high frequency of discharging. Other results of this test series are discussed in B.9.

B.11 Dukek, W. G., Lunt, R. S., Young, D. A., "Evaluation of the Hazards of Static Electricity in POL Systems," Exxon Research and Engineering Company, January 1976.

Tests were conducted at air bases and in a full-scale rig to evaluate the hazards of static electricity in petroleum, oil and lubrication (POL) systems. Field testing at two air bases revealed a low level of charge in JP-4 fuel delivered to aircraft through DOD filter-separators. The low levels resulted from the high conductivity of JP-4 due to the presence of approved DOD corrosion inhibitor and the design of filter-separators which provided considerable residence time for charge relaxation. Single stage filter separator units were shown to generate less charge than older two-stage units. Teflon screens charged at about half the level of paper separators. Aluminum hydrant systems were found to have a lower charging tendency than carbon steel systems.

Tests in a full-scale rig showed that the surface voltage generated in tank truck filling is determined by the inlet charge regardless of the use of a Static Charge Reducer. Spark discharges were observed at very low surface voltage levels if charge collectors were present. Tests with JP-4 in fiberglas reinforced plastic (FRP) pipe showed that charge relaxation rates are the same as in steel pipe, a result contrary to tests with nonadditive fuel. Tests in epoxy coated drums indicated that surface voltage relaxes at a rate equal to or greater than bare metal.

o Consideration should be given in design specifications for DOD filter-separators to provide maximum charge relaxation volume after the final elements. Operating manuals should draw attention to the importance of relaxation volume in fuel handling systems, particularly in aircraft fueling.

136

o Special precautions should be observed in filling an empty filter vessel after installing new elements due to their high initial charging tendency. Slow filling, preferably by gravity, is recommended during the air bleed period to avoid vapor space discharge.

o Continued use of low charging Teflon-coated screens in preference to paper separator elements is recommended until a procedure has been developed for qualifying other types of low charging elements.

o Further investigation should be made of the operating procedures needed to meet the break-in requirements of new filter elements. In addition, the thruput limits of filter elements in terms of increasing charging tendency should be investigated.

o Additives specified in MIL-I-25017 for control of pipeline corrosion should be tested for electrical conductivity and charging tendency response in reference fuels using laboratory procedures.

o A wider survey of JP-4 fuels in the field is desirable to measure electrical conductivity and charging tendency in MIL-T-5624J fuels in order to relate these properties to the type of corrosion inhibitor used.

o The continued use of the Static Charge Reducer should be discouraged unless a monitoring program is adopted.

o Aluminum, stainless steel, FRP or coated metal as materials for POL hydrant systems are preferable to carbon steel because of their lower charging tendency and freedom from corrosion deposits.

o Epoxy coatings for vessels should be required to satisfy a maximum resistivity requirement of 10^{14} ohm-cm.

o Charge levels were too low in the field to measure surface voltages in an R-9 fueler truck being filled with JP-4 fuel charged through a DOD filter-separator unit. However, in the Exxon Full-Scale Facility, tests in a tank truck using the JP-4 additive package showed that surface voltage was directly related to incoming charge density and fuel conductivity.

o It was not possible to measure the efficiency of the Static Charge Reducer (SCR) in the field because of low input charge level. However, in the Exxon Full-Scale Facility, tests with the SCR showed that surface voltage in a tank was determined by the input charge density whether or not the SCR was in the circuit. This result is different than when delivering fuel from the SCR into plastic pipe where high surface voltages can develop with fuel averaging zero net charge.

o The SCR required several minutes of start-up time to function as a charge reducer and the efficiency of reduction was related to fuel polarity and charge level; both factors had been observed in earlier work. Deposits from the field SCR were analyzed and found to contain metal debris typical of fuel system materials.

o Spark discharges were observed when bottom filling a tank truck with charged fuel at a surface voltage as low as 1 kv when an unbonded charge collector was present. In the absence of these sources of spark energy, no discharges were observed up to a surface voltage of 28 kv.

o JP-4 fuel of MIL-T-5624J quality showed the same charge relaxation characteristics when pumped through FRP pipe as through steel pipe regardless of the polarity of the input charge. This result is contrary to the earlier data obtained with Jet A fuel and may be related to the presence of corrosion inhibitor in JP-4 which would absorb on pipe walls and lower their surface resistivity.

o In drum filling tests under controlled conditions, epoxy coatings cause charged fuel to relax in surface voltage at the same rate or higher rate than bare metal without coatings. However, a fluorinated coating with a resistivity several orders of magnitude greater than epoxy held charges on its surface for several days.

o The presence of a rod or cable did not effect the rate at which a charged fuel relaxes regardless of whether a drum coating was used.

o The field test program revealed that the charging tendency of filters increased with age (or throughput) from the equilibrium value, probably because of the accumulation of ionic species, e.g., corrosion inhibitors.

B.12 Bachman, K. C. and Dukek, W. G., "Static Electricity in Fueling Superjets," Esso Research and Engineering Company, Linden, NJ, January, 1972.

A test program on static electrification of jet fuels carried out by Esso Research and Engineering Company provided a high degree of assurance that high-speed fueling of superjet aircraft could be carried out safely. The program as conducted in a full-scale fueling rig which included the key section of an aircraft wing tank. A unique method was developed for measuring the energy in the spark discharges which occurred in the tank. The method involved blanketing the vicinity of a float (similar to the float on a fueling gage) with gas blends whose minimum ignition energies were known from prior work and determining whether ignition occurred. The float was surrounded by propylene bag which was flushed with known gas blends as the fuel level rose. The rest of the tank was blanketed with nitrogen so that the only gas that could ignite was in the localized area surrounding the float where sparking occurred. A gas feed line and a sampling line to test the actual concentration of reactants in the vicnity of the float were attached to the float. The technique was very successful. Ignitions occurred in a repeatable manner and were readily self-extinguishing. The spark energy measurement had a great advantage over a probe in that it did not distort the field nor add electrical capacitance to the system to prejudice the energy measurement.

139

The test results revealed that manifolding the tank inlet to distribute charged fuel is highly effective for minimizing the static hazard. With only normal aircraft components in the tank no discharges could be produced under conditions simulating a manifold (multiple orifice) inlet. Under comparable conditions, discharges displaying energies of less than 0.06 millijoules, well below the minimum ignition energy of 0.26 millijoules for hydrocarbons in air at sea level, were detected when the tank was fueled through a single inlet. It was also demonstrated that incendiary sparks with energies as high as 0.6 millijoules could be produced when fueling through a single inlet if an unbonded charge collector were present in the tank. The maximum spark energy appeared to occur with fuel of about 3 pS/m rest conductivity. No incendiary sparks were detected with the unbonded charge collector present under conditions which represented filling through a manifold.

The most important conclusion reached in this study was that the design of the distribution system used to deliver fuel into an aircraft tank had a major influence on spark generation. Under normal conditions (e.g., without deliberate augmentation of charge collecting characteristics of any system components), it was established that at maximum fueling rate:

o No sparks were produced under conditions simulating a manifold inlet as used in superjets to distribute fuel into several compartments.

o Sparks were produced, however, when fueling through a single submerged inlet at charge density levels above 70 $\mu C/m^3$.

o Maximum spark energies concurrent with charge densities up to $\mu C/m^3$ were < 0.06 millijoules (less than one-quarter of minimum ignition energy for hydrocarbon/air mixtures).

 secondary conclusion was that incendiary spark discharges could be
 unbonded charge collector was deliberately installed

o Sparks were generated with energies as high as 0.8 millijoules, more than three times the minimum energy required to ignite hydrocarbon/air mixtures, when fuel was delivered through a single submerged inlet with the float wrapped in foil.

o Incendiary sparks were eliminated under conditions which represented filling through a manifold inlet even with the float wrapped in foil.

The overall results showed that manifolding a fuel inlet was highly effective in minimizing the static hazard. The design tested was apparently safe from this hazard when fueled at maximum rate.

Finally, it should be noted that 370 $\mu C/m^3$ was the maximum charge density that could be attained at the tank inlet in these studies, although there was no reason to believe this was the maximum level that might be experienced in the field.

o The fact that one type of filter could generate several times more charge than another illustrated the variation to be expected in filter charging tendency.

o While fuel of low conductivity (< 1 CU) generally produces low charge levels, the fact that filters have a "memory" for inpurities trapped on their surfaces illustrated that low conductivity cannot be equated with low charging density.

In summary, the Esso Research test program was successful in providing a high degree of assurance that the high-speed fueling of superjets could be carried out safely. The program provided quantitative data of the energies in static discharges under completely realistic conditions.

B.13 Bruinzeel, C., "Electric Discharge During Simulated Aircraft Fueling,"
      Institute of Petroleum Journal, Vol. 49, No. 473, May 1963.

Large-scale tests revealed that when highly refined aviation fuels were pumped
through microfilters and hoses into aircraft wing tanks potential gradients
may develop inside, which easily exceed the spontaneous breakdown value.

Electrical discharges near the air-fuel interface in the vicinity of tank
inlet systems were often observed throughout a simulated fueling operation.
The occurrence and nature of these types of discharge were more closely
observed in a mock-up of a fueling installation and receiving tank. Results
indicated that the most critical periods were the first stage of the fueling
operation and the stage in which the tanks are nearly full.

Discharge energies were determined from the hypothesis that they are the
product of the quantity of charge transferred in a single discharge and the
driving force (potential). The charge transferred was measured by attaching a
calibrated capacitor to a probe and recording the increase across the
capacitor after a discharge to the probe. The discrete nature of a discharge
was checked with a fast-sweep oscilloscope. The driving potential during
charge transfer was found indirectly from the product of field strength and
gap width and checked by direct measurement of the potential at the fuel
surface with a capacitive probe.

The energy content of the discharges was found to vary from below 0.2
millijoules (the minimum required for ignition) up to several tens of
millijoules. Their duration varied from a few microseconds down to a fraction
of a microsecond. The incendiary nature of these sparks was demonstrated in
certain tests. Photographic techniques were used for recording and studying
charging conditions inside a tank and the discharge mechanism.

Sparking phenomena were further investigated as a function of increasing fuel
conductivity. It was observed that sparking in the first stage of a filling
operation was the more difficult phenomenon to suppress. The results
indicated that with present day fuel handling facilities and under severe

fueling conditions a fuel conductivity of at least 50 picomho/meter is required to prevent all sparking hazards.

In practice, a dangerous condition will result from the existence of a flammable vapor/air mixture at the same time and place as the occurrence of a spark of sufficient energy to ignite this mixture. It has to be remembered that in the course of millions of fueling operations of civil aircraft, no explosions have yet occurred due to the discharge of static electricity generated during the fueling operation. However, in view of the results of the tests described here, this does not justify complacency, though it perhaps puts the situation into perspective. This study indicated that under certain conditions dangerous discharges could arise, and thus confirmed the need to investigate means of controlling the generation of static electricity during the fueling of aircraft.

The following additional observations of interest were made in the report:

o   Spark discharges began when field strength values reached 400-500 KV/m. When the final breakdown occurs, the field strength must locally have reached the value of 3000 KV/m which is the breakdown voltage of air.

o   "On the strength of all available data one can affirm that protection of the vapor space of a tank by sharp points inducing corona discharges, which bleed off the energy in the vapor space, is not a very safe procedure."

o   "It is also known that various types of fuel-inlet designs, including those which split the incoming flow over several compartments simultaneously, have been tested as a means for reducing the electrostatic charging hazards, but these measures have generally produced only minor improvements."

B.14   Strawson, H. and Lewis, A., "Electrostatic Charging in the Handling of
        Aviation Fuels," AGARD-CP-84-71, Aircraft Fuels, Lubricants, and Fire
        Safety, NATO, Shell Research Limited, August 1971.

The conditions which lead to a hazardous electrostatic discharge cannot be
precisely predicted. The use of a static dissipator additive eliminates the
hazard. Methods of introducing the additive and of maintaining the correct
conductivity during fuel distribution were discussed, as well as possible side
effects and interactions with other fuel additives. On the basis of
world-wide airline use over many years, supported by many laboratory tests, it
was concluded that the additive provides a safe, simple and trouble-free
solution to the problem.

The primary conclusions from this study were:

o   In the absence of special precautions, a real tank explosion hazard
    exists under some conditions when fueling aircraft at high rates, even
    with kerosene fuel. The particular conditions are not entirely
    predictable.

o   The use of a static dissipator additive, such as ASA-3, is a fully
    effective safeguard against this hazard.

o   No significant problems have occurred in nine years use of the ASA-3
    additive in aviation fuels, in which time some 10,000 million gallons
    have been supplied at over 150 airports.

o   While maintenance of fuel conductivity up to the airfield does not
    present any problem, in some long and complex distribution systems
    conductivity depletion may occur to an extent which necessitates
    re-doping at or near the airfield.

The process which leads to electrostatic discharges and subsequent explosions
in fuel tanks can be broken down into four parts:

144

o Charge generation

o Transport of charges into the aircraft tank

o Production of electric fields inside tanks

o Spark discharges to ignite flammable mixtures

The status of these items at the time the work was done follows:

o Charge Generation
   Microfilters of all types were the most prolific charge generators in
   fueling systems. The magnitude and polarity of the charge of different
   microfilters was extremely variable and unpredictable, depending on
   types and amounts of trace elements in the fuel. Filters incorporating
   layers of different filter material giving charging of opposite
   polarity which then cancel out were not likely to work due to the
   unpredictable nature of the filter charging. Although it was generally
   true that filter charging increased with flow rate there were
   circumstances where filter charging peaked and then fell with further
   increase in flow rate.

o Transport of Charges into the Aircraft Tank
   As fuel flows from a microfilter to the aircraft tank, it loses charge
   to earth by 'relaxation', at a rate determined by its conductivity.
   Ideally, charges will relax exponentially, according to the relation:

$$\frac{Q}{Q_o} = e^{-Atk}$$

where t = time
       K = fuel conductivity, and
       A = calculable constant.

The fact that charging is associated with trace quantities of ionizable
material does not mean that low conductivity fuel will give low charging.
This was borne out in tests with low conductivity fuel and by the fact that
trace quantities of some materials did not increase conductivity. Tests with

ASA-3 showed that throughout the range of concentrations the charge density produced by doped fuel was always less than undoped fuel when flowed through a microfilter.

o Production of Electric Fields Inside Tanks
   The shapes of aircraft tanks and inlet diffusers were too irregular for calculations of the electric fields to be of much practical value. Measurement of the electric fields experimentally was preferred.

o Spark Discharges to Ignite Flammable Mixtures
   The overall field strength in a tank was a poor criterion of the hazard. It had been thought that an overall field of several hundreds of KV/m would be needed for local fields to be high enough for incendive sparks. However recent test results resulted in an ignition with an overall field of 340 kV/m and the production of a .2 mj spark with an overall field of 48 kV/m. (A photomultiplier was calibrated and used to assess the energy of a spark.)

B.15 Leonard, J.T., "Generation and Dissipation of Electrostatic Discharges in Aircraft Fuel Systems," Conference on Fire Safety Measures for Aircraft Fuel Systems, Department of Transportation, Washington, D.C., December 11-12, 1967, page 35-64, (N68-36268).
Charge separation occurs in fuel flowing through a pipe resulting in charged fuel being deposited in the tank. Filtration systems cause greater charging and can result in 10 to 15 times more charge in the tank. If fuel conductivity is low the charge will not be able to relax and electric fields can reach the breakdown value of the vapor space.

For explosions to occur, a flammable mixture must be present and a spark of sufficient energy and duration must occur. A study was done to determine the effect of electrode configuration on the type of discharges from a charged fuel surface and from a charged metal plate. The results are given in the table below:

| Grounded Electrode | Discharge From Fuel Surface | | Discharges From plate | |
	Gap. Cm.	Type of Discharge	Gap. Cm.	Type of Discharge
Needle	1.0-5.0	Corona	1.0-3.0	Corona
60° Point	2.5	Spark	0.25	Spark
	2.5-15.0	Corona	1.0-8.0	Corona
1/4" Sphere	2.5-15.0	Corona	0.9	Spark
			0.9	Prebreakdown streamers
1/2" Sphere	2.5-12.5	Prebreakdown streamers	1.0	Spark
			1.0	Corona and prebreakdown streamers
1" Sphere	2.5-15.0	Prebreakdown streamers	0-1.6	Spark

Significant observations which can be made include:

o For the 60° point a spark was produced at the smallest gap widths. Although corona discharges were produced at larger gaps it is quite possible that sparks might also be produced with this type of point.

o For different sized spheres only corona discharge or prebreakdown streamers were produced from a fuel surface. From the metal plate, sparks were produced at smaller gaps and prebreakdown streamers followed by sparks were produced at larger gaps.

o For discharges from the metal plate to the spherical electrode the spark energy increased with both gap width and sphere diameter.

o The energy in discharges from a fuel surface also increased with gap width but was much lower than discharges from the metal plate at the same gap width.

o The duration of the discharges obtained from a fuel surface were up to seven times longer than those from the metal plate.

In spite of these findings Bruinzell demonstrated during a previous test effort that when fuel is charged to its maximum capacity true sparks can be obtained from the fuel surface. Less highly charged fuel would produce the type of discharges encountered in this study.

B.16   Johnson, J.K., "The Ignition of Vapour and Droplets by Liquid-to-Metal Sparks," Shell Research Limited, Journal of Electrostatics, Vol. 4, pp. 53-65, December 1977.

The flow of hydrocarbon product can accumulate a charge in the liquid *sufficient to lead eventually to a spark in the ullage space of a tank being* filled. Depending on the volatility of the product, the ullage space may contain flammable mixture with air in which the fuel ranges from wholly vapour to almost wholly liquid droplets. As an aid to the assessment of hazard in fuel handling operations, this paper described the discharges between earthed metal electrodes and a charged product surface that have ignited a small number of such mixtures.

When all the fuel was in vapour form a spark charge transfer of 0.1 µC caused ignition and the spark could be drawn by a partially immersed, 8-mm-diameter rod or a 50 mm X 25 mm-diameter ellipsoidal electrode suspended 15 mm above a surface charged to 60 kV. At 65% of the fuel as droplets, a charge transfer of 1 µC was incendive and with 95% as droplets, 2 µC caused ignition.

The minimum ignition energies of the three different vapor concentrations of the fuel were measured between metal electrodes 2 mm apart, and were found to be 0.4, 2.6 and 4.0 mJ respectively.

During early testing it was found that the electrode was wetted by spray from bursting bubbles on the surface of the kerosene or from a stream of kerosene drawn from a bubble by the electric field. Further, the discharge was found to break-up into a train of current pulses when the root of the bright channel of the spark passed through the wetted tip of the electrode. Elliptical electrodes were used to avoid this phenomenon. Then, the root of the spark

was at the small radius near the side while any liquid on the electrode ran to the bottom.

The charge transfer was adjusted by varying the electrode size. It was found that the charge transfer of a spark to a hemispherical electrode increased as the square of the radius. For a rod partially immersed in the kerosene the charge transfer was found to vary as the 1.6 power of the diameter of the rod.

The charge density at the inlet to the tank was adjusted to give sparks at intervals of one to three seconds. The spark magnitude was adjusted so that ignition of a given fuel occurred once for 20 sparks above the incendive charge transfer, a probability of 5%.

B.17 Bridges, J. E., Zalewski, R., and Nanda, V., "Gap Energy, A More Accurate Criterion for Ignition Threshold of Flammable Mixtures," 1975 IEEE Electromagnetic Compatibility Symposium Record, San Antonio, Texas, October 7-9, 1975.

Proper determination of minimum ignition thresholds for explosive mixtures is an essential element in preventing hazardous explosions. The results of an experimental study show that one of the more common methods of determining the minimum energy to cause ignition--that of discharging the energy in a capacitor -- is likely to produce variable results. A laboratory bench setup formed from off-the-shelf lumped parameter components is likely to produce ignition thresholds significantly in excess, by one or two orders of magnitude, of the minimum observed value which can be developed by more refined techniques.

This problem can be overcome by calculating the energy actually absorbed in the spark gap. This is done by forming the product between the voltage across the gap and the current through the gap for various values of storage capacity. Test results from four different experiments were given which demonstrate that conventional test methods are likely to produce energy thresholds too high. Modification of currently used test procedures are suggested.

It was demonstrated in four cases that the stored energy in the discharge capacitor was not the correct measure of the energy required for ignition of flammable mixtures or pyrotechnic devices. The minimum ignition threshold given by the stored energy on the capacitor, especially for the larger values (about 100 pfd), is a strong function of the internal series impedance of the capacitor, and this impedance can increase the apparent thresholds by a factor of 3 to 10. When using very small capacitors (< 100 pfd) which develop very short pulse (about 100 nsec) discharges, the physical arrangement of the test apparatus appears the dominant factor rather than the series impedance as in the larger capacitors. In actual situations, there is no positive assurance of how the energy losses will occur. In situations involving discharge paths between very low-loss and low-inductance conducting bodies, most of the energy may be delivered into the gap.

This strongly suggested that the method of determining ignition thresholds should be revised and the use of a gap energy concept applied, especially for large storage capacitors (> 100 pf). In the case of small storage capacitors (< 100 pf), the test arrangement needs revision to better control the distributed fields and resulting parasitic currents. UHF and microwave circuit arrangement and measurement techniques should be emphasized, rather than a routine extension of low-frequency lumped parameter methods. Any waveform dependence should also be investigated.

Additional observations: A series of tests were conducted on the minimum ignition energy of propane. Due to equipment availability problems the gap voltage could not be measured at the same time as the gap current. A method was developed for estimating the energy delivered to the gap which could be used with reasonable confidence. An ignition energy of 0.038 mJ for a 4-5% mixture of propane in air was estimated. This is an order of magnitude lower than the values of 0.41 mJ at a 4% fuel mixture and 0.25 mJ at a 5.5% fuel mixture which Lewis and Von Elbe quoted. There is some question about the test arrangement used in these tests but it does appear that the minimum ignition energies of hydrocarbon vapor and air mixtures may be much lower than previously suspected.

B.18   Bright, A. W.; Boodworth, G. G.; Smith, J. G.; and Yuratich, M. A.,
       "The Development of Electronic Field Meters for Use in Automatic
       Systems for Control of Electrostatic Charge in Fuel Tanks," University
       of Southhampton, U.K, Conference on Lightning and Static Electricity,
       Abingdon,   Oxon,   England,   April   14-17,   1975,   Proceedings
       (A76-1440203-01).

Equations for calculating the maximum electric field in the ullage cannot
account for many of the variables encountered during actual refueling.
Instrumenting the fuel tank to make actual measurements of the charge density
or electric field at an appropriate point in the system was an alternative.
Existing electric field meters were unsuitable for use in operational fueling
systems due to their bulk, weight, and susceptibility to mechanical damage.
Therefore, prototypes of a flush-mounted Virtual Earth Field Meter were
developed.   Preliminary work indicated that "electronic field meters do not
present any risk of ignition and can be used to measure electric field in the
ullage space as the fuel level approaches the top of the tank."

The field meter could be mounted in the roof of the tank, and output from the
instrument could be used to trigger an alarm or shut off the pumps as the
critical electric field is approached. Alternatively an active system could
be used in which the field meter is used to control charge injections into the
tank to produce zero charge density and electric field in the tank.

B.19   Rogers, M. E., and Wyeth, H. W. G., "Investigation into a Fuel Tank
       Explosion Britania G-ARKA," Royal Aircraft Establishment, Technical
       Report 67080, April 1967.

During pressure refueling of British Eagle International Airlines Ltd.
(B.E.I.A.) Britannia G-ARKA at London Airport at 00.15 hours on 30th August
1966, an explosion occurred within the starboard wing causing tank rupture and
limited structural damage in the region of No. 4 bag and to the engine nacelle
skinning beneath it.

Heavy rain was reported to be falling at the time of the incident. The
aircraft had been on the ground nine hours since its return from Italy and

although some engines had been tested in this interval the one nearest to the explosion had not. The crew were on board at the time doing pre-flight checks, which involved activating the fuel gauging system, though the tank pumps were not switched on.

There were few obvious ignition sources in the region of the tank which exploded and hence an electrostatic discharge within the tank itself was suspected as the cause of the accident. Since this would be the first known incident in a civil aircraft (a number of Canadian military aircraft had suffered tank explosions during refueling which were attributed to this cause), an exhaustive examination of all possible ignition sources had to be made.

Recommendations to Prevent a Recurrence of this Incident

o Measures should be taken to prevent the buildup of charge within fuel entering the aircraft tanks. The employment of anti-static additive or charge relaxation techniques should give a substantial reduction in the risk of explosion due to electrostatic charging of the fuel.

o Alternatively the extension of the filling pipe to the bottom of the tank would give a marked improvement in safety and make the fueling arrangements comparable to those of the majority of present day aircraft.

o Standard refueling bonding points more convenient than those now provided should be specified and used, and bonding standards generally should be maintained.

o Sharp projections within fuel tanks (i.e., locking wire and split pins) should be avoided if possible, and special attention should be devoted to the bonding of all components in or adjacent to the fuel system, including tank support buttons. (Implementation of this recommendation is desirable, but does not warrant retrospective modifications if these prove difficult.)

o Bag embrittlement (due to overheating by the jet pipe) should be prevented by improved insulation techniques.

B.20 Godwin, J. B., "Static Electricity in Air Force Refueling Systems," Lightning and Static Electricity Conference, 3-5 December 1968, Part 2, Conference Papers, Final Report (Air Force Avionics Lab, AFAL-TR-68-290 Part 2, May 1969).

The primary turbine fuel used by the Air Force, JP-4, qualifies as an intermediate vapor pressure fuel. It's volatility and electrostatic generating tendencies make it dangerous in any fuel transfer operation. To prevent ignition due to electrostatic discharge, the Air Force developed grounding and bonding procedures to maintain electrical continuity during aircraft refueling. Static grounds and flexible cables with battery clips were used. The main deficiencies of this system were:

o The battery clips were fragile and when broken would cause extensive damage.

o The paint on aircraft (usually camouflage) acted as an insulator between the hardware and the airframe and prevented electrical continuity.

o Adequate grounding points were lacking on assigned aircraft. Example: Post World War II aircraft A-IE (converted Navy assault bomber) had no receptacles for grounding, and several century series aircraft (P-100, P-102) had only one grounding point so that concurrent servicing could not be accomplished without compromising safety.

o Real estate at air bases in Southeast Asia was inadequate and aircraft were often parked with overlapping wings. Any ignition of flammable vapor or ordnance by static electricity or improper grounding, therefore, would result in a major accident.

o The number, location, and method of attachment of grounding receptacles clearly dictated a need for standardization on all aircraft in the inventory.

Air Force Logistics Command established a project to standardize aircraft grounding. A female electrical receptacle was designed for mounting on each aircraft and a male plug mounted on a 3/32 inch flexible cable was designed for each servicing vehicle. Aircraft were modified with this new grounding equipment.

B.21 Perry, B. L., "Static Discharge," The Aeronautical Journal of The Royal Aeronautical Society, January 1971, Vol. 75, p. 70-71.

This paper outlines the static electricity hazards associated with light aircraft. If plastic funnels are used for refueling they may become charged even at the low fueling rates. In an actual incident, fuel was being poured from a four-gallon drum to the tank through a plastic funnel over a dry chamois. Some fuel had spilled and fuel vapors accumulated around the filler. A spark from the funnel ignited the vapor and resulted in the loss of the aircraft.

To prevent such accidents, bonding connections between the aircraft, funnel or nose nozzle and fuel container should be made. The bonding connections may be of high electrical resistance since only small currents need flow to equalize the different voltages. The system should also be earthed either at the aircraft or refueling tank, preferably both. Bonding connections should be made on bare metal and before any fuelcaps are opened.

B.22 Sommer, E.C., "Preventing Electrostatic Ignitions," Esso Research and Engineering Co., presented at API Central Committee on Safety and Fire Protection Meeting, Tulsa, OK, April 20, 1967.

The movement of petroleum products will result in the generation of an electrostatic charge. Whether or not this charge accumulates to a spark potential is a function of the severity of the electrostatic generation mechanism, conductivity of the liquid or product, and paths available for the

charge to leak off or recombine. For an electrostatic discharge to be incendiary, there must be a spark gap where a flammable vapor-air mixture might occur, and sufficient electrostatic energy which can be discharged in the form of a spark.

Experience and tests had shown that items such as splash filling, agitation, high liquid flow velocities and water contamination all give rise to the generation of high electrostatic charges. Tests had also shown that flow through a filter or filter separator could generate an extremely high electrostatic charge. A 30 second relaxation time downstream of the filter before the liquid enters a tank was recommended to provide sufficient time for the charges to recombine. Because filters are such prolific charge generators, this precaution is advocated regardless of the product classification.

Spark promoting mechanisms must be avoided where electrostatic charges can accumulate in the presence of a flammable vapor-air mixture. Spark promoting mechanisms are such things as conductive tape gages and sampling devices, conductive projections and probes, and floating conductive objects. Unless nonconductive tape gages and sampling devices are used, a waiting time should be allowed before insertion into the tank.

In order to determine if a product or liquid presents an electrostatic ignition potential, it is necessary to determine if it is an electrostatic accumulator and whether a flammable mixture can be formed where a spark can occur.

If a product or product handling operation can accumulate an electrostatic charge and a flammable vapor-air mixture can occur, special precautions must be observed. These precautions are aimed at either reducing the level or charge generated, eliminating the spark gap or spark promoter, or changing the environmental conditions so that a flammable vapor-air mixture does not occur where a spark might occur. Recommendations designed to avoid electrostatic ignitions were presented.

The minimum ignition energy of petroleum vapor and air mixtures is approximately .25 mJ and occurs at a slightly rich concentration (except in the case of methane and air which requires a slightly lean concentration for its minimum ignition energy). The energy requirement is increased by a variety of factors which tend to decrease the availability of the stored energy to the flammable mixture:

o A portion of the energy will be dissipated in a resistive portion of the discharge circuit and will not be available at the spark gap.

o The electrodes, across which the sparking occurs, will be of a shape and material so that a portion of the energy in the spark will be used to heat the electrodes and will not be available in its entirety to heat the material in the gap. This is more pronounced with short gaps and is known as its quenching effect.

o The spark gap may be so long that the energy is distributed over too great a path length. The energy is not sufficiently concentrated to heat the mixture to ignition temperature.

B.23 King, J.C., "Effectiveness of the Static Charge Reducer in Attenuating Static Charges during Hydrocarbon Fuel Handling Operations," Final Report, March 1971-December 1973, Naval Civil Engineering Laboratory, Port Hueneme, CA, February 1975.

Discharge of static electrical charges during fuel-handling operations poses a high hazard of fire and explosion. The Static Charge Reducer (SCR) was developed to eliminate the need for a relaxation tank. The Civil Engineering Laboratory (CEL) tested the SCR's performace and compared it with that of relaxation tanks in reducing static charges associated with the handling of JP-4 and JP-5 fuel. It was found that the performace of the SCR and relaxation tanks was essentially the same in reducing static charges of up to $-340 \mu C/m^3$, except during turnon of the SCR, when a potentially hazardous condition might exist. Because of this potential hazard, it was recommended that the SCR not be used without a relaxation tank backup until it had been

determined that use of the SCR alone is free from hazard during turnon. If an SCR was developed which is safe under turnon conditions, considerable savings could be realized through use with large fuel systems, but not with systems smaller than 500-gpm because of the expense of monitoring equipment.

The results listed below were based on tests with the two batches of fuel (one each of JP-5 and JP-4).

o The performance of the SCR and relaxation tanks was essentially equivalent in satisfactorily reducing fuel charges of up to -340 $\mu C/m^3$, except during turnon of the SCR.

o Relaxation of the normal JP-5 was more difficult to attain at $30^{\circ}F$ than at any other test temperature.

o There was considerable overcapacity in the 30-second relaxation tank at $68^{\circ}F$ and $100^{\circ}F$ because no difference in charge relaxation could be detected regardless of whether 10, 20 or 30 seconds of relaxation time were used. However, at $30^{\circ}F$, 20 seconds were still adequate but 10 seconds permitted charges of over 40 uC/m^3 to pass through the tank.

o The charging tendency of the test fuels which had their conductivity lowered by clay filtration was not the same as when the conductivity was lowered by cooling.

o The factors that influence charging tendency of a fuel were not understood, and charge generation cannot be predicted in advance.

It was recommended that:

o The SCR not be used without a safety backup until firm evidence is available that a hazard does not exist during turnon of the SCR.

AFWAL-TR-83-2015

o A field-test program utilizing a 30-second relaxation tank as a safety backup be undertaken to: (a) establish reliability and endurance of the SCR in a high-rate refueling system, (b) obtain field data on the range of electrical conductivities of military jet fuels, and (c) obtain fuel data on charging levels that presently occur under steady flow and surge conditions.

o Use of an SCR/small-relaxation-tank combination, connected in series, be investigated for use in large refueling systems where considerable cost savings could be obtained.

o For reasons of economics, the SCR should not be considered for use on systems smaller than 500 gpm unless the requirement for monitoring performance of the SCR is rescinded.

REFERENCES

1. Leonard, J. T., "Generation of Electrostatic Charge in Fuel Handling Systems: A Literature Survey," Naval Research Laboratory Report 8484, September 1981.

2. Bachman, K. C, Dukek, W. G. and Popkin, A. H., "Aircraft Incidents Attributed to Static Electricity, 1959-1969," Report No. RL-45M-69, Esso Research and Engineering Co., Linden, N.J., July 21, 1969.

3. Mills, J. S., "Electrostatic Charging in Reticulated Foams," AFWAL-TR 81-2015, March 1981

4. Leonard, J. T. and Affens, W. A. "Electrostatic Charging of JP-4 Fuel on Polyurethane Foam," Naval Research Laboratory Report, 3 March 1978.

5. Dukek, W. G., Ferraro, J. M. and Taylor, W. F., "Static Electricity Hazards in Aircraft Fuel Systems," Exxon Research and Engineering Company, Technical Report AFAPL-TR-78-56, August 1978.

6. Hillman, T. C., Manheim, J. R. and Spencer, G. A., "Electrostatic Hazards of Urethane Packed Fuel Tanks," AFWAL-TR-82-2022, July 1982.

7. Radgowski, E. and Dantunono, D., "Final Report for Investigation of Electrostatic Discharge in A-10 Fuel Tanks During Refueling." Fairchild Republic Company, Report GT160RO164, 27 March 1978.

8. Dukek, W. G., Lunt, R. S. and Young, D. A., "Evaluation of the Hazards of Static Electricity in POL Systems," Exxon Research and Engineering Company, January 1976.

9. Bruinzeel, C., "Electric Discharge During Simulated Aircraft Fueling," Institute of Petroleum Journal, Vol. 49, No. 473, May 1963.

10. Bachman, K. C. and Dukek, W. G., "Static Electricity in Fueling Superjets," Esso Research and Engineering Company, Linden, NJ, January, 1972.

11. Johnson, J. K., "The Effect of Stadis 450 and ASA-3 on Sparking in Foam-Filled Tanks: Final Report," Shell Research Limited, September 1977.

12. Leonard, J.T., "Generation and Dissipation of Electrostatic Discharges in Aircraft Fuel Systems," Conference on Fire Safety Measures for Aircraft Fuel Systems, December 11-12, 1967.

13. Bridges, J. E., Zalewski, R. and Nanda, V., "Gap Energy, A More Accurate Criterion for Ignition Threshold of Flammable Mixtures," 1975 IEEE Electromagnetic Compatibility Symposium Record, San Antonio, Texas, October 7-9, 1975.

14. Johnson, J. K., "The Ignition of Vapour and Droplets by Liquid-to-Metal Sparks," Shell Research Limited, Journal of Electrostatics, Vol. 4, pp. 53-65, December 1977.

15. Carruthers, J. A. and Wigley, K. J., "The Estimation of Electrostatic Potentials, Fields, and Energies in a Rectangular Metal Tank Containing Charged Fuel," Journal of the Institute of Petroleum, Volume 48, Number 462, June 1962.

16. Dukek, W. G., Ferraro, J. M. and Taylor, W. F., "Static Electricity Hazards in Aircraft Fuel Systems," Exxon Research and Engineering Company, Technical Report AFAPL-TR-78-56, August 1978.

17. Hillman, T. C. and Spencer, G. A., "Electrostatic Evaluation of Aircraft Fuel Tank Inlets," AFWAL-TR-82-2091, September 1982.

18. Crouch, J. O. and Hillman, T. C., ASD/ENFEF, Wright-Patterson Air Force Base, Ohio, Private Communication.

19. Kalt, D. H., "Final Report, A-10A Fuel Tank/Vent System Vapor Ignition Investigation," ASD/ENFEF Report, 14 October 1981.

20. Farrand, T. E., "Investigation of Pinhole Failures in Teflon Hose Assemblies," Aeroquip Corp., Jackson, MI, Test Report No. 4063, November 1959.

21. Abbey, J. C. and Upham, "An Investigation of Electrostatically Induced Failures in Teflon Hose," presented at the SAE Committee Meeting, Detroit, April 1961.

22. Kuchta, J. M., "Fire and Explosion Manual for Aircraft Accident Investigations," AFAPL-TR-73-74, August 1983.

23. Coordinating Research Council, Inc., "A Survey of Electrical Conductivity and Charging Tendency Characteristics of Aircraft Turbine Fuels," CRC Report No. 478, April 1975.

END

FILMED

02 – 84

DTIC