

Report No. DS-67-9

**FINAL REPORT**

Project No. 520-002-05X

Contract No. FA66WA-1486

**AIRFLOW VELOCITY EFFECTS ON LIGHTNING  
IGNITION OF AIRCRAFT FUEL VENT EFFLUX**



JULY 1967

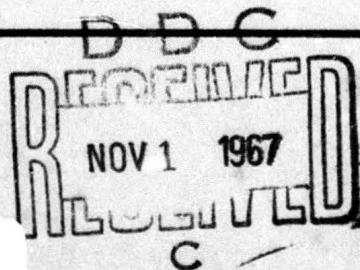
**DEPARTMENT OF TRANSPORTATION**

**FEDERAL AVIATION ADMINISTRATION**

**AIRCRAFT DEVELOPMENT SERVICE**

Washington, D. C. 20590

AD66U206



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**ON**  
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**ALEXANDRIA, VIRGINIA**

**JULY 1967**

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**DEPARTMENT OF TRANSPORTATION**  
**FEDERAL AVIATION ADMINISTRATION**  
**Aircraft Development Service**  
**Engineering and Safety Division**  
**Washington, D. C. , 20590**

## FOREWORD

This report was prepared by the Lightning and Transients Research Institute for the Federal Aviation Administration. The work effort was part of a program of the Engineering and Safety Division, Aircraft Development Service, Washington, D. C. Engineering liaison and technical review for this project was conducted by the Instruments and Equipment Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

## ABSTRACT

Studies of the effects of airflow, at aircraft holding velocities up to 250 knots, over the surface of an aircraft wingtip containing a recessed fuel vent showed that the probability of lightning ignition of the fuel vent efflux was greatly reduced by the airflow. From almost certain ignition with no airflow and the optimum fuel flow rate and mixture obtainable, the ignition frequency dropped to one in 34 shots with 50 knots airflow, one in 31 shots at 90 knots, none in 200 shots at 200 knots and none in 10 shots at 250 knots.

Streamering at the recessed fuel vent studied, due to a five megavolt surge, did not produce ignition, even with no airflow. However, with swept strokes the ignition frequencies were greatly increased to six in 8 shots at 100 knots and two in 36 shots at 200 knots. This result demonstrates that a swept stroke could be most hazardous. Even though the probability of swept strokes from the wing leading edge appears very low, further study should continue.

Very high flame speeds, of the order of 1,000 feet per second, have been measured. The lightning blast wave and the airstream effects appear to increase the flame speeds. Since present flame suppression devices and flame arresters are not effective against such very high flame front velocities, further study is also indicated. (1) /

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## I. Introduction

In previous F. A. A. sponsored programs (References (1) and (2)), directed towards overcoming lightning hazards to aircraft fuel systems, wingtip fuel vent hazards were studied under various simulated lightning and fuel-air mixture conditions. However, since the programs were short range, it was not possible to simultaneously provide an airflow across the vent scoop as would occur over the wingtip of an aircraft in actual flight. These airflow studies required the construction of a special wind tunnel. Such a generator-wind tunnel was constructed by LTRI, and this program is part of a long range continuing study of fuel vent lightning hazards and their reduction or elimination. Consultant aid and technical support on some of the wind tunnel and fuel vapor mixing problems was provided on this program by the Atlantic Research Corporation.

The main purpose of the generator-wind tunnel combination, described in the next section, was to duplicate lightning streaming near the vent for measurements under airflow conditions. As described in the report, no ignition of fuel vent efflux was obtained due to this mechanism, even with no airflow. Thus it was not necessary to use this combination for continuation of the investigation of the effects of lightning strokes near the fuel vent with airflows up to 250 knots. A new wind tunnel was constructed, as described in Appendix I, for completion of this investigation. In addition to study of nearby stroke effects, the new tunnel can be used for the study of "swept stroke" effects. Initial studies of such strokes are also reported in Appendix I.

## II. Combination High Voltage Generator and Wind Tunnel

In order to produce a high velocity air flow over the vent scoop on the under surface of an aircraft wingtip, with the wingtip at a high voltage, a mockup of the wingtip was mounted on the top of the ten million volt generator located aboard the Research Vessel THUNDERBOLT, as shown in the two views of Figure 1. The structure is capable of being lowered to a horizontal position for transport, but must be used in the vertical position shown to have adequate high voltage insulation. This high voltage generator was converted to also serve as the main duct of the wind tunnel. Normally there are two columns of capacitors in the generator with an aisle in between. One capacitor column was removed so that, along with the aisle space, adequate room was provided for the relatively low velocity air flow at large cross section. The tunnel tapered to a 12 x 20 inch rectangular opening and high velocity air flow directed toward the fuel vent scoop at the top of the tunnel. A curved plexiglass wall, shown at the right of Figure 2, was used to cover the capacitor column. It was curved in a manner suggested by Atlantic Research Corporation to break up any boundary layer which might develop and tend to reduce the effective cross sectional area of the tunnel.

Wingtip

High voltage  
generator  
(core used as  
wind tunnel)



Wingtip

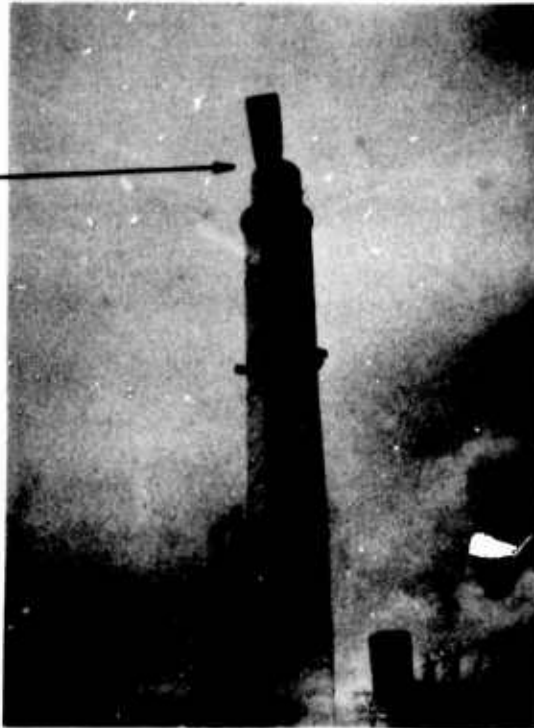


Figure 1. Two views of combination high voltage generator - wind tunnel in erected position.



Plexiglass  
wall

**Figure 2.** Inside of top of wind tunnel with curved plexiglass wall at right used to break up possible boundary layer.



Four bladed  
propeller  
hub

Upper  
gear  
box

**Figure 3.** Wind tunnel propeller at base of high voltage generator. Note gear box and provision for second propeller at left.

The air velocity was produced by the aircraft propeller shown at the right of Figure 3. The propeller is located at the base of the high voltage generator. The propeller axis is horizontal and the air was directed vertically into the bottom of the generator by a system of vanes. The driving gear box for the propeller makes a right angle turn and is shown at the left of Figure 3. Provision for mounting an additional propeller on the shaft is also shown between the propeller and gear box. Another view of the right angle gear box, looking down on the top of the box, is shown in Figure 4. A vertical drive shaft is below the box and its lower end is connected to a second right angle gear box, Figure 5, located in the main engine room of the THUNDERBOLT. This gear box is driven by one of the ship's main propulsion motors. The motor is electric and is, in turn, driven by a diesel-electric generator. The maximum power available to drive the propeller system was about 600 horsepower although the single propeller could not be loaded to utilize this much power.

The air velocity, obtained at the top of the tunnel in the first part of the program, was about 90 knots. Need was indicated for one or more additional propellers to obtain an adequate pressure head for the 250 knot wind velocities desired. There was insufficient time on this part of the program to add propellers and the initial fuel vent studies proceeded with the velocities obtainable. Later airstream velocities up to 275 knots were obtained with a separate wind tunnel as reported in section III and Appendix I.

Air flow velocities of the order of 90 knots made ignition, under conditions of most vulnerable fuel vent efflux mixture and flow rates, very difficult. Thus air flow was definitely established as a major factor in ignition even at low air velocities, and extrapolation of the results would indicate that the effects of increased wind velocities would be difficult to determine statistically because of the large number of No-Ignition strokes likely to be required before obtaining one ignition. Basically, a mixture, which will support flame propagation in the vent may be leaned out by the air flow so that it cannot ignite at the vent outlet. Then, if the mixture is made rich enough to ignite, it might be too rich to support propagation into the vent.

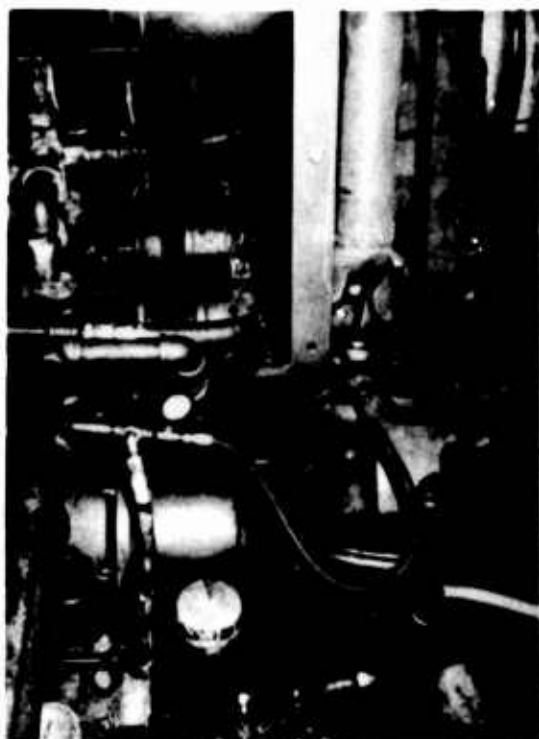
### III. Fuel Vent Efflux Ignition Measurements

The rotameters (flowmeters) and other equipment, used to establish known fuel-air ratios and flow rates of the propane ( $C_3H_8$ ) mixtures with air required, are shown in Figure 6 and schematically in Figure 8. To obtain maximum flow rates with the rotameters used, the air flow rate was measured at 100 psi which was the maximum pressure available. Since a smaller flow of propane was required for the mixtures desired, this flow rate was measured at atmospheric pressure. This accounts for the respective positions of the control valves shown in Figure 8. The



Propeller

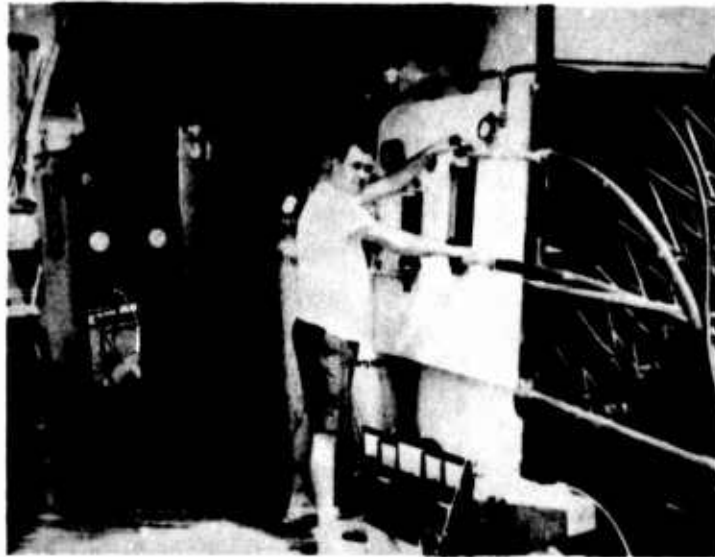
Figure 4. Top view of propeller upper gear train with provision for second propeller shown at right near propeller.



Drive shaft  
to upper  
gear box

Lower  
gear box

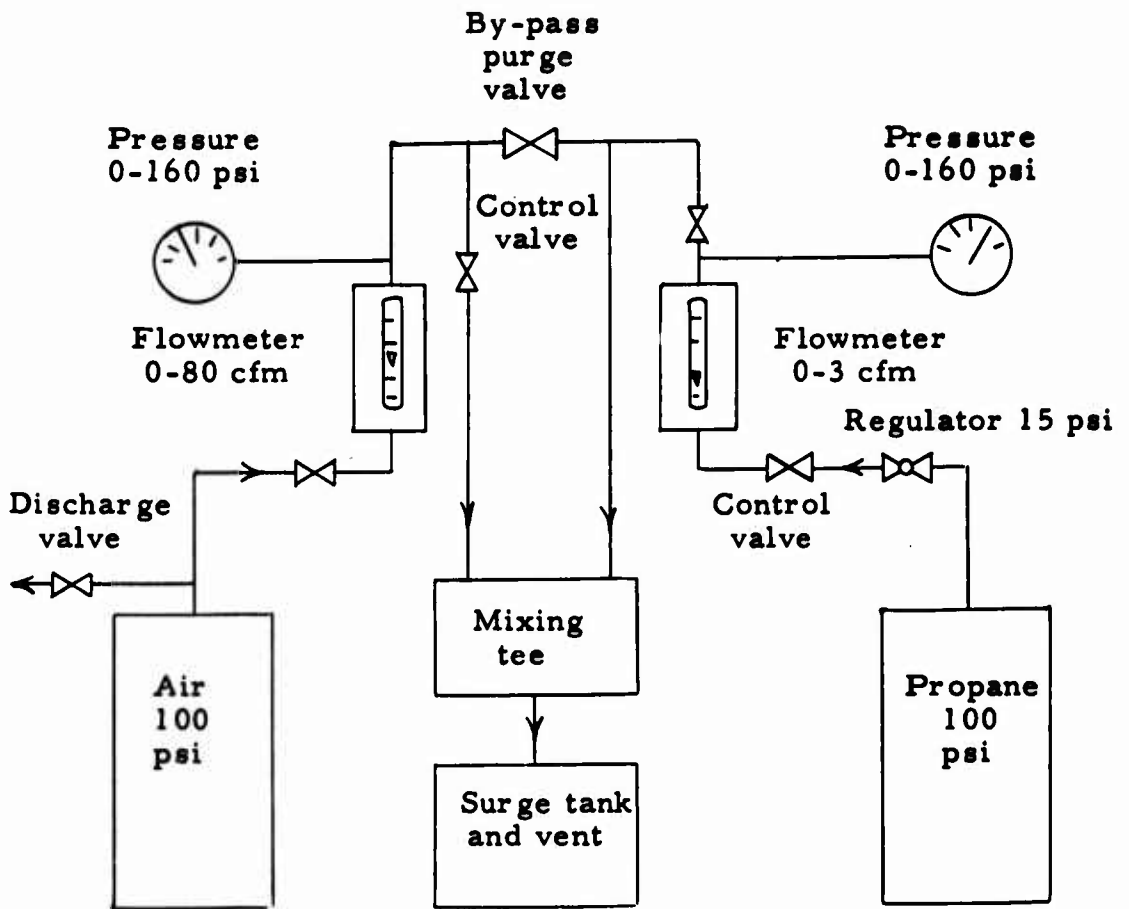
Figure 5. Propeller lower gear train under vertical drive shaft is driven by ship's main propulsion motor.



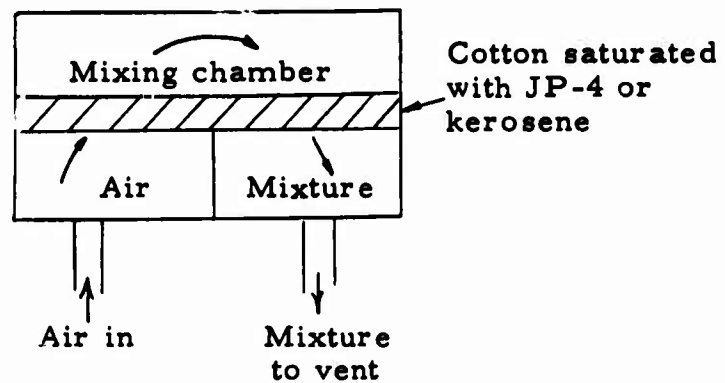
**Figure 6.** View of mixing equipment set-up for propane and air. Operator continually monitors flow-meters and gages. High voltage generator control panel at bottom right.



**Figure 7.** Carburetor for mixing air with JP-4 or kerosene.



**Figure 8.** Flow diagram of fuel-air mixture system.



**Figure 9.** Simple test carburetor for JP-4 and kerosene mixtures.

air and propane were carried in separate hoses to a mixing tee located just below the surge tank of the vent tube system. This separate feed prevented any possible flame propagation back toward the fluid supply systems. From the tee the mixture flows into the surge tank and out the S tube and vent. A blowout bag was provided on a pipe connected to the surge tank to help relieve the pressure of a sudden explosion.

The operator continually monitored the flow meters and pressure gages to obtain the correct mixtures and flow rates required. The various readings were held at the proper levels long enough to insure that the correct mixture had filled the vent system before a simulated stroke was applied. The vent outflow velocities selected were 1, 2, 5 and 10 feet per second and the mixtures used were proportioned for 0.5, 1.0 and 1.5 stoichiometric by volume. After each stroke the operator shut off the propane flow and flushed the propane line with air. Both air and propane were then shut off until the high voltage generator was ready for the next stroke, an interval of usually at least 5 minutes. Changes of propane temperature at the input to rotameter were monitored and showed a maximum increase of 5° F during operation, indicating negligible temperature effect on the flow rate. Before and after each set of 5 to 20 strokes, the mixture was checked by igniting the efflux under no air flow conditions in a control test. The high voltage generator control panel and triggering station is shown at the bottom right of Figure 6.

A special carburetor for mixing air with JP-4 or kerosene was constructed, Figure 7, and is shown schematically in Figure 9. While this carburetor was tested, as reported later, the results of this program were obtained primarily with propane-air mixtures. As pointed out in the Atlantic Research Corporation report, reference (2), "The fuels used in jet aircraft are usually paraffinic hydrocarbons. The nature of the combustion process in the vapor of these compounds is such that their pertinent combustion properties are nearly independent of their molecular weight. For example, the heat of combustion per gram, flame temperature, quenching distance, burning rate, and lean limit of combustion for the various paraffins are nearly equal. For this reason it is possible to employ any of the higher homologs of the paraffin series. Propane (C<sub>3</sub> H<sub>8</sub>) is readily available and easily manipulated in the gaseous state and hence was used in this program".

The wind tunnel output chute, Figure 10, directs the air flow over the fuel vent scoop. The air velocity was measured with and without the flow straightening grid shown on the mouth of the tunnel in Figure 11. The velocity was measured by the pitot tube shown mounted on a bracket which presented a knife edge in the direction of air flow for minimum interference. The spark gap electrode in the vent, also shown in Figure 11, was used for preliminary ignition tests where sparks were placed just inside the vent outlet slot.

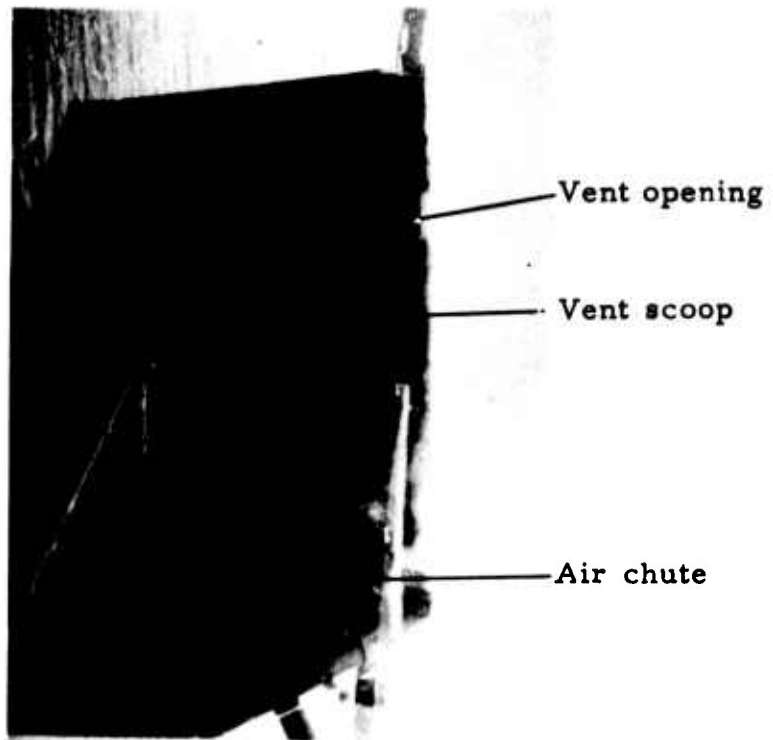


Figure 10. Wind tunnel plexiglass chute directs air flow over fuel vent scoop of wingtip mockup.

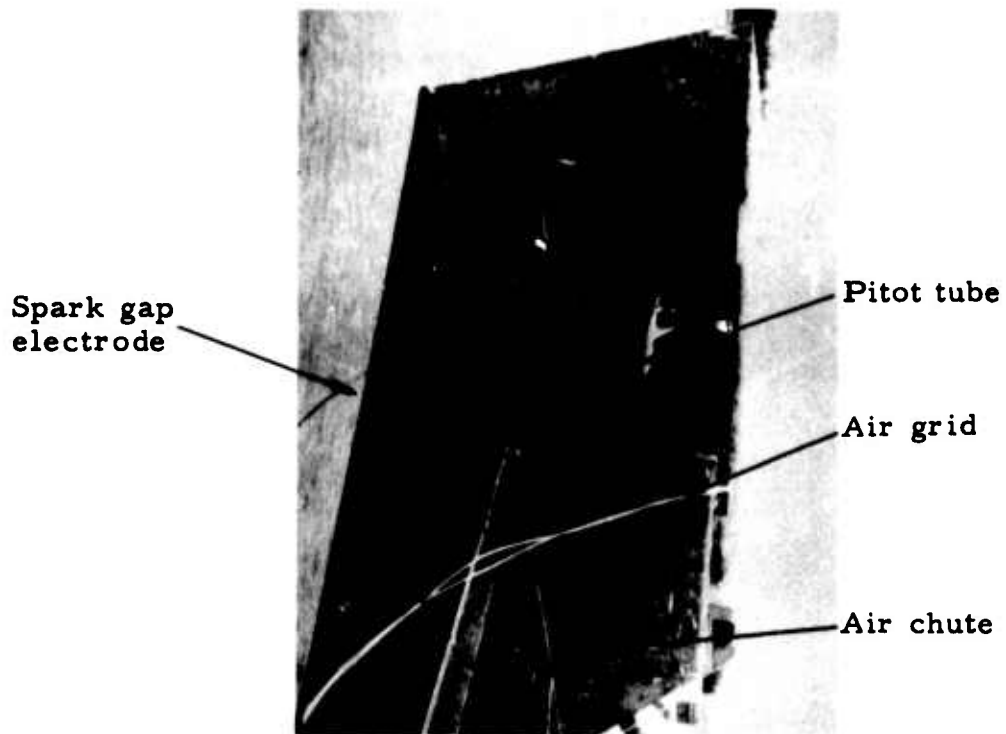


Figure 11. Air flow was straightened by grid at mouth of chute and the velocity was measured by the pitot tube shown. Spark gap electrode is shown in vent tube outlet slot.

A grounded probe was placed close enough to the vent to insure stroke contact at the edge of the vent scoop, as close to the vent outlet as is possible for an actual lightning stroke except for swept strokes. The probe in position near the scoop with a stroke to the vent scoop is shown in Figure 13. The waveform is a damped sinusoid in order to obtain highest peak currents. Figure 14 shows a close-up of the stroke and Figure 15 shows the pit marks of the stroke contact points, which verify that the strokes contacted the edge of the scoop near the vent outlet, as desired. Two views of ignitions due to such strokes are shown in Figure 16. The plasma width of natural lightning strokes is being studied in other programs (Reference (3)). While the pinch effect and other effects keep the ionized channel narrow for large current peaks, some of the observed strokes have a long duration, low current flowing between the high current peaks, which keeps the ionized channel alive and allows some of the ionization to spread out.

The discharge test results are summarized in Table I. Without air flow, measurements, using a spark gap in the vent outlet, Figure 11, produced reliable ignition at 1.0 and 1.5 stoichiometric for outflows of 5 or 10 feet per second. The 0.5 stoichiometric mixture was too lean when mixed with air at the vent outlet and likewise outflows of less than 5 feet per second were difficult to ignite. This result was verified with an air flow of 50 knots at 1.0 stoichiometric and, under these conditions, no ignition was obtained at outflow rates of less than 5 feet per second.

Simulated strokes to the edge of the vent scoop showed that the most vulnerable mixture and flow rate was 1.5 stoichiometric and 5 feet per second respectively. Combining the 1.0 and 1.5 stoichiometric mixtures at the 50 knot airflow, one ignition was obtained at an efflux rate of 5 feet per second out of 33 shots, giving a single sample probability of about 3%. With a 90 knot air flow no ignition was obtained in the first 30 shots at the 5 feet per second efflux rate and 1.0 and 1.5 stoichiometric. In a subsequent demonstration test under the same conditions, the first shot at 90 knots caused an explosion in the vent and surge tank which severely damaged the vent tube outlet box as shown in Figures 17, 18 and 20. Figure 19 shows an undamaged vent outlet box for reference. It was not possible to repeat this type of explosion on this program, but a similar explosion occurred during a later program sponsored by Pan American World Airways. This explosion also damaged the vent outlet and blew off an inspection cover bolted on a simulated surge tank. The flame speed associated with this explosion was measured in excess of 1,000 feet per second. Such a high flame speed may be due to an interaction of the flame front with the pressure and turbulence of the lightning blast wave. The wave may come from the blast pressure wave of the stroke or from turbulence or "organ pipe effect" (Reference (2)) set up by the high speed air flow over the vent scoop. More study in this area is indicated to determine the mechanisms involved and to reliably reproduce these high flame front velocities. Vent tube modifications or other measures required to reduce the maximum possible flame speed in the vent could then be worked out. The maximum flame speed

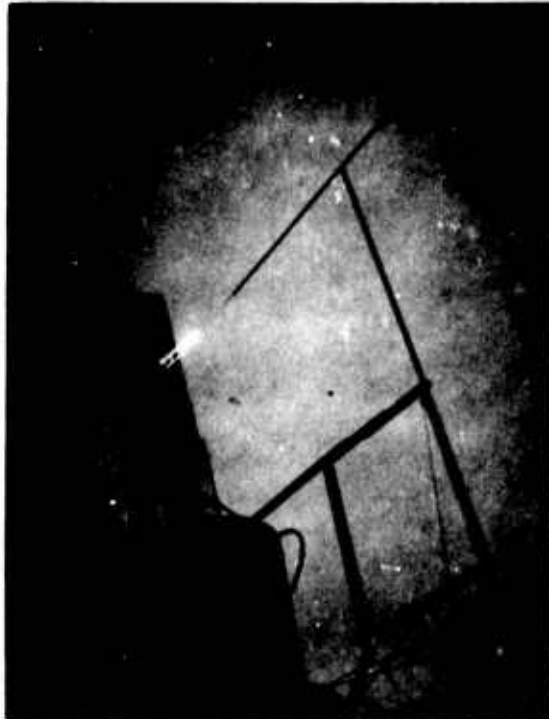


Figure 12. Stroke directed to trailing edge of vent scoop.



Figure 13. Typical current oscillogram. Scale 20 kiloamperes and 5 microseconds per large division.

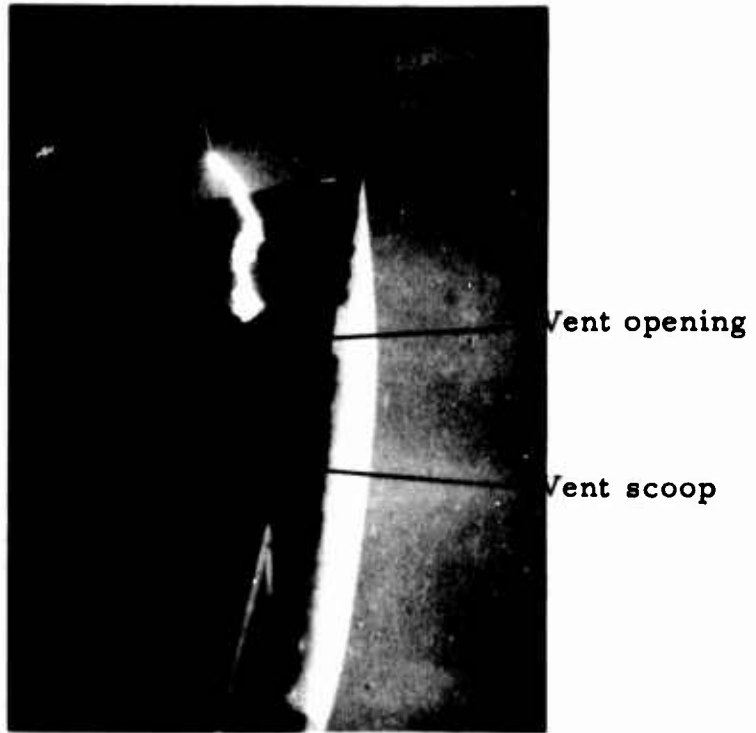


Figure 14. Close-up of stroke directed to edge of vent scoop.

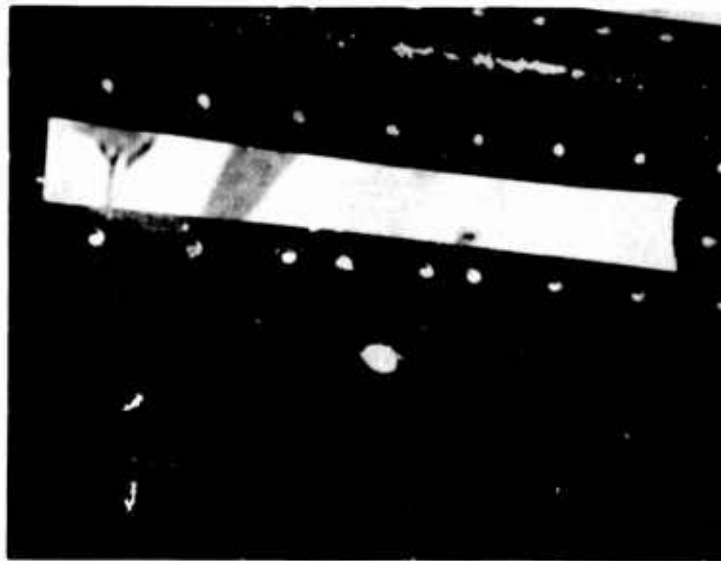


Figure 15. Pit marks show locations of stroke contact points along edge of vent scoop near vent outlet slot.

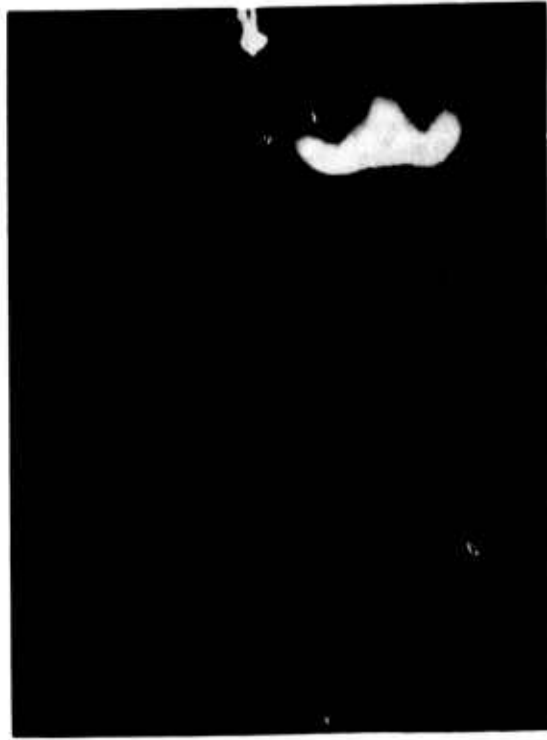


Figure 16. Ignition by stroke to vent scoop near vent outlet.

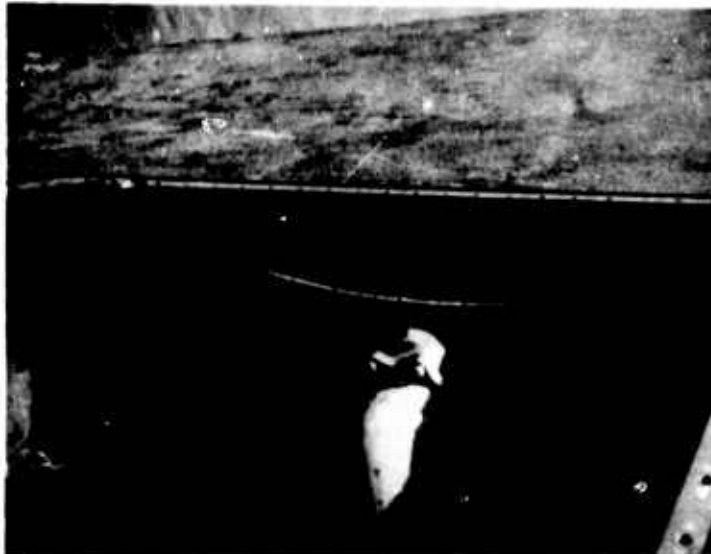


Figure 17. Vent tube outlet was distorted following a severe explosion in the vent tube system.

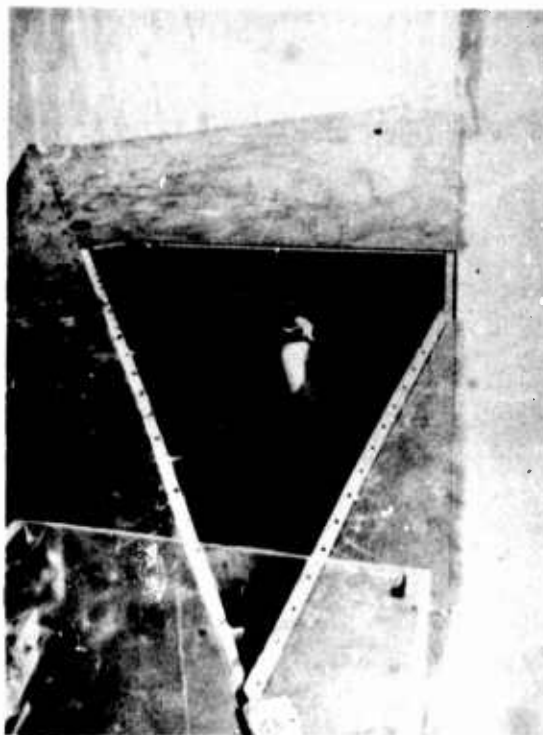


Figure 18. Vent tube after explosion showing S tube in place.

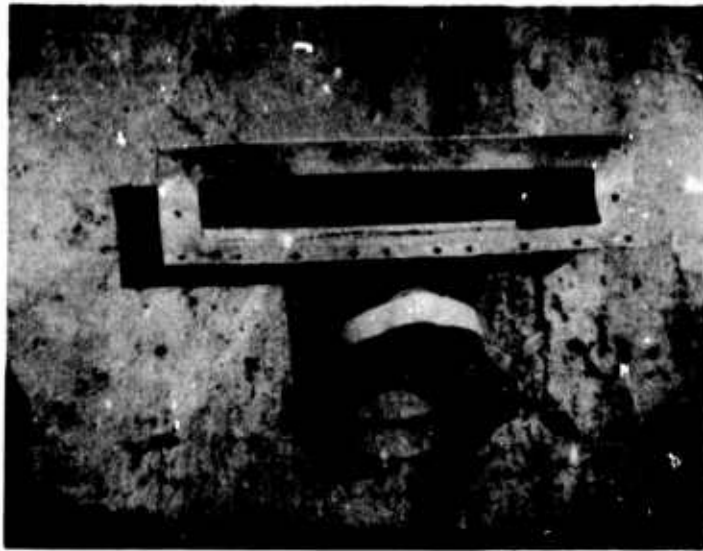


Figure 19. Normal vent tube outlet before explosion.

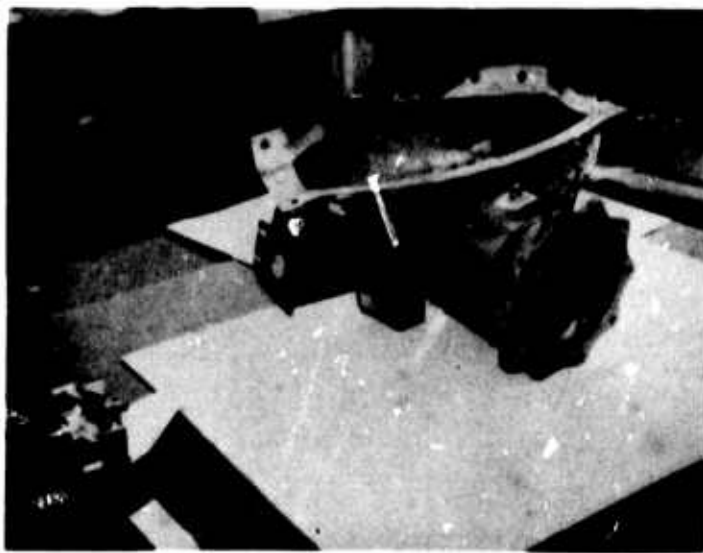


Figure 20. Close-up of vent tube outlet slot after explosion.

TABLE I

Summary of Discharge Test Results

Air Flow (knots)	Mixture (Stoich by volume)	Vent Outflow (fps)	No. of Shots	No. of Ignitions	Notes
0	0.5	1	1	1	Spark discharge in vent outlet.
		2	7	1	
		5	1	1	
		10	4	0	
	1.0	1	3	1	
		2	3	2	
		5	2	2	
		10	2	2	
	1.5	1	6	1	
		2	8	2	
		5	1	1	
		10			
50	1.0	1	2	0	"
		2	2	0	
		5	2	2	
		10	2	2	
0	0.5	1	1	0	Simulated stroke to trailing edge of fuel vent scoop.
		2	1	0	
		5	1	0	
		10	1	0	
	1.0	1	4	0	
		2	7	1	
		5	11	5	
		10	5	0	
	1.5	1	1	0	
		2	1	0	
		5	12	12*	
50	0.5	1	1	0	"
		2	1	0	
		5	1	0	
		10	1	0	
	1.0	1	1	0	
		2	1	0	
		5	16	1	
		10	1	0	
	1.5	1	1	0	
		2	1	0	
		5	17	0	

\*Most vulnerable condition.

TABLE I (Continued)

Summary of Discharge Test Results

Air Flow (knots)	Mixture (Stoich by volume)	Vent Outflow (fps)	No. of Shots	No. of ignitions	Notes	
90	0.5	1	1	0	Simulated strokes to trailing edge of fuel vent scoop.	
		2	1	0		
		5	1	0		
		10	1	0		
	1.0	5	15	0		
	1.5	5	16	1**		
200	1.15	5	60	0	"	
200	1.5	5	140	0		
250	1.15	5	5	0		
250	1.5	5	5	0		
90	1.15	5	7	4	Swept strokes	
90	1.5	5	8	7		
100	1.15	5	5	0		
100	1.5	5	8	6		
125	1.15	5	5	0		
125	1.5	5	5	1		
150	1.15	5	6	0		
150	1.5	5	5	0		
200	1.15	5	28	1		
200	1.5	5	18	1		
250	1.5	5	2	0		
0	1.5	5	10	0*		Streamers off wing-tip and vent at $5 \times 10^6$ volts.

\*\*Severe explosion. \*Most vulnerable condition.

should be low enough to be easily stopped by available explosion prevention devices, such as explosion suppression systems or acceptable flame arresters.

With simulated stroke to the trailing edge of the fuel vent scoop, no ignition was obtained at the higher air flow velocities of 200 and 250 knots. Results with swept strokes are also tabulated in Table I. The flame speeds and other swept stroke measurements are discussed in Appendix I.

Using the carburetor shown in Figure 7, an explosive mixture was obtained with a sampling of JP-4 fuels from all over the world obtained by Pan American World Airways. Ignition could be produced only once with a spark in the vent and no air flow over the vent scoop. The efflux velocity was one foot per second. An improved carburetor employing heat for vaporizing the fuels to facilitate more accurate mixing is indicated.

As discussed in the introduction, the main reason for applying the high voltage to an insulated wingtip at the top of the combination generator-wind tunnel, rather than grounding the assembly, was to check the possibility of ignition by streamers on or near the vent scoop. As is shown in Figure 21, 5 million volts produced streamering off the wingtip. The fuel mixture was adjusted to 1.5 stoichiometric at an outflow of 5 feet per second, the most vulnerable condition. Using simulated lightning discharges with no air flow earlier, we had obtained 12 ignitions out of 12 strokes to the vent scoop. Under streamering conditions, Figure 21, we obtained no ignitions in ten applications of the high voltage surge.

To check effects of angle-of-attack, a shallow climb was simulated by using a deflector, Figure 22, to deflect the average air flow toward the vent. In a check for control purposes, ignition was obtained without air flow with strokes directed to the vent scoop edge, using the established vulnerable mixture and efflux of 1.5 stoichiometric and 5 feet per second respectively. Under these conditions, when the air flow was added, no ignition was obtained in 5 shots at 50 knots or in 5 shots at 90 knots air flow.

Since there is some possibility of a stroke sweeping over the vent scoop, preliminary studies, as reported in Appendix I, were conducted using air flows from 0 to 250 knots.

#### IV. Conclusions

(1) The results of this study clearly show that windstream velocities up to 250 knots are a major factor in ignition and they reduce the limited sample probability of ignition from 100%, with no air flow velocity, to about 3%, with 50 to 90 knot air flows, for the most vulnerable conditions of mixture and vent efflux velocity. Higher windstream velocities further reduce this probability, but it is difficult to measure statistically because of the large number of carefully controlled measurements required. No ignitions were obtained in 200 shots at a 200 knot air flow and 10 shots at 250 knots.

(2) The most vulnerable fuel vent fuel-air ratio was found, in this study, to be 1.0 to 1.5 stoichiometric with an efflux velocity of about 5 feet per second.

(3) Streamering off the wingtip, produced by the application of a 5 million volt surge, did not cause ignition under the most vulnerable conditions of mixture and efflux velocity established in this program, even with no airflow.

(4) Very high flame speeds can occasionally occur upon ignition and are probably due to an interaction between the lightning blast wave and the flame front. These very high flame speeds, of the order of 1,000 feet per second, would pass through most flame arresters and other explosion suppression devices into the fuel tanks. It is, therefore, advisable to find means of reproducing fast flame fronts and of reducing the maximum possible flame front velocity.



Figure 21. Streamers off wingtip mockup did not ignite the fuel vapor efflux under the most vulnerable conditions of mixture, air flow and vapor flow from the vent.



Figure 22. A deflector was added to the wind tunnel plexiglass chute to change the direction of air flow over the vent scoop and thus vary the effective angle-of-attack.

(5) Changing the angle-of-attack of the air stream hitting the vent scoop on the underside of the wingtip mockup did not appear to increase the probability of ignition.

(6) An improved carburetor for generating a known fuel-air ration for JP-4, kerosene and a mixture of both would probably require a major effort and, theoretically, the results may be similar to those already obtained on this program for propane-air mixtures.

(7) Preliminary results using swept strokes, as discussed in Appendix I, indicated a high probability of ignition at 100 knots, decreasing to the order of about 4% for 46 shots at a 200 knot airflow.

#### V. Recommendations

(1) Basic studies of natural lightning plasma width and ionization characteristics, acoustic waves and likely swept stroke paths, applicable to strokes which contact the aircraft near the vent, should continue.

(2) Assuming for the present that swept strokes near the vent are possible, the ignition probabilities and flame speeds generated by this mechanism should be studied further.

(3) In order to reduce the maximum possible vent tube flame speeds, studies should continue on the mechanisms involved in producing these high velocity flame fronts so that methods of duplicating the proper conditions in the laboratory can be devised. For example, a stroke pressure wave could be produced far enough away from the vent so that ignition could not occur. The pressure waveform or current waveform could then be used to trigger a controlled spark, at various locations in the vent, timed, by simple delay networks, to produce a flame at a known time ahead of, on or behind the acoustic wave in the vent. Flame speeds could then be studied versus spark location in the vent space and in time relative to the acoustic wave, placing the flame at various positions relative to the acoustic wave. Such a systematic procedure would insure that the proper conditions, once found, could easily be reproduced. When the flame speeds can be reproduced, they may be reduced by the addition of baffles or other techniques with the objective of insuring that, in combination with available explosion prevention devices, the fuel vent system would be protected against known ignition hazards due to lightning, within the state of the art.

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The original wind tunnel calculations were carried out by consultant R. E. Rose of the University of Minnesota Aeronautical Department.

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## APPENDIX I

### Wind Tunnel for Direct Stroke Lightning Studies in Airstream Velocities Up to 250 Knots

#### I. Wind Tunnel for 250 Knot Airstream

An airflow over the surface of the wing is necessary to simulate actual flight conditions. Such a flow affects the lightning ignited fuel vent flame front velocities by causing turbulence and interacting with the lightning produced blast wave. LTRI has constructed a wind tunnel, Figure 1, aboard the Research Vessel THUNDERBOLT for duplicating the effects of airflow across the vent scoop on the wingtip surface in fuel vent studies and also for other aircraft lightning studies involving airflow simulation. The wind tunnel consists of three blowers in series driven by three 250 horsepower motors and has produced airflow velocities to about 275 knots using a rectangular opening about 5" by 33".

The wind tunnel air velocity was measured using the pressure difference developed by a pitot-static tube, Figure 2(a). The pitot tube could be moved to various locations about the vent when it was fitted on a pipe, Figure 2(b). The velocities about the vent were uniform within about 10 percent. The pitot-static pressure was measured with a water manometer and the readings converted to knots of air stream velocity with the help of a table, provided by Pan American, after correction for air temperature and barometric pressure. These results were checked against the readings of an air speed indicator and a Hastings Airmeter which uses a number of heated wires exposed to and cooled by the airflow. The change in resistance of these wires is measured and correlated with wind velocity. Good agreement was obtained between the air speed indicator and the manometer-air speed table readings. The low range of the Airmeter (readings of the order of 100 knots) also showed good agreement, but at the higher readings (about 150 knots) the scale of the Airmeter was too compressed for accurate comparison.

The maximum wind velocity measured at the fuel vent produced about 50 inches of water pressure at 60°F and 29.92 inches of mercury using the pitot tube, corresponding to a wind velocity of about 275 knots.

#### II. Preliminary Swept Stroke Studies

When an aircraft is struck by a long duration lightning flash, some of which last for about a second and may have from 2 to 40 repeated high current pulse components, the aircraft essentially flies through the relatively stationary lightning channel. Since an aircraft flying at 600 mph is traveling

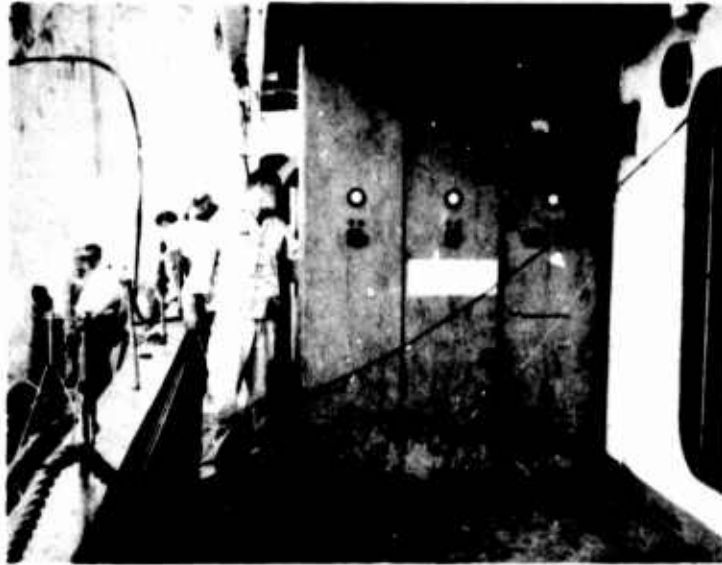


Figure 1-1(a). Control panels for three 2300 volt, 250 horsepower test cell blowers used in series for new wind tunnel.

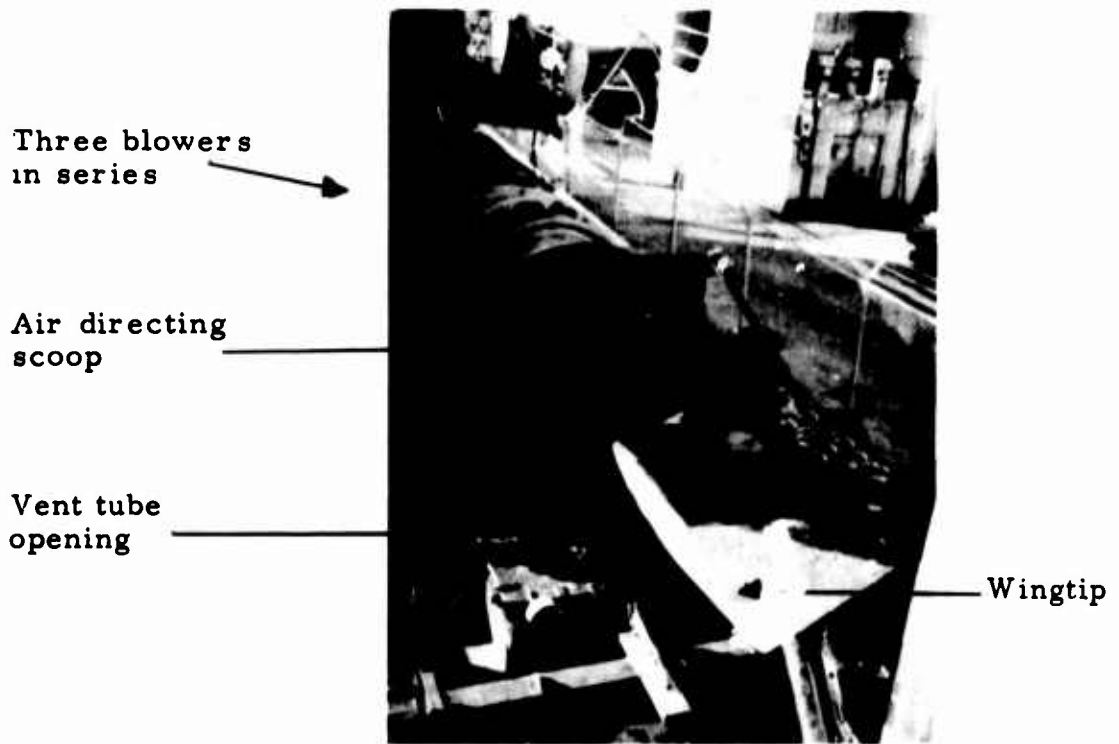


Figure 1-1(b). Wingtip section containing fuel vent was installed at the mouth of the wind tunnel. Airflow velocities up to 275 knots were obtained.

Spark gap  
electrode

Pitot tube



Figure 1-2(a). Normal position of pitot tube used to monitor airflow velocity near vent.



Figure 1-2(b). Airflow velocities at other points about the vent were monitored by mounting the pitot tube on a pipe and moving it to the desired position of the windstream.

about 880 feet per second, the channel can sweep across the surface of the aircraft, occasionally leaving a series of pit marks. By using the wind tunnel to produce the windstream effects, it is possible to sweep an artificial lightning stroke over the fuel vent to duplicate and study such "swept stroke" effects. The study of swept stroke effects has been proposed for further study.

Swept strokes to the fuel vent would normally follow the air stream from the wing leading edge. While there appears to be little evidence of leading edge strikes, such evidence, which usually takes the form of lightning pit marks, may be difficult to find or nonexistent in the case of a rapidly swept stroke.

To obtain swept strokes the duration of the simulated current pulse was increased from 50 microseconds to about 2 milliseconds. A typical short duration stroke is shown in Figure 3(a) with a swept stroke shown in Figure 3(b). Preliminary fuel vent investigations, using the current waveform shown in Figure 4, showed that two ignitions could be obtained out of 46 strokes in an airflow velocity of 200 knots.

The longer duration waveform is still a damped sinusoid with an initial peak current of about 50 kiloamperes but its duration was increased by using a generator having higher capacity. While the 50 microsecond stroke was adequate for stroke contact points close to the vent without air flow, the increased duration was necessary since, at an air flow of 200 knots corresponding to about 0.34 feet per millisecond, the current must continue while the stroke contacted ahead of the vent slot and was swept across it. From the swept stroke photograph, Figure 3(b), it is evident that the plasma was swept across the vent slot. The ionization quickly attains the velocity of the air stream. Thus about the same relative velocities are produced as in the in-flight conditions where the aircraft is moving through the ionization. Of course, natural lightning strokes may have durations of the order of a second and can sweep the entire length of an aircraft.

Special ionization sensors were installed in the fuel vent tube to measure flame front velocities. One of the ignitions, at the 200 knot windstream velocity, showed an initial flame front velocity of about 200 feet per second for the first foot inside the vent tube, in contrast to the 2 to 10 feet velocities usually obtained without air flow. The flame speed measurement oscillograms are shown in Figure 5. Further swept stroke and ignition studies have been proposed.



Figure 1-3(a). Typical short duration stroke to edge of vent scoop.



Figure 1-3(b). Typical stroke, of about two milliseconds duration, striking ahead of vent and sweeping over it in a 200 knot airflow.

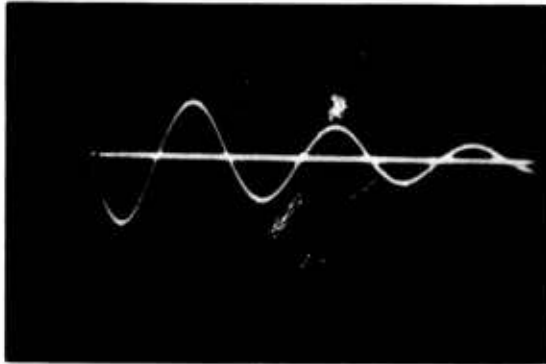


Figure 1-4. Waveform of current used for swept stroke studies near fuel vent. Scale 50 kiloamperes and 200 micro-seconds per large division.

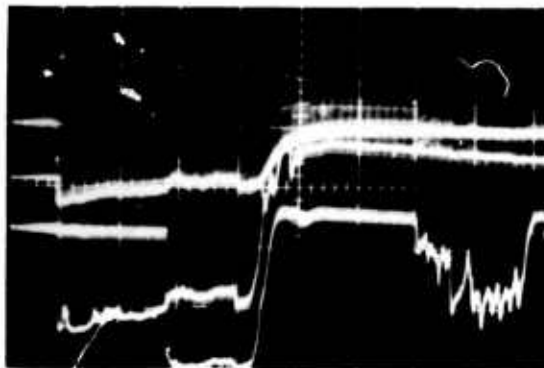


Figure 1-5. Oscillograms from three ionization probes located one foot apart in the vent tube. Ignition was due to a swept stroke in a 200 knot wind velocity. The time scale is 0.1 second per large division. The first time interval appears to be about 5 milliseconds corresponding to a flame front velocity of about 200 feet per second.