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A TEST TECHNIQUE FOR MEASURING LIGHTNING-INDUCED VOLTAGES ON AIRCRAFT ELECTRICAL CIRCUITS

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16. Abstract

This report describes the development of a test technique used for the measurement of lightning-induced voltages in the electrical circuits of a complete aircraft. The resultant technique utilizes a portable device known as a transient analyzer capable of generating unidirectional current impulses similar to lightning current surges, but at a lower current level. A linear relationship between the magnitude of lightning current and the magnitude of induced voltage permitted the scaling up of measured induced values to full threat levels. The test technique was found to be practical when used on a complete aircraft.

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SUMMARY

This report concerns the induced or indirect electrical effects of lightning upon aircraft. It is known that lightning currents which flow through the skin and structure of a metallic aircraft can induce hazardous voltages into electrical circuits within. There are also incidents of avionics equipment being disabled as a result of lightning strokes to aircraft.

With the knowledge that lightning may cause induced voltages of a magnitude probably sufficient to interfere with or damage sensitive aircraft electrical and avionics equipment (ref. 1), a program was undertaken with objectives to:

(a) Develop a technique to determine the potential effect upon aircraft electrical systems of lightning currents passing through the skin and structural members of a complete aircraft.

(b) Relate the effective electrical parameters associated with the induced-voltage phenomena to the physical and electrical characteristics of an aircraft and its circuitry.

(c) Evaluate the susceptibility of avionics equipment for control, communication, and other flight functions in modern aircraft to lightning-induced voltages.

This report concerns the first objective of this program. Toward this objective a test technique utilizing a portable low-energy impulse generator was developed as a workable tool in the investigation of lightning-induced voltages on aircraft. This portable impulse generator, which is referred henceforth to as an aircraft transient analyzer, is capable of providing unidirectional current impulses similar to lightning current surges but at a lower amplitude than that representative of natural lightning.

Using the complete right wing of a Northrop F89-J aircraft as a test bed and with the use of a complete F89-J aircraft to develop the practicality of

field testing, measurements were made of voltages and currents induced in selected wing and fuselage circuits as a result of the lightning currents passing through the wing skin and structural members.

It was found that a test technique could be developed making it possible to obtain valid measurements of lightning induced voltages on the electrical circuits of complete operational aircraft.

The results of transient analyzer tests at low amplitudes on a complete aircraft compared favorably with similar measurements at "full scale" current levels on circuits within a wing. The associated instrumentation was perfected to a high degree of noise-free accuracy, enabling the authentic reproduction of very low level transients in some aircraft circuits. Thus, a transportable, nondestructive test and measurement technique is now available with which to assess the possible lightning-induced voltages in any operational aircraft.

INTRODUCTION

The work described in this report is a continuation of a program conducted under NASA Contract NAS3-12019 and described in NASA report CR 1744 (ref. 1). In this previous report it was shown that lightning currents flowing through a metallic aircraft structure can cause transient voltages to appear in electrical circuits within the structure. These voltages are a combination of a resistive voltage rise caused by lightning currents passing through the finite resistance of the aircraft structure and a magnetically induced voltage arising in the electrical circuit as a result of linkage of magnetic flux created by the lightning current. In nearly all cases this voltage, appearing at the open-circuit terminals of the circuit, could be expressed as a mathematical combination of these two voltage components, where each in turn is expressable as a function of the lightning current itself, as follows:

$$e_{oc} = R\, i_L + M \frac{di_L}{dt}$$

where:

e_{oc} = voltage appearing across open circuit terminals in aircraft

R = an effective structure resistance

M = an effective mutual inductance between the lightning current and the particular electrical circuit

i_L = Lightning current (a time-varying function)

Because the induced voltages are dependent upon the lightning current, they vary considerably in amplitude and wave shape according to the lightning current parameters of amplitude and wave shape. Induced voltages are also dependent upon the characteristics of the circuit in which they are measured and the location at which the lightning stroke attaches to the aircraft.

The tests reported in NASA report CR 1744 used simulated full-scale lightning stroke currents up to 100 kA to induce voltages ranging from several millivolts to one hundred volts in electrical circuits in the complete right wing of a Northrup F89-J fighter aircraft.

One of the drawbacks of such full-scale test techniques is that the test equipment is usually stationary or at least expensive to move. The aircraft must usually be brought to the simulated lightning current impulse generator for test. This is a cumbersome operation at best and may be completely impossible in some cases. Another serious disadvantage of such full-scale tests is that they may be destructive to one or more systems in the aircraft being tested. Often this is unacceptable if the aircraft being investigated is operational.

During the previous program a series of tests were made in which a transient analyzer was utilized to provide low-amplitude nondestructive current surges to the F89-J wing. The transient analyzer is a development of the High Voltage Laboratory used in transient response studies of power transformers. In this series of tests, the induced voltage response to low-level currents from the transient analyzer was compared with similar measurements of voltages induced by full-scale lightning currents. The comparison was favorable, indicating that the results of low-level tests can be scaled proportionately upward to determine the results obtainable from full-scale lightning currents.

Therefore, developing a test technique utilizing the transient analyzer has several advantages over full-scale lightning tests. Being small and easily transportable, the transient analyzer has few restrictions as to location of test, and associated test setup times are greatly reduced. Instead of bringing the aircraft to the lightning generator, the transient analyzer can be taken to a complete aircraft, connected to certain attachment points on the aircraft, and resulting induced-voltage measurements can be made on the circuitry within short order.

The electromagnetic field interference between the high-energy simulated lightning generator and the sensitive induced voltage measurement equipment requires that elaborate shielding be provided this equipment to assure integrity of the measurements. With the low-energy transient analyzer this interference problem is minimized.

This technique has been used successfully at the High Voltage Laboratory for years in similar analyses of power transformers. Transient analyzers for this purpose are available, but several test parameters unique to the aircraft situation made it desirable to design and build a new one suited especially for aircraft use. Therefore, under this program a prototype transient analyzer was constructed with the desired capabilities. The transient analyzer must have the capability of injecting an impulse current through a complete aircraft at waveshapes representative of natural lightning and at a magnitude sufficient to create measurable induced voltages on the electrical circuits within.

To have the portability required for such a test technique all important test equipment must be self-contained except for AC power and grounding.

The work described in this report represents the development of the test technique from the design of the required aircraft transient analyzer to the actual use of the technique on a complete aircraft.

DEVELOPMENT OF AIRCRAFT TRANSIENT ANALYZER

LIGHTNING SIMULATION

A word must be said about lightning simulation. The lightning currents which pass through an aircraft when it is struck by lightning are believed to be a combination of high amplitude, short-duration "strokes" and low-amplitude, long-duration "continuing currents" (ref. 2, 3). The continuing currents are known to produce thermal erosion and resultant damage to aircraft skins. These currents, however, cannot produce significant induced voltages in internal circuitry.

The high-amplitude, short-duration strokes, however, may have very high rates of rise and the resultant rapidly changing magnetic flux (ϕ) can induce large voltages in magnetically coupled circuits. Therefore, simulated lightning currents produced by the aircraft transient analyzer must be the short-duration strokes, with fast rates of rise.

Description of the wave shape of the simulated lightning current is facilitated by use of the standard wave shape notation for current impulses. An impulse current, simulating a high-amplitude, short-duration lightning stroke is ideally an aperiodic transient current which rises rapidly to a maximum value and falls less rapidly to zero. The wave shape of such an impulse is defined by:

(1) polarity

(2) front time or time to crest (t_1)

(3) time to half value on the tail (t_2)

The wave shape is then described by the notation:

$$(t_1 \times t_2)$$

where t_1 and t_2 are usually expressed in terms of microseconds (μs). Thus, a wave rising to crest in 5 μs and decaying to 50% level in 10 μs is referred to as a 5 x 10 μs wave.

Since natural lightning currents vary greatly in wave shape, lightning simulation equipment must have great flexibility in terms of current wave shape parameters. If one can sacrifice amplitude, a transient analyzer can be designed to have an electrical versatility lacked by most full-scale impulse generators, and can generate a much wider range of current wave shapes. MIL-B-5087B, "Bonding, Grounding and Lightning Protection for Aerospace Vehicles" calls for a current wave form of 200,000 amperes peak, a pulse width of 5 to 10 microseconds at the 90% point, not less than 20 microseconds width at the 50% point, and a maximum rate-of-rise of at least 100,000 amperes per microsecond. The current wave shapes modeled include ones which have maximum rates-of-rise both faster and slower than MIL-B-5087B, and tails shorter as well as longer than 5087B calls for, as shown in Table I. No test oscillogram of the MIL-B-5087 wave shape has ever been reproduced in the literature, nor has it ever been graphically defined in the official standard. The only graphical representation we are aware of is shown in Figure 1, based on the interpretation in Reference 4.

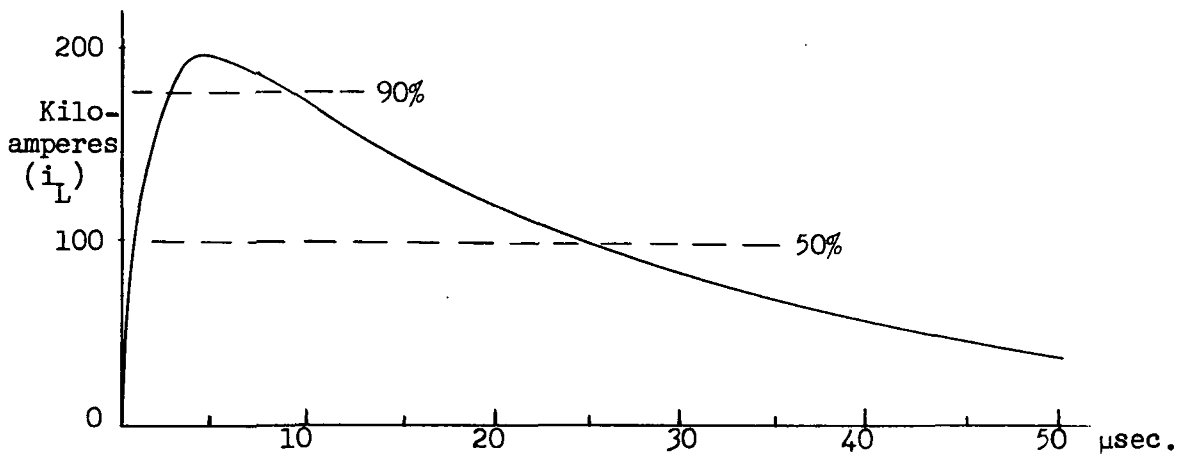


FIGURE 1. - LIGHTNING CURRENT WAVE SHAPE as per MIL-B-5087B.

Although few natural lightning strokes measured have had rates-of-rise this high, it was desired however to have the aircraft transient analyzer generate currents with wave shapes at least this fast, and when desired, 100 times as slow.

OBJECTIVES OF DEVELOPING A TEST TECHNIQUE

In developing a test technique for investigating the effect of lightning currents on aircraft electrical circuits in a complete aircraft a number of design objectives had to be met. These objectives fall into two categories, electrical and physical.

Electrical Design Objectives

(1) Provide enough charging capability within the transient analyzer to inject a few hundred to a few thousand amperes through a complete aircraft. This would insure that the resultant voltages induced on the aircraft electrical circuitry will range from millivolts to a few volts.

(2) The transient analyzer must produce a current pulse that would induce voltages on aircraft electrical circuitry similar to what the identical circuitry would see if the aircraft were struck by actual lightning. Therefore, the current pulse created by the transient analyzer must be unidirectional, rising to crest and falling to half crest value in times similar to actual lightning. The transient analyzer must also have the capability of producing current pulses similar to accepted lightning test standards, such as MIL-B-5087B.

(3) Since the possibility exists that some induced voltages will be in the millivolt range a measuring system must be provided that would reduce extraneous noise on the system.

(4) The transient analyzer should require no more than standard 110 volts AC power. This is to insure that power requirements can be satisfied in remote test areas either by line power or portable AC generators.

Physical Design Objectives

(1) There must be limitations on the size and weight of the transient analyzer. It must be able to be moved, if need be, by the personnel doing the testing, requiring no elaborate devices such as cranes, etc., that would not be available in remote test areas.

(2) Although personnel safety in regard to this test technique has mainly to do with prevention against electrical shock and would seem to be an electrical design objective, it is a physical design objective to provide sufficient grounding devices, warning lights and signs. Since this test technique is to be used in the field without the benefit of AC power interlocked test facilities, such as in a laboratory, adequate precautions must be taken to insure personnel safety.

(3) Due to the many possible locations where tests on an aircraft using this technique could be made the basic test setup must be simple. In fact, if possible, the size of the test site should be governed only by the size of the aircraft to be used.

(4) Since the test technique utilizes a complete, flyable aircraft as the test piece, the technique must not cause deterioration of the aircraft skin due to the injected current impulses. Such deterioration could occur at higher peak current levels (40 kiloamperes) as used in full scale testing. It is an objective of this test technique not to cause deterioration of the aircraft skin.

Also, the procedure used for connecting on to an electrical circuit for test must be nondestructive to the wiring when connections are made. The connections made to the electrical circuit from the measuring equipment must be simple, but yet must be of a nature as to insure measurement integrity.

(5) Connections must be made on circuits as they are positioned in the aircraft to obtain valid measurements. All access panels and other structural parts providing shielding for the circuits must be kept in place if possible.

GEOMETRIC MODELING OF LIGHTNING CURRENT TEST CIRCUITS

The transient analyzer is basically an energy storage device utilizing capacitors as the energy storage units. The capacitors are charged up to a certain DC voltage using a high voltage DC power supply. When the capacitors are charged to a specific voltage level, the energy is released through a sphere gap. By adding resistance and inductance in series with the output of the transient analyzer, the output current wave could be shaped into a unidirectional wave rising from zero to a peak current level in a specific time and falling to half peak value in a specified time.

In designing a transient analyzer to accomplish the objectives listed above the complete test circuit must be taken into consideration. This test circuit includes a complete aircraft structure in series with the transient analyzer impulse circuit. The contribution that an aircraft would make to the test circuit impedance was not completely known.

A complete aircraft was not available during the preliminary design of the aircraft transient analyzer. Therefore, in order to select design parameters for an aircraft transient analyzer capable of injecting the required lightning current wave shapes and current levels through a complete aircraft, the aircraft test circuit, including the aircraft, was geometrically modeled.

A geometric type model is a scale model in which no attempt is made to duplicate the power levels to which the full size structure is subjected. For this type of model, if scale factors are applied to any three quantities, the scale factors for all other quantities are fixed.

A typical choice of parameter scales is one such that the impedance, Z, of the model is the same as the impedance of the full-size structure. The impedance scale fixed is thus unity. The length scale was determined by the model aircraft used (ℓ = 1/70). A third parameter to conveniently set is the dielectric constant ($\epsilon = 1$). Thus,

$$\text{length} = \ell = 1/70 \tag{1}$$

$$Z = 1 \tag{2}$$

$$\epsilon = 1 \tag{3}$$

If the impedance, Z, is 1, then the resistance, R, of the model is 1. From dimensions of units in the MKS system (ref. 5):

$$R = 1 = \frac{M\ell^2}{tQ^2} \tag{4}$$

where:

M = mass

ℓ = length

t = time

Q = charge (coulomb)

From equation (4):
if:

$$\frac{\ell^2}{t} = \frac{Q^2}{M} \tag{5}$$

then:

$$C = \text{capacitance} = \frac{t^2Q^2}{M\ell^2} = t \tag{6}$$

$$L = \text{inductance} = \frac{M\ell^2}{Q^2} = t \tag{7}$$

$$\epsilon = \text{dielectric constant} = \frac{t^2Q^2}{M\ell^3} = \frac{t}{\ell} \tag{8}$$

From equation (3):

$$\epsilon = 1 = \frac{t}{\ell} \tag{9}$$

$$t = \ell = 1/70 \tag{10}$$

Thus the length scale (ℓ) and the time scale (t) are the same.

With the length and time scales both equal to 1/70, the scale factors for the component values used in the geometric model are:

$$\text{Resistance} = R = 1$$
$$\text{Inductance} = L/70 = 1/70$$
$$\text{Capacitance} = C/70 = 1/70$$

With this information, aircraft transient analyzer component values were selected to give the desired range of wave shapes, with adequate amplitudes, by simply varying the model component parameters, without having the actual test aircraft. It also allows one to vary other parameters and study the effects.

The entire circuit, representative of a real-life situation was laid out using a 1/70 model. The airplane in this case was a plastic model, T33-A jet trainer, similar in size and shape to an F89-J aircraft, which would be used for the actual field tests. The model aircraft was coated with a silver-loaded (conductive) paint. (An F89-J model was not available.) The layout of the circuit can be seen in Figure 2.

The current conducting loop was kept a distance of approximately one "wing span" distance from the aircraft in order to minimize return circuit proximity effects. As shown in Figure 3, a 67-volt battery charged up a capacitor, C, through approximately 400 ohms. The capacitor was then discharged through series resistance, R, and through the model aircraft. The current, i_L, returned via the double loop. The inductance, L, was the inductance of the complete circuit.

Three current wave shapes were obtained using the model circuit. The circuit components used to create these wave shapes are listed in Table I. with values for the peak lightning currents obtained.

From measurements made using this geometric model, the projected maximum amperes obtained with a transient analyzer operating at a charging voltage of 50 kV would be as shown in Table II. A comparison is made in Table II with the projected current wave shapes and the current wave shape as specified in MIL-B-5087B.

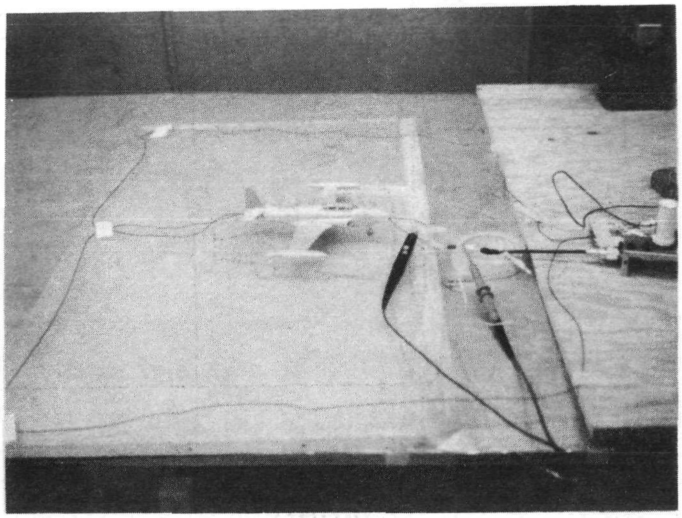
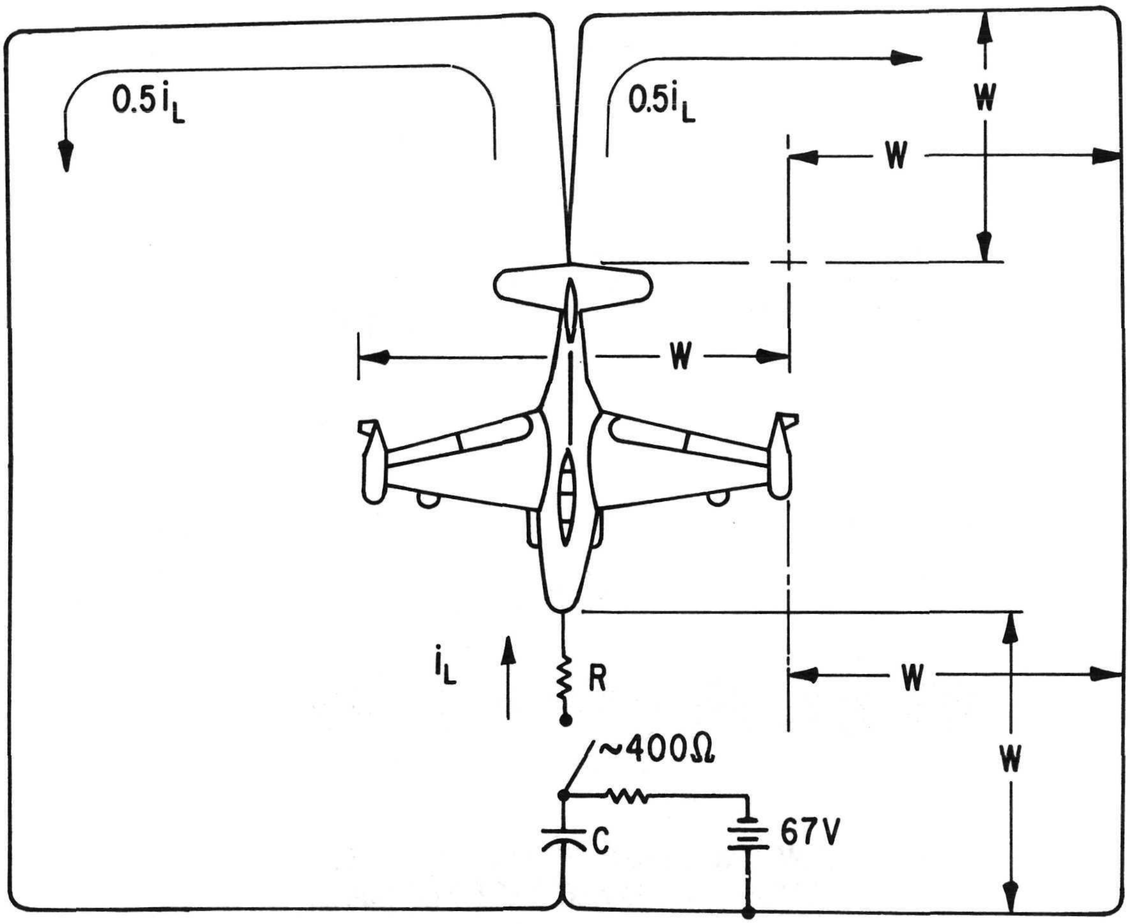


FIGURE 2 - GEOMETRIC MODEL CIRCUIT LAYOUT OF TRANSIENT ANALYZER TEST TECHNIQUE



NOTE 1. "W" EQUALS LENGTH OF WING SPAN

2. NO LUMPED INDUCTANCES WERE INCLUDED. CIRCUIT INDUCTANCE WAS THE DISTRIBUTED SELF AND MUTUAL INDUCTANCES OF EACH BRANCH CIRCUIT.

FIGURE 3- PLAN VIEW OF GEOMETRIC MODEL CIRCUIT LAYOUT OF TRANSIENT ANALYZER TEST TECHNIQUE

TABLE I - ACTUAL VALUE OF TEST CIRCUIT PARAMETERS USED IN GEOMETRIC MODEL WITH GENERATED WAVE SHAPES

Lightning Current Wave Shape Generated microseonds	Circuit Inductance, L/70 microhenries	Series Resistance, R, ohms	Generator Capacitance, C/70 microfarads	Actual Peak Lightning Current, i_L at 40 volts Charging Voltage amperes
0.07 x 0.25	model circuit	47	0.007	0.68
0.15 x 0.30	model circuit	12	0.02	1.80
0.40 x 1.0	model circuit + 3.7 microhenries	39	0.03	0.78

TABLE II - PROJECTED VALUES OF TEST CIRCUIT PARAMETERS WITH PROJECTED PEAK LIGHTNING CURRENT OBTAINABLE WITH AIRCRAFT TRANSIENT ANALYZER WITH CHARGING VOLTAGE OF 50 KILOVOLTS

Lightning Current Wave Shape Scaled-Up microseconds	Circuit Inductance, L, microhenries	Series Resistance, R, ohms	Generator Capacitance, C, microfarads	Projected Peak Lightning Current, i_L at 50 kilovolts Charging Voltage amperes
4.9 x 17.5	circuit	47	0.49	850
10.5 x 21	circuit	12	1.40	2250
28 x 70	circuit + 259 microhenries	39	2.10	975
5 x 20	Wave shape specified in MIL-B-5087B			

It was possible to obtain a compact 50 kilovolt DC power supply that would suit the needs of this test technique.

The projected current output sufficiently met the design objectives. Based on previous induced-voltage measurements, it is clear that lightning current amplitude in excess of 100 amperes would be capable of inducing measurable levels of voltage in the aircraft circuitry. It is also noted from Table II that the required values of generator capacitance, C, did not vary widely. Thus, the generator capacitance could be composed of four 0.5 μf capacitors with 50 kilovolt ratings; one or more of which could be in the circuit as needed for particular wave shapes. The wave shaping series resistance placed in the generator circuit would be non-inductive resistors with values of from 10 Ω to 50 Ω. Series inductance, L_s, needed for the longer wave shapes would be hand-wound coils externally placed in series with the output of the transient analyzer, to make up, together with the inherent test circuit path inductance, the total inductance, L, required for the desired wave shape.

The initial tests had wiring taped tightly to the ground plane. Model testing continued by raising the wiring off the ground plane to study any associated variations in inductance. The wiring was placed on a sheet of plexiglass. No changes were noted in wave shapes or current amplitudes.

Instead of the double loop return path, a single foil return was used on the model. This would simulate a foil run back under the aircraft. Again, no changes were noted in wave shapes or current amplitude. In actual testing, comparisons were made between the single return path and the double loop return under the same lightning current test conditions. It was found that for either return path configuration, the lightning tests were the same. In addition, during the actual tests it was found that resulting induced voltages were the same for either return path configuration. In other words, the proximity effect of current returning to the generator did not noticeably influence the amount of induced voltages in an electrical circuit inside the metal airframe.

DESIGN AND OPERATION OF THE AIRCRAFT TRANSIENT ANALYZER

Keeping in mind the electrical and physical design objectives, the aircraft transient analyzer was built. Photographs and descriptive sketches of the transient analyzer are shown in Figures 4, 5, and 6. The electrical circuit diagram of the transient analyzer is shown in Figure 7. A list of the major components used in the transient analyzer are found in Table III.

AC POWER

AC power for the aircraft transient analyzer is supplied by an external 115 V AC 60 hertz source. Power requirements are 250 watts at the maximum charge of 50 kilovolts. The on-off power switch is a lock switch which can only be operated by a specific key to prevent unauthorized personnel from operating the transient analyzer.

When AC power is switched on, a yellow indicating light comes on, on the front panel. This indicates that power is being supplied to the trigger pulse generator and the remote trigger relay.

Charging of the capacitor banks can be initiated either by a charging switch on the front panel of the transient analyzer or by a remote charging switch which is usually placed in the area where the measurement oscilloscopes are. This permits remote control of the complete operating procedure from transient analyzer discharge ("firing") to applied lightning current and induced voltage measurement.

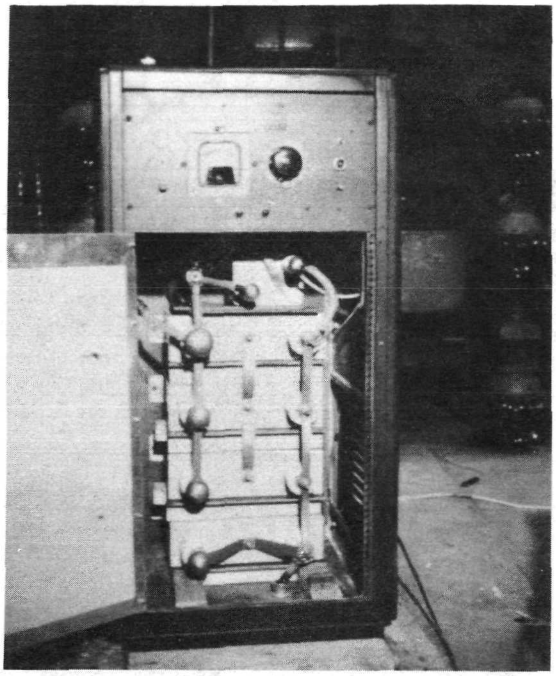
When charging is initiated, a red light on the front panel comes on. Also a larger red light, indicating charging, is mounted on the top of the aircraft so all personnel within the nearby area are aware of the fact that the transient analyzer is being energized.

AC SAFETY INTERLOCK SYSTEM

Due to the high voltages used in the production of the simulated lightning current impulses, precautions must be carefully taken to provide personnel safety.

The cabinet used for the transient analyzer is completely enclosed, with energy storage, power supply and control components used in the production of

FIGURE 4. - AIRCRAFT TRANSIENT ANALYZER



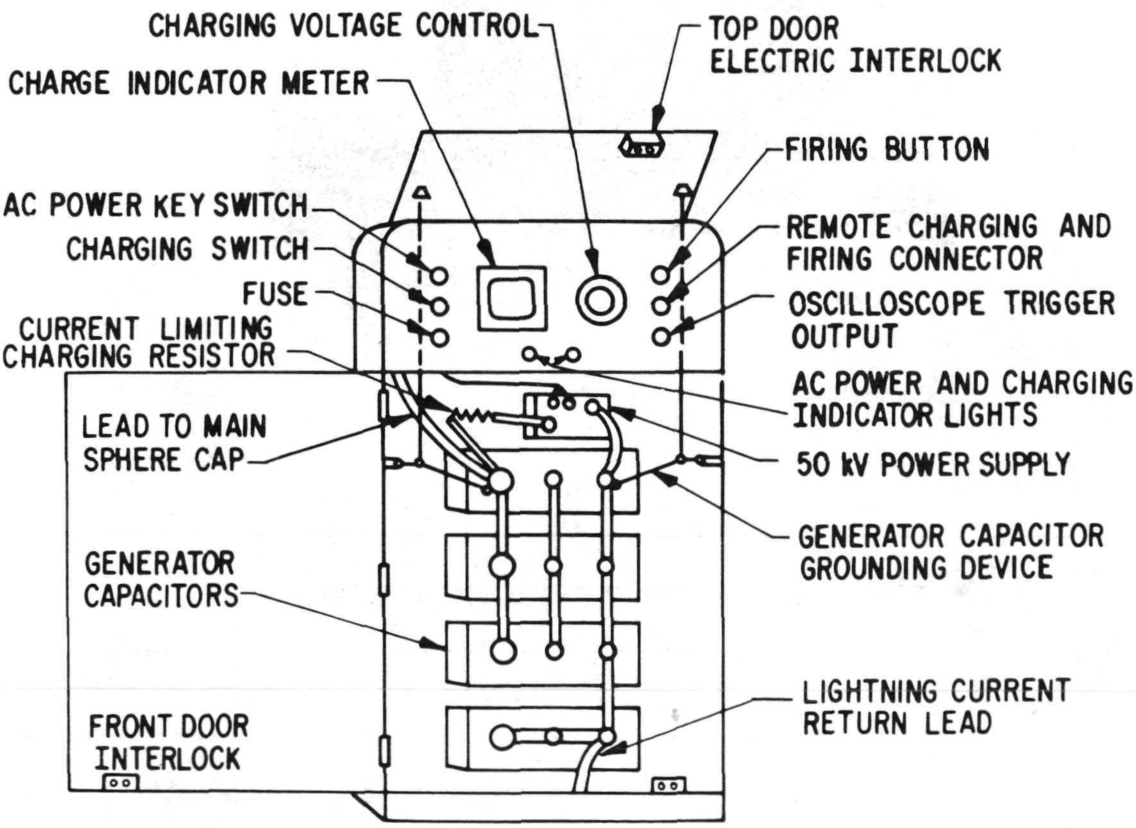
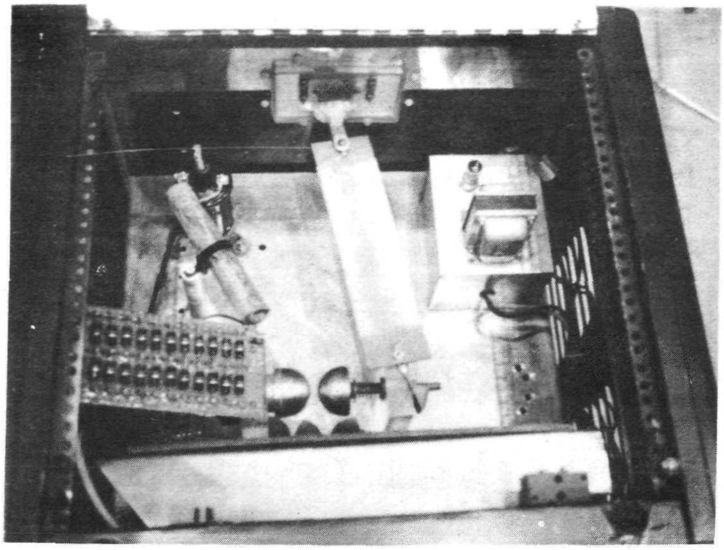


FIGURE 5 - AIRCRAFT TRANSIENT ANALYZER SHOWING POWER SUPPLY, GENERATOR CAPACITORS, AND GROUNDING SYSTEM.



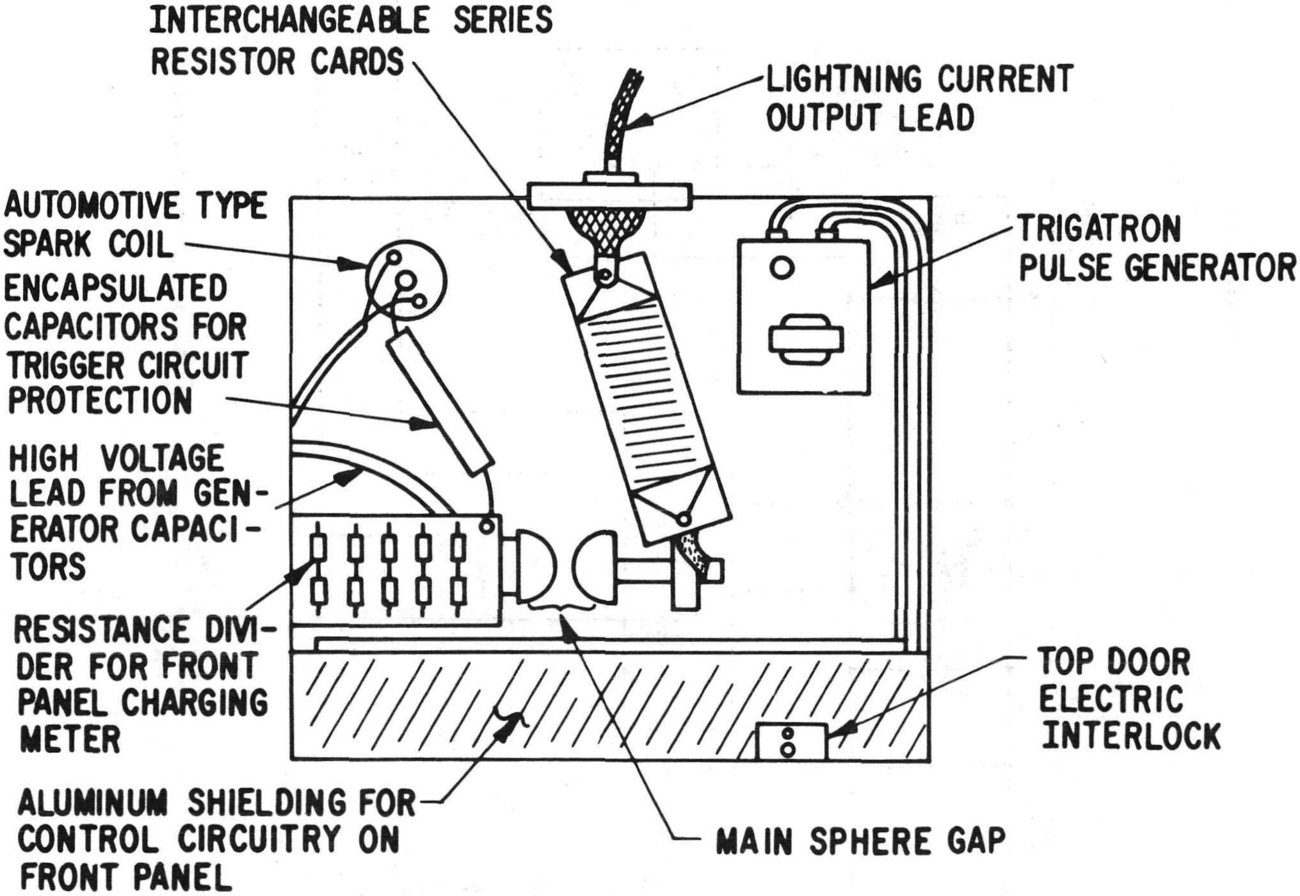


FIGURE 6 – EXPOSED TOP VIEW OF AIRCRAFT TRANSIENT ANALYZER SHOWING PLACEMENT OF COMPONENTS.

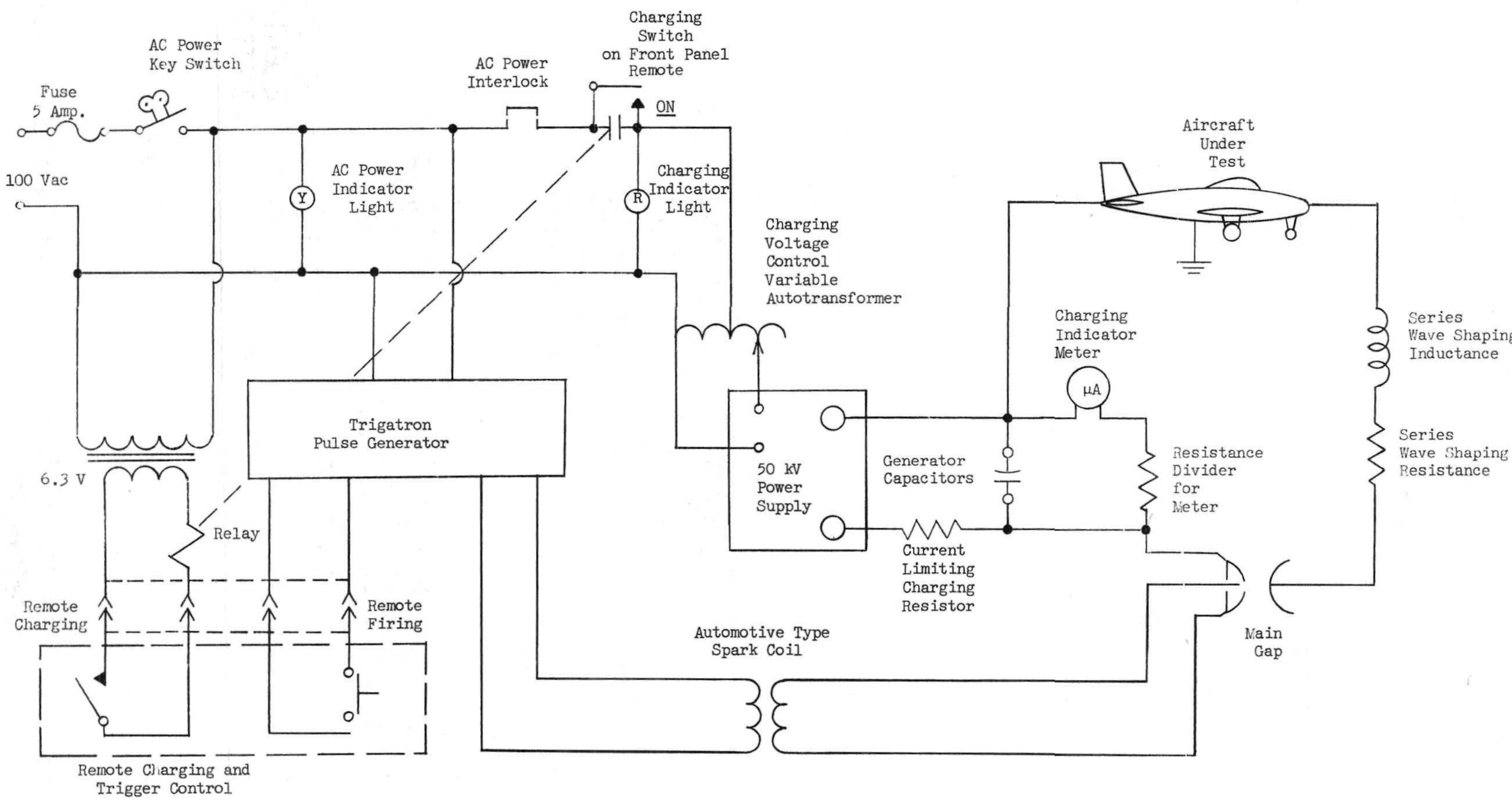
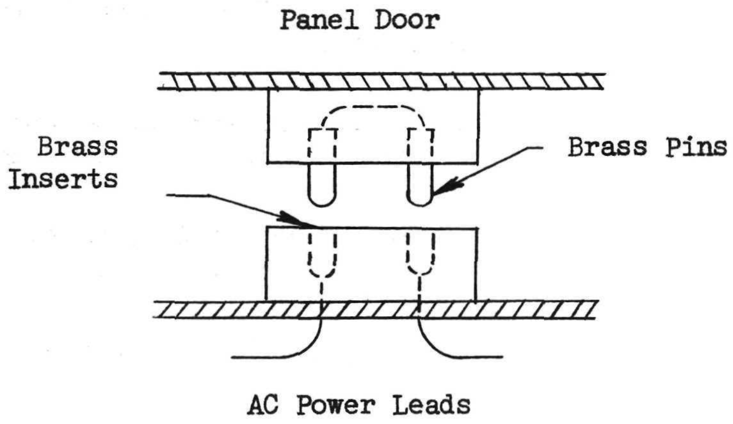


FIGURE 7. - AIRCRAFT TRANSIENT ANALYZER WIRING DIAGRAM

TABLE III - AIRCRAFT TRANSIENT ANALYZER MAJOR COMPONENTS		
Enclosure	-	Borg-Warner Electronics Cabinet 2' x 2' x 4'
Power Supply	-	Plastic Capacitors HV 500-502M 0-50 kilovolts DC, 5 milliampere
Capacitors	-	General Electric Catalog No. 14F1292 0.5 μfd, 50 kilovolt rating
Charging Resistor	-	1 R.D. Type MVO 10 megohms
Charging Indicator Meter	-	General Electric Type 106 0 - 100 microamperes DC
Charging Voltage Control	-	Superior Electric Co. Variable Autotransformer
Resistance Divider	-	50 Megohm, 50 - 1 megohm resistors
Triggering Circuit	-	Trigatron Pulse Generator

the simulated lightning currents included within. External components include any lumped inductance coils and, of course, the circuit through the aircraft. 115 V AC power is required from an external source via a removable cord from a recessed male outlet mounted in the base of the cabinet.

There are two panel doors that can be opened for access to the charging circuitry, wave shaping elements, sphere gap, and capacitors. The panel doors are interlocked for incoming AC power, by means of two pin connectors as shown below.



The front panel door not only is interlocked, but has a rod that is inserted through the top access door that locks the front door in a closed position. A capacitor grounding mechanism grounds both terminals of the capacitors when the top access door is opened. To insure complete grounding of the capacitors when changes in the capacitor connections are required, a ground stick is provided for the operator's use to ground the center point of the capacitors, which is the capacitor case itself, and all other live elements when the front panel door is opened.

The transient analyzer cabinet is grounded at all times.

PERSONNEL SAFETY

The field test nature of this test technique can imply elimination of controlled safety procedures that automatically exist in indoor laboratories such as electrically interlocked test areas with limited access to the electrical generation equipment and the test pieces. Therefore, to comply with established High Voltage Laboratory safety rules and to rule out any questionable procedure that would endanger the personnel involved in this type of test program, specific safety regulations were instituted.

High Voltage Laboratory safety rules specify for "Temporary Testing Setups and Portable Equipment" that:

> "Temporary fence properly grounded and interlocked to enclose the high voltage test apparatus should be used when possible. Good grounds and ground sticks must be provided. If the use of temporary fence is impractical, the dangerous area must be enclosed, with adequate clearance, by red-striped white tape (alone) or rope with suitable signs such as DANGER-HIGH VOLTAGE and DANGER-UNAUTHORIZED PERSONS KEEP OUT.
>
> Special care should be observed with all portable test equipment. The removable ground connections should be securely connected. Unless completely self-contained, portable sets should have their high voltage circuits within a regular test area or a special interlocked temporary area."

In this particular case, the test area is defined by encircling the test piece, transient analyzer, and measurement equipment enclosure with red rope, with warning signs attached, in compliance with the aforementioned rules.

As was stated before, warning lights were installed on the transient analyzer that signify when AC power is on and when the generator charging voltage is on. A red light, mounted on top of the transient analyzer, signifies charging voltage is on. It was found that, when lit, this light could not be seen more than a few feet from the transient analyzer. A future modification is to replace this light with a large flashing red light that could be seen up to a hundred feet away.

HIGH VOLTAGE INSULATION

Since the design required high charging voltages and subsequently high output currents from a device of compact size, the placement of all components important to the operation of the aircraft transient analyzer was very critical. High stresses placed on components by the charging voltage had to be reduced and minimized. Spacings between the high voltage power supply bushings and the enclosure panels, between the capacitor bushings and the capacitor grounding devices, between capacitor cases and enclosure panels were most critical. DC leakage currents flowing during the capacitor charging period were perhaps the most troublesome. The capacitors used, of the 2-bushing ungrounded type, were used in this application because of availability. Therefore, the electrical circuit of the transient analyzer called for isolating the cases of the capacitors and several other components from ground. This isolation was needed since with these particular capacitors, the cases are the midpoints of the capacitors, with a maximum of 25 kV possible between each bushing to case and 50 kV between bushings. The isolation in this prototype unit was accomplished by using wood to support the capacitors and Herkolite, a treated laminated insulating material, for supporting and isolating the capacitors. By using grounded-case capacitors much of this insulation could be eliminated.

IMPULSE CIRCUIT

To achieve the magnitudes of simulated lightning current needed to fulfill the design objectives of the aircraft transient analyzer a 50 kilovolt DC power supply was employed for charging the capacitors. The charge level is regulated by a variable autotransformer controlling the input voltage to the power supply.

The power supply has a five milliampere rating and is protected by a

10 megohm resistor in series with the output of the power supply to the capacitors.

As was stated previously, capacitors 0.5 μf each, are used. From one to four of the capacitors can be connected in parallel to provide the amount of capacitance needed to create a certain wave shape.

The percent charging voltage (up to a maximum of 50 kV) is indicated on a meter mounted on the front panel of the transient analyzer. The meter is connected across the output of the DC power supply. It has resistance in series with it to limit its current to a maximum of 100 milliamperes at a charge of 50 kilovolts.

When the capacitors are charged to the specified voltage level, the energy is released through a sphere gap. This sparkover is initiated by a trigatron gap. Figure 6 shows the gap structure. A trip pulse sparks the annular pilot gap and so distorts the field in the main gap that it will spark at a voltage considerably lower than the inherent breadown voltage for the sphere gap itself. The trip pulse is applied by a pulse generator utilizing an automobile type spark coil in series to step up the trip pulse voltage.

All wave shaping, triggering, voltage monitoring, and AC power control circuitry is mounted above an aluminum plate which separates this part of the circuit from the power supply and energy storage capacitors, which are mounted beneath. The arrangement of these items is shown in Figure 5.

PRELIMINARY TESTING OF AIRCRAFT TRANSIENT ANALYZER

A series of outdoor tests were made to simulate the situation that would be encountered when a complete aircraft was subjected to tests using the aircraft transient analyzer. Grounding configurations and measuring techniques were investigated.

The test piece used for these outdoor tests, a wing from an F89-J aircraft, is described in NASA report CR-1744. It was moved to the High Voltage Laboratory outdoor test facility and induced voltage measurements were made on circuits within the wing using the aircraft transient analyzer as the lightning current source. Figure 8 shows the wing in the test area.

GROUNDING CONFIGURATIONS

Figure 9 shows the test setup in the outdoor area.

The current from the transient analyzer was injected at points likely to be struck by lightning, the current then flowing down the wing and being removed at the root end, returning to the generator through a foil return path.

The case of the aircraft transient analyzer was grounded and connected to the measurement trailer by an aluminum foil connection. Foil was also placed directly beneath the induced voltage measurement cable. This foil was joined to the foil connecting the case of the transient analyzer and the measurement trailer. All of the simulated lightning current returns to the aircraft transient analyzer after flowing through the wing. Even though there was the foil connection from the root end of the wing to the grounded measurement trailer this foil did not carry any of the lightning current, since all current must return to the negative side of the generator capacitors, which were ungrounded.

There are further comments on grounding in regard to personnel safety. A complete aircraft is used as the test piece in this example.

Since the test circuit ground is made from an airframe to instrument and earth ground, as shown in Figure 10, it is safe for a person to touch the airframe during the charging or discharging of the transient analyzer,

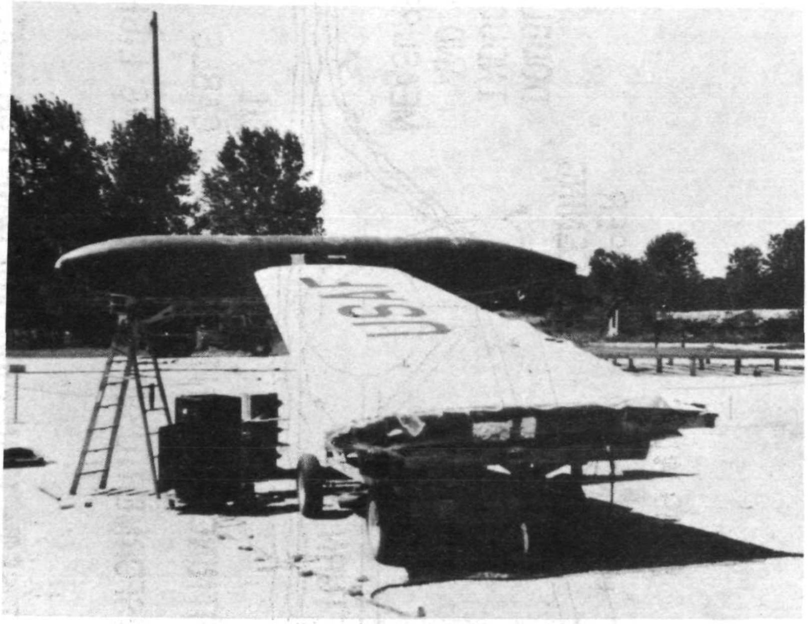


FIGURE 8 - RIGHT WING FROM F89-J AIRCRAFT POSITIONED IN G.E. HIGH VOLTAGE LABORATORY OUTDOOR TEST AREA FOR PRELIMINARY TESTS USING AIRCRAFT TRANSIENT ANALYZER

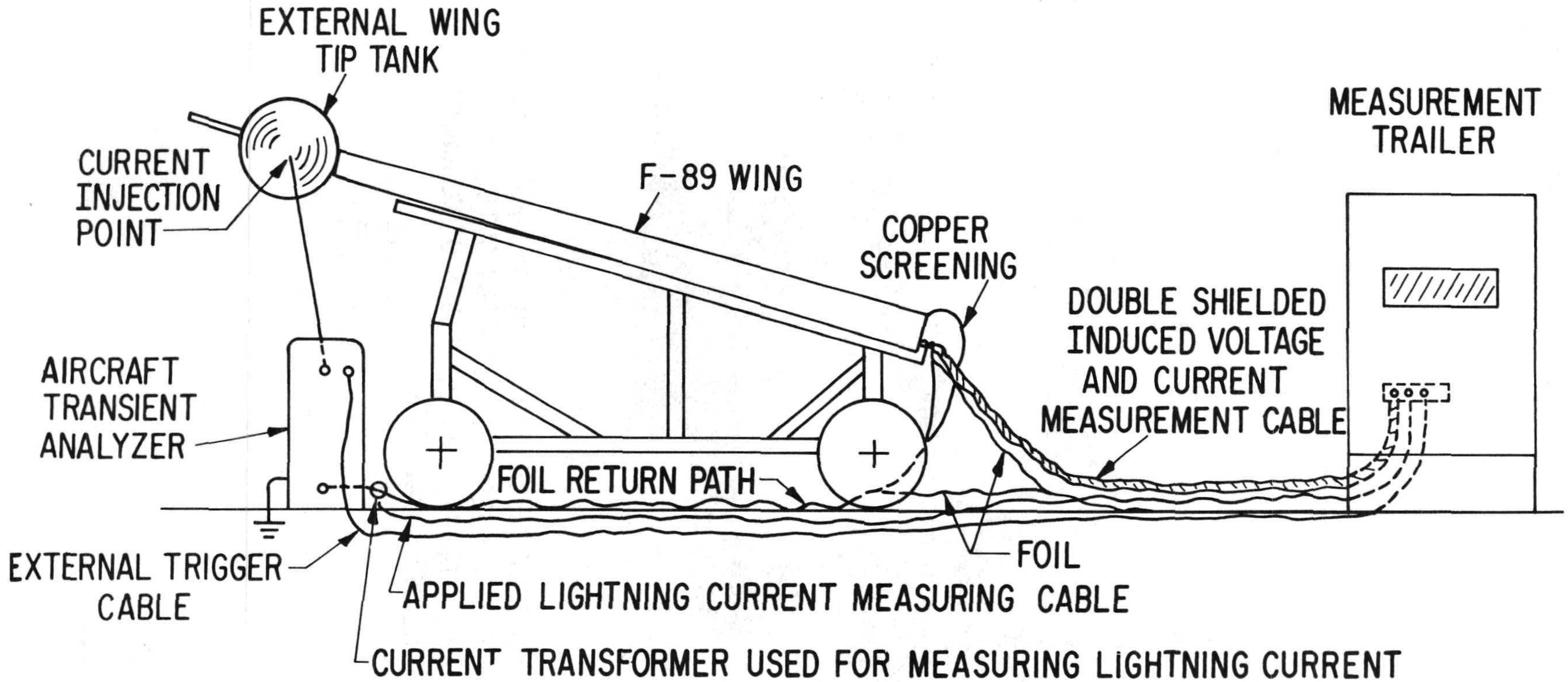


FIGURE 9 - F89 - J WING TEST SET-UP IN HIGH VOLTAGE LABORATORY OUTDOOR TEST FACILITY

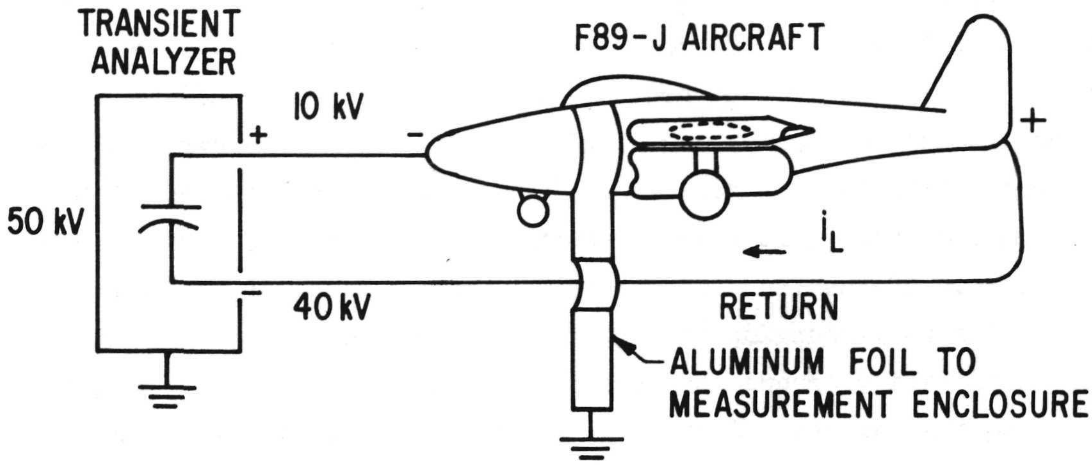


FIGURE 10-DIAGRAM OF TEST CIRCUIT SHOWING ISOLATED LEADS TO AND FROM TRANSIENT ANALYZER

providing the person is standing on an equally grounded or unbiased surface, such as the earth or a concrete path, etc. Inductive voltage drops around the test circuit loop must add up to the total charge voltage at t = 0+ (until current starts to flow in the circuit). However, the relatively low inductance of a large metal airframe results in very low voltage differential along the airframe. Instead, the voltage exists across lumped circuit inductances and the return path or connecting leads. Therefore, both the positive and negative terminals of the transient analyzer are above or below ground by a significant voltage, as shown in Figure 10.

Thus, while the airframe is at ground, the negative side of the transient analyzer can be at a large potential below ground. This is why the negative side of the transient analyzer capacitance must be insulated by at least the full charging voltage from the cabinet, and it is why one cannot arbitrarily ground the negative side of the transient analyzer capacitance to the cabinet. Further study of the above circuit also indicates that a ground stick placed on the positive output lead of the transient analyzer will not necessarily "ground" the transient analyzer, as an open circuit return lead could render such a ground completely ineffective.

DIFFERENTIAL MEASURING SYSTEM

The simulated lightning current created by the aircraft transient analyzer flows through a wing or other parts of an aircraft creating a magnetic field that induces voltages on electric circuits in the aircraft. A differential measurement system is used to measure voltages induced on the electrical circuitry. The reason for using a differential instead of a coaxial measurement system is to cancel out error voltages and currents induced in the cable leads by external fields leaking through the measurement cable shields or by cable shield currents induced by such external fields.

Figure 11 shows a comparison of coaxial and differential measurement systems. A coaxial cable system, Figure 11a, used with this test setup can permit extraneous signals to travel down the cable conductor and shield with the result that the induced voltage seen on the oscilloscope could be the induced voltage plus the extraneous noise.

Figure 11b shows the differential system used. With a differential measurement one conductor is connected to a wing circuit in question. The other conductor is connected to the cable shield and the airframe at the point where the measurement is made. The two conductors are connected to the channel "A" and channel "B" inputs of a Tektronix Type G preamplifier which subtracts one incoming signal from another, with the resultant output being the true induced voltage on the wing circuit.

Further explanation of the differential measurement system is illustrated in Figure 12.

Current is flowing along a wing or any other structural part of the aircraft. The connection to the differential measurement system is shown in the figure as the shielded twin-axial cable connected to a circuit. In a line-to-ground measurement one lead of the twin-axial cable would be connected to the wing and the cable shield.

Figure 12 illustrates two cases where measurement errors could exist. In case (1), if the cable shield is not connected to the airframe at b, the voltage induced along the loop formed by the airframe, aluminum foil, and cable shield appears between the airframe at b (channel "B") and the shield at "s", so that channel "B" alone has a large error voltage in it.

In case (2), if the instrument cable shield at "s" is tied to the airframe at "b", then a circulating current exists in the loop. This circulating current can induce common mode error in both channels "A" and "B" due to current flow in the cable shield. If significant, such an error may saturate the channel "A" and channel "B" amplifiers of the measurement oscilloscopes rendering signal measurements inaccurate.

Thus, to insure valid measurements the aluminum foil ground connection must be grounded to the airframe as close as possible to the desired zero-voltage reference location on the airframe and solidly connected there. No other ground connections can be made anywhere to the airframe. The measurement cable must be brought to and inside the airframe along the foil and its shield also connected to the airframe at the desired zero-voltage reference location. No loops or "openings" must exist between the foil and the measurement cable shield as shown in Figure 12.

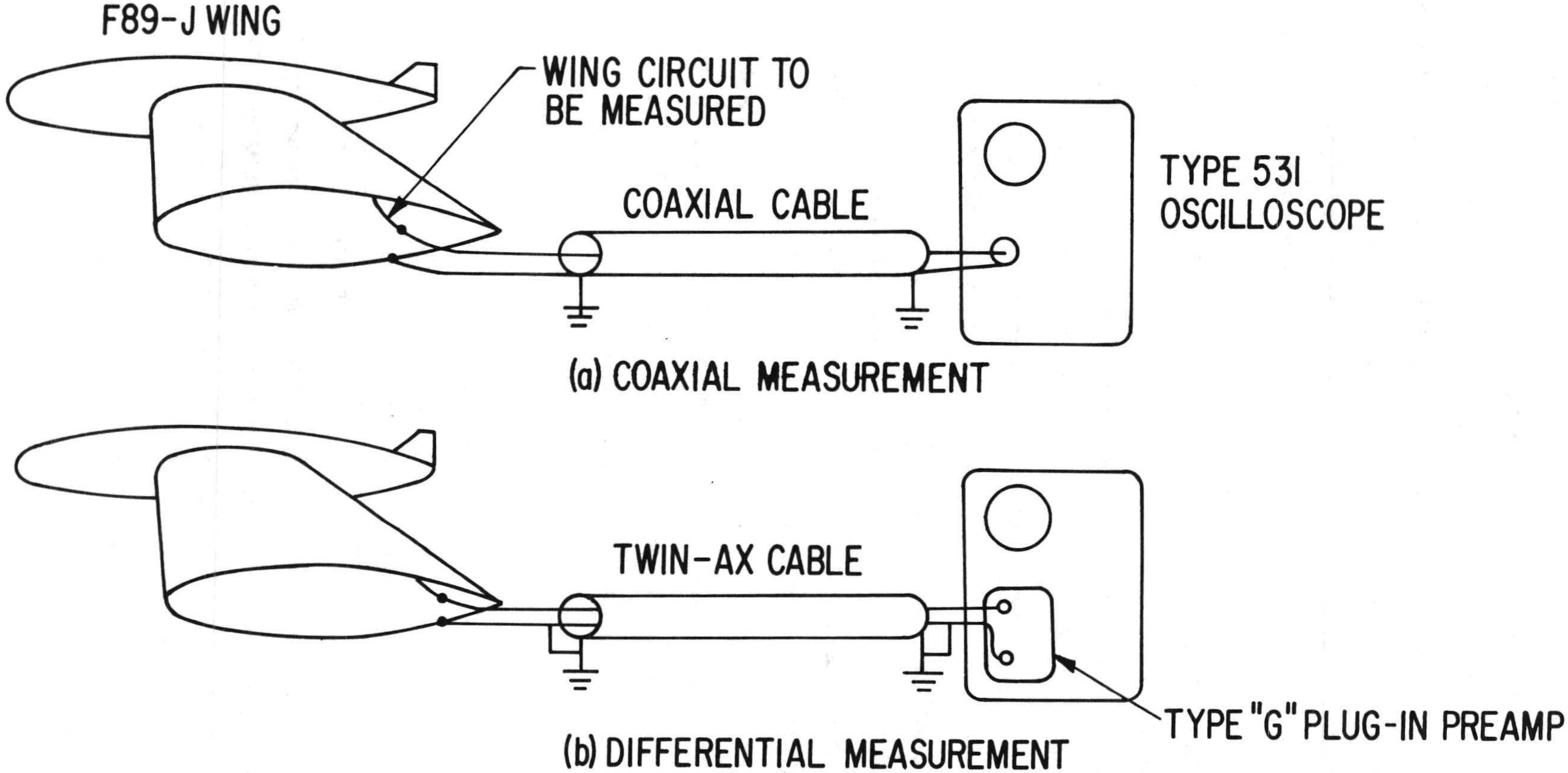


FIGURE 11 - COMPARISON OF COAXIAL AND DIFFERENTIAL MEASUREMENT TECHNIQUES FOR MEASURING LIGHTNING INDUCED VOLTAGE ON AIRCRAFT

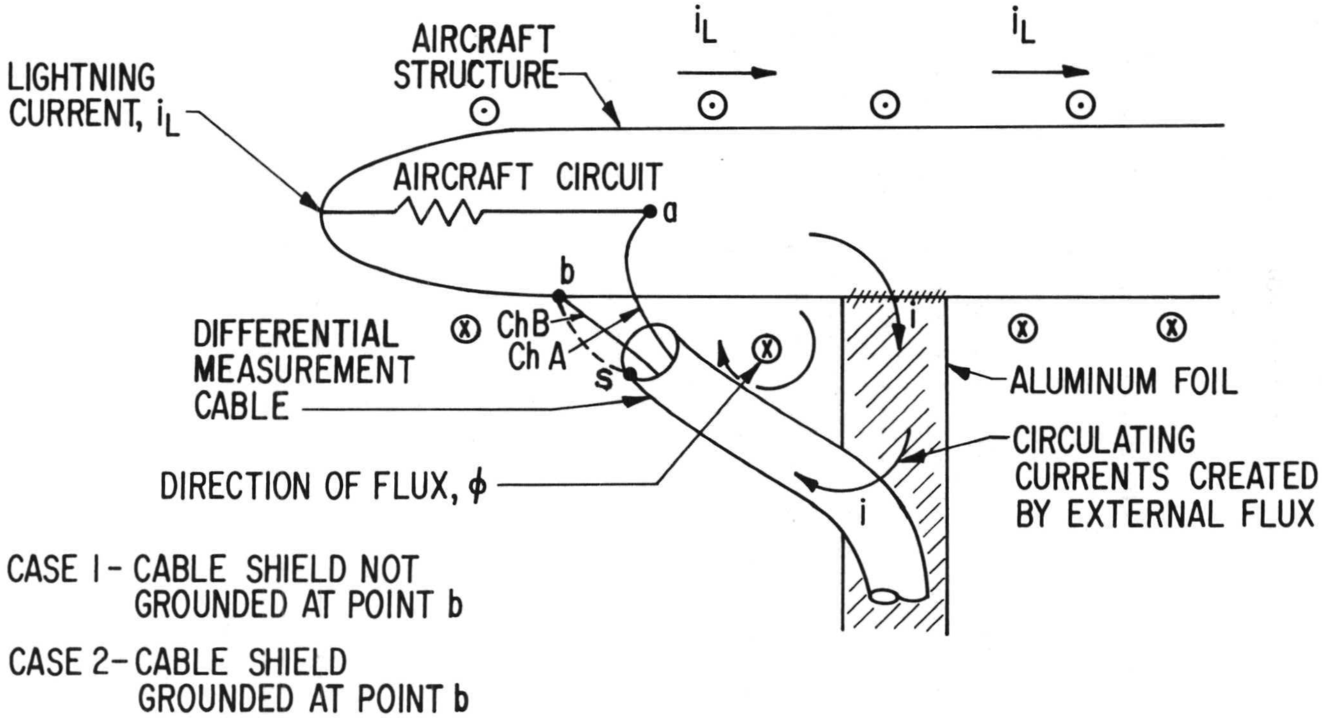


FIGURE 12 - DESCRIPTION OF CONNECTIONS THAT CAUSE MEASUREMENT ERRORS ON DIFFERENTIAL MEASUREMENT SYSTEM USED WITH AIRCRAFT TRANSIENT ANALYZER TEST TECHNIQUE.

Figure 13 shows an actual connection on to a circuit for test. Shown is the aluminum foil used to connect the airframe and the measurement trailer. This foil is placed as close as possible to the circuit under test. The line-to-ground connection is made here by clipping on directly to the circuit lead and the airframe. These clip leads, which are kept as short as possible, are actually the conductor and the shield of a coaxial cable which goes to a termination box from where the lead becomes a twin-axial cable to the preamplifier of the measurement oscilloscope.

There are various other ways connections can be made to the aircraft electrical circuits, especially if the circuits are difficult to get at.

1. Straight pins inserted in jacks or plugs.
2. Pins through insulation. (This is not encouraged since this is supposed to be a nondestructive test technique.
3. Ideally, connections should be made at terminal boards or circuit breaker panels. This type of connection would not disturb or alter the circuit run.

CURRENT MEASUREMENTS

The measurement of short circuit currents on the aircraft circuitry was accomplished by using a Pearson current transformer, Model 110A, connected as shown in Figure 14.

The input and output leads to the current transformer are the same leads that would go to channels "A" and "B" of the differential preamplifier in the oscilloscope when induced voltage is being measured.

The simulated lightning current is measured by the use of a Pearson current transformer, model No. 110, with a 0.10 volt per ampere ratio. The current transformer is placed outside the transient analyzer case around the return connection of the transient analyzer as shown in Figure 15.

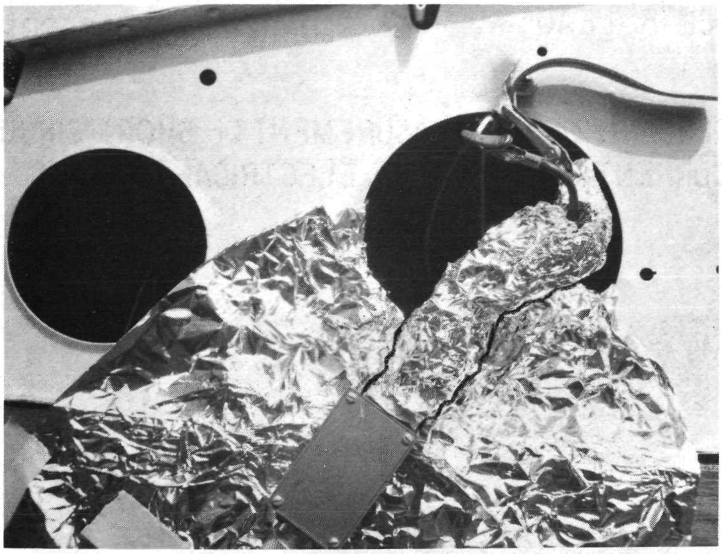


FIGURE 13. - CONNECTIONS FOR LINE-TO-GROUND INDUCED-VOLTAGE MEASUREMENT SHOWING CONNECTION TO CIRCUIT, TERMINATION BOX TO TWIN-AXIAL CABLE, AND ALUMINUM FOIL CONNECTIONS.

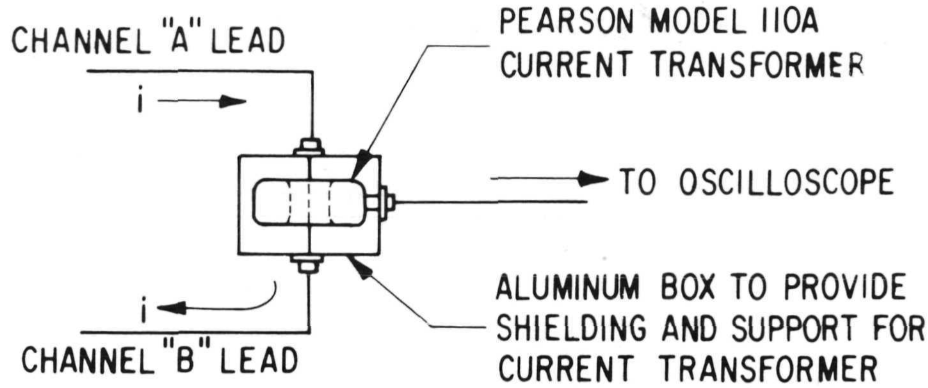


FIGURE 14 - DESCRIPTION OF MEASUREMENT OF SHORT CIRCUIT INDUCED CURRENTS ON AIRCRAFT ELECTRICAL CIRCUITS

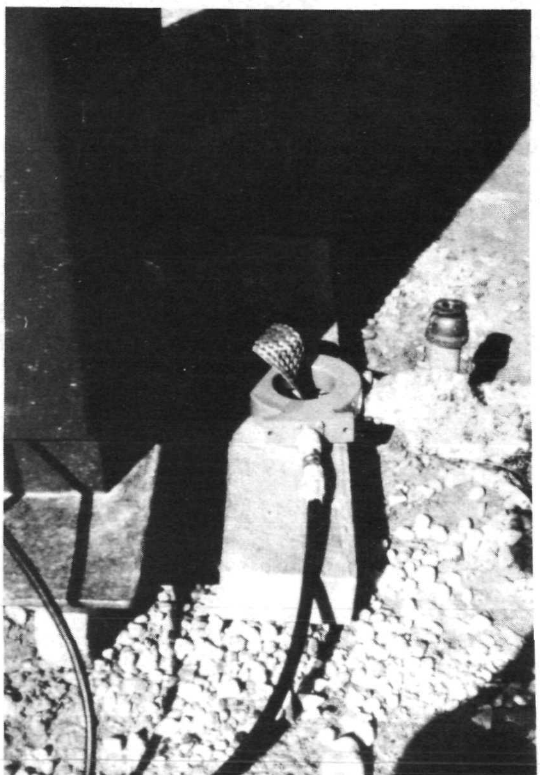


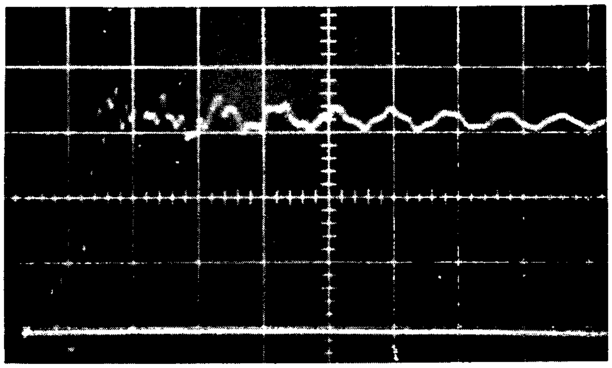
FIGURE 15 - CURRENT TRANSFORMER IN RETURN CONNECTION TO AIRCRAFT TRANSIENT ANALYZER USED FOR MEASURING SIMULATED LIGHTNING CURRENT

RESULTS OF PRELIMINARY FIELD TESTING AT HIGH VOLTAGE LABORATORY

One of the observations made was a comparison of a single-loop and double-loop applied current return path. This double-loop return was used on the preliminary geometric model of the transient analyzer and aircraft test circuit to minimize reflections. It would be desirable if satisfactory results could be obtained with only a single return path in the field size situation. This would simplify the test setup and reduce the area immediately involved with the test. It was found that by replacing the double loop with a single foil return path beneath the aircraft, it was possible to duplicate the lightning current wave shape obtained with the double loop. In the double-loop test circuit, a fast-rising, long-duration wave shape was made possible by using the inductance of the double loop itself and 250 Ω noninductive resistors distributed at the corners of both loops. By replacing the distributed R and L with equivalent lumped series inductance and resistance in series to the output of the transient analyzer it was possible to obtain the same fast-rising, long-duration lightning current wave shape with a foil current return path placed underneath the F89-J wing. Figure 16 shows a comparison of the lightning current wave shapes for the two different current return paths. Oscillations on the front-of-the-wave were even more prominent with the double-loop return path than with the single aluminum foil return path. Even though resistance was distributed around the loops there were reflections along the double loop that created these oscillations on the front-of-the-wave. The current magnitudes of both waves were identical.

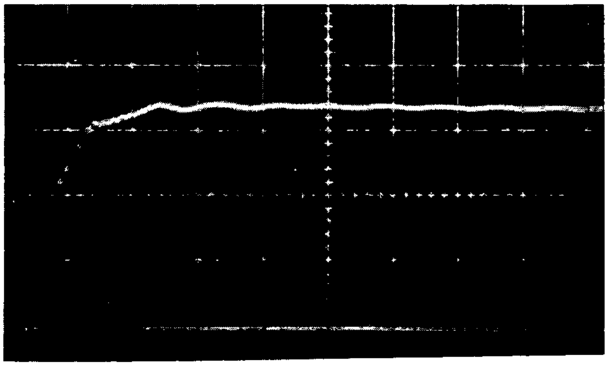
In preliminary testing it was found that #6 insulated cable could be substituted for the aluminum foil current return path to the generator with only a slight increase in total circuit inductance. This insulated cable was found to be much easier to work with and insured an isolated current path back to the negative side of the generator capacitors.

Lightning Current Double Loop Return Path



40 amps/Div.   0.5 μsec/Div.

Lightning Current Foil Return Path



40 amps/Div.   0.5 μsec/Div.

FIGURE 16. - COMPARISON OF SIMULATED LIGHTNING CURRENT WAVE SHAPES WITH DOUBLE WIRE LOOP AND SINGLE FOIL RETURN PATHS.

FIELD TESTS ON F89-J AIRCRAFT AT CHINA LAKE NAVAL WEAPONS CENTER

After the tryout of the aircraft transient analyzer in the outdoor area of the High Voltage Laboratory, the measurement techniques was used on a complete aircraft. This aircraft, an F89-J fighter, was located at the Naval Weapons Center at China Lake, California.

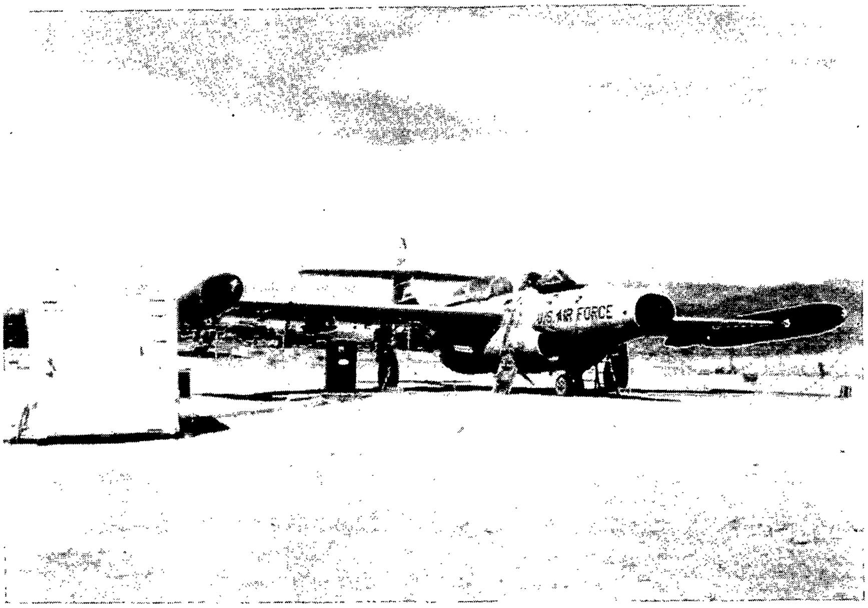
The objective of the tests at China Lake Naval Weapons Center was to try the test technique in a realistic application and compare results obtained in the High Voltage Laboratory on the F89-J wing with results obtained on a complete F89-J aircraft at China Lake.

China Lake Naval Weapons Center personnel were instrumental in obtaining a suitable shielded enclosure for the oscilloscopes used to observe the induced voltage measurements. Using special equipment for handling complete aircraft, Naval Weapons Center personnel placed the aircraft in test position. This test setup is shown in Figure 17.

Due to the hard, dry soil a good ground point was hard to find. A good ground is desirable to reduce circulating AC ground currents in the AC power circuits. Circulating currents could create a personnel safety hazard. With the assistance of Naval Weapons Center personnel, a ground point was located thirty feet from the aircraft. This ground point was connected to the water well casing at the test site.

LIGHTNING CURRENT FLOW PATH

Figure 18 shows various lightning current flow paths used on the F89-J aircraft at China Lake. It is noted that the current injection point is the same in all three cases, Position #1, the forward end of the tip tank. The flow path with the lightning current passing through the right wing, Figure 18a, repeats the flow path used on the F89-J wing at the High Voltage Laboratory. A more realistic flow path is with the lightning current passing from wing tip to wing tip as shown in Figure 18b. Figure 18c is another possible flow path. The simulated lightning current used for these flow path tests had a 6.7 x 18.2 microsecond wave shape with a peak current of 1000 amperes.



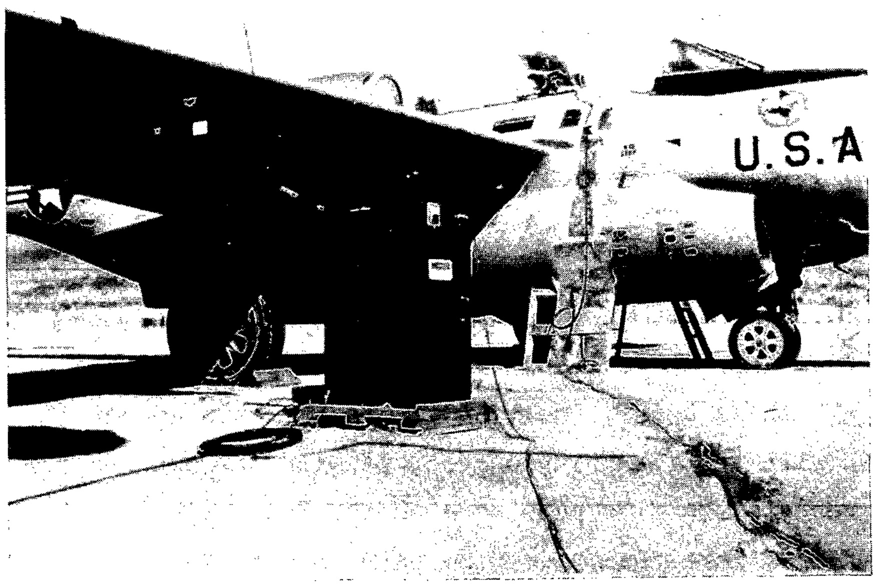


FIGURE 17 - INDUCED VOLTAGE TEST SET-UP AT CHINA LAKE NAVAL WEAPONS CENTER SHOWING POSITION OF AIRCRAFT TRANSIENT ANALYZER AND MEASUREMENT ENCLOSURE

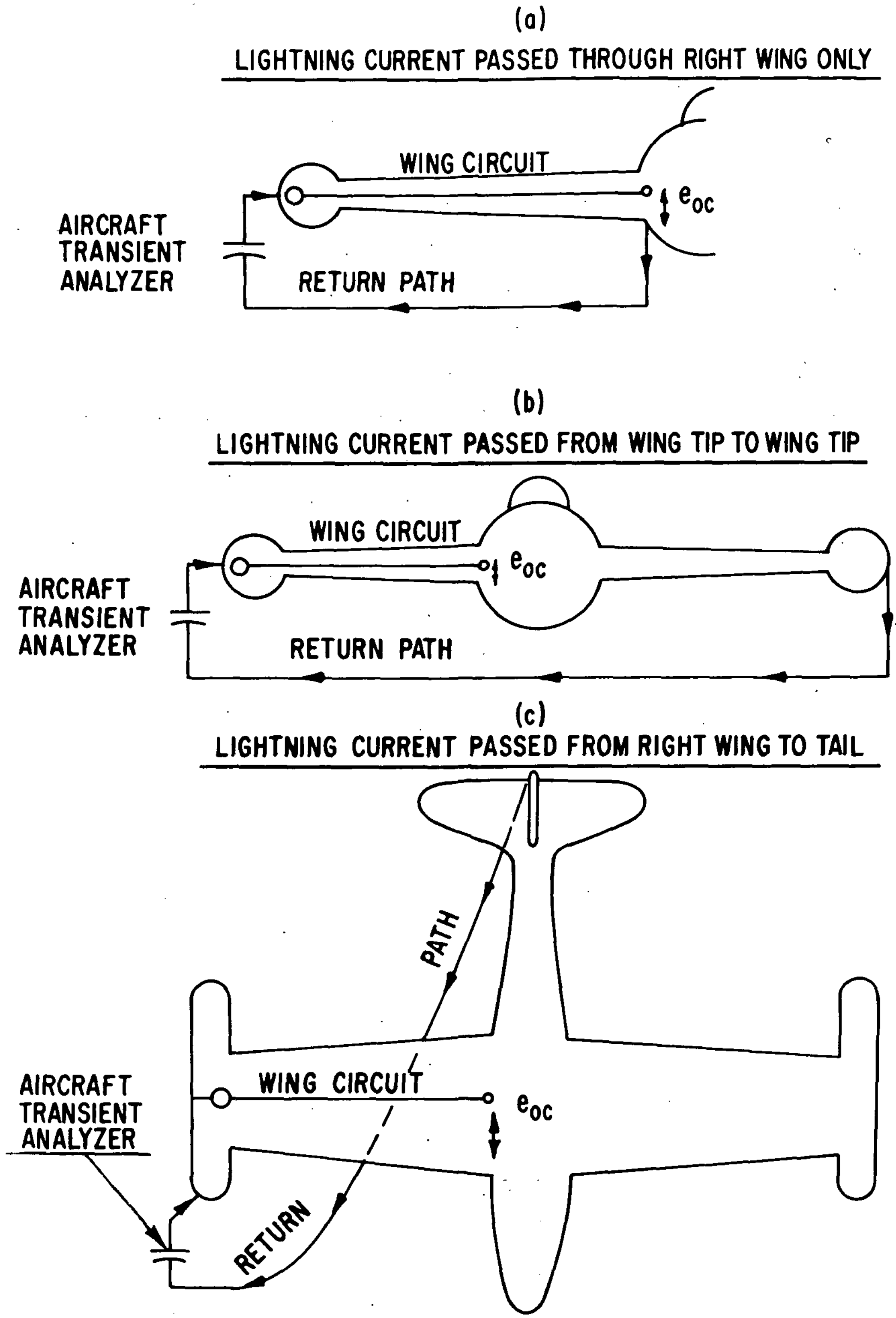


FIGURE 18-VARIOUS LIGHTNING CURRENT FLOW PATHS USED ON F89-J AIRCRAFT AT CHINA LAKE

Figures 19 and 20 show induced voltages and currents measured on the Position Light Circuit, L.050, conductor 2L10E18, using the three different lightning current flow paths. The time varying induced voltages and currents are almost identical for the three cases. These data illustrate that the voltages induced in the light circuit in the right wing, are solely a function of the current flow through that wing and are not measurably influenced by the current flow situation in other parts of the airframe where this circuit does not exist. The subsequent lightning current flow paths through the rest of the airframe and external return path have no measurable effect on the voltage induced in the right wing light circuit, as can be seen in Figures 19 and 20.

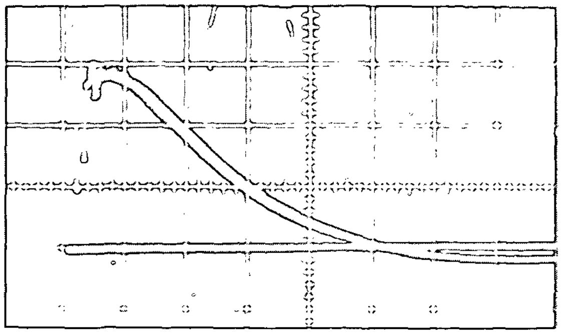
Only current flowing in the portion of the aircraft enclosing the circuit in question is effective in causing an induced voltage in that circuit. The factors that influence the magnitude and wave shape of the induced voltages are listed in Table IV. These factors were observed in previous work (ref. 6).

POSITION OF A CIRCUIT IN RELATION TO APPLIED CURRENT ATTACHMENT POINT

To illustrate some of the factors that influence the magnitude of voltage induced on a circuit, Figure 21 shows induced voltages on the Position Light Circuit, L.050, conductor 2L10E18, with the lightning current being injected at points shown on Figure 22. An applied current wave shape of 7.4 x 20.5 microseconds at a maximum value of 1033 amperes was used.

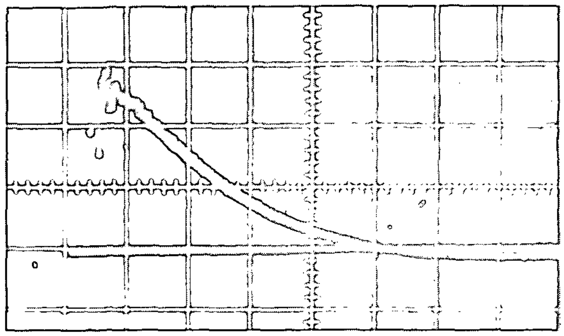
For Position 1, a maximum induced voltage of 3 volts was measured. This wave shape can be seen on Figure 19. Induced voltages for Positions 2 to 5 are shown on Figure 21. The induced voltage is drastically reduced when the lightning current is injected in the wing instead of the wing tip fuel tank. Current flowing down the fuel tank, if struck at Position 1, greatly influences the induced voltage on the light circuit. Injecting the current at Positions 2 and 3 creates a lower induced voltage due to the location of the circuit run and the shielding afforded by the wing structure. Currents injected at Positions 4 and 5 provide less influence on the circuit due to location, shielding and length of circuit influenced by the lightning current.

LIGHTNING CURRENT PASSED THROUGH RIGHT WING ONLY



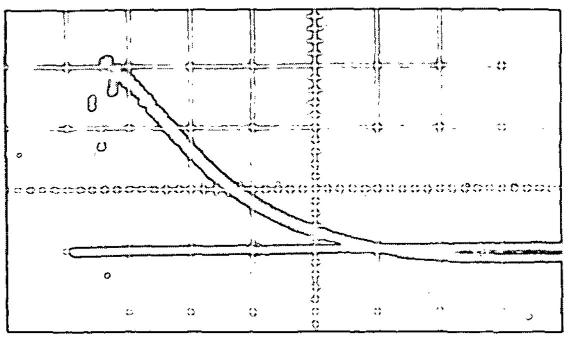
1 VOLT/DIV 5μSEC/DIV

LIGHTNING CURRENT PASSED FROM WING TIP TO WING TIP



1 VOLT/DIV 5μSEC/DIV

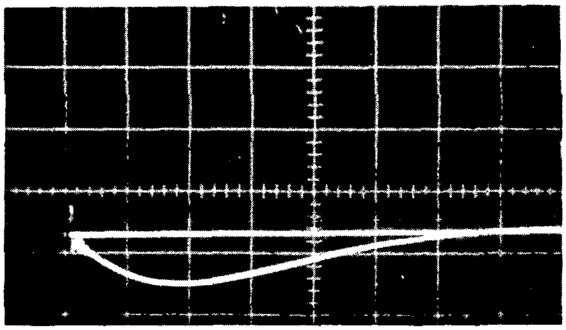
LIGHTNING CURRENT PASSED FROM RIGHT WING TO TAIL



1 VOLT/DIV 5μ SEC/DIV

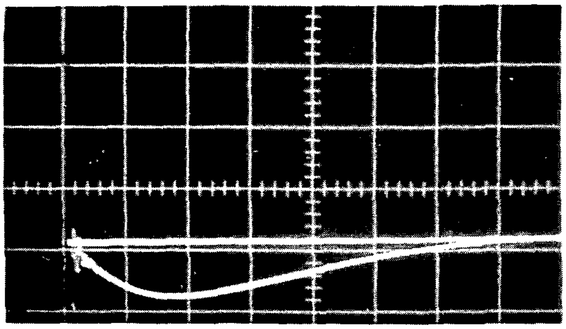
FIGURE 19-COMPARISON OF INDUCED VOLTAGES ASSOCIATED WITH VARIOUS LIGHTNING CURRENT PATHS. CIRCUIT L.050 POSITION LIGHTS CONDUCTOR 2L10E18

LIGHTNING CURRENT PASSED THROUGH RIGHT WING ONLY



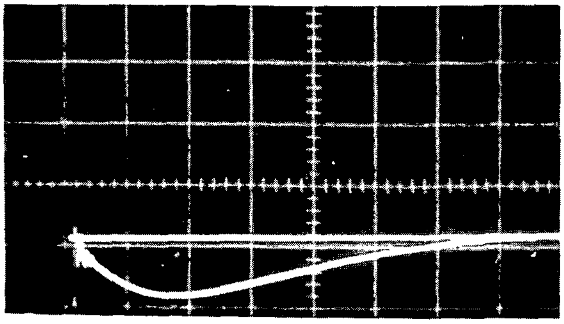
0.5 AMPERE/DIV 5μ SEC/DIV

LIGHTNING CURRENT PASSED FROM WING TIP TO WING TIP



0.5 AMPERE/DIV 5μ SEC/DIV

LIGHTNING CURRENT PASSED FROM RIGHT WING TO TAIL



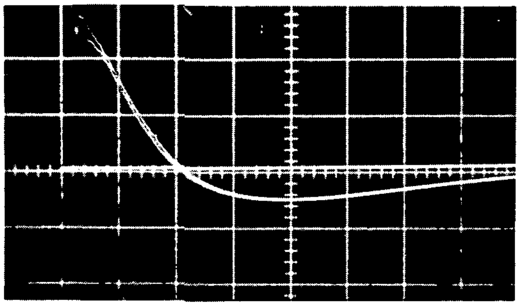
0.5 AMPERE/DIV 5μ SEC/DIV

FIGURE 20 - COMPARISON OF INDUCED CURRENTS ASSOCIATED WITH VARIOUS LIGHTNING CURRENT PATHS. CIRCUIT L.050 POSITION LIGHTS CONDUCTOR 2L10E18

TABLE IV - FACTORS THAT INFLUENCE THE MAGNITUDE AND WAVE SHAPE OF INDUCED VOLTAGES

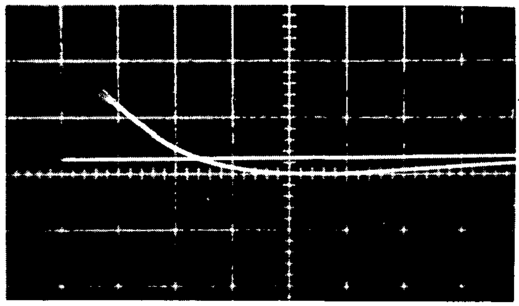
Influencing Factors	Influencing Characteristics
length of circuit	A longer length circuit can have a large voltage induced on it due to an increase in the effect of lightning current on the aircraft.
position of circuit	Although this factor can have many characteristics, the main one is the amount of exposure to the electromagnetic fields that the circuit would have in its position in the aircraft.
shielding of circuit	Adequate circuit shielding can be accomplished by utilizing the metallic structure (position of circuit) or placing the circuit conductors in conduit or metal sheath, such as coaxial cable.
thickness of aircraft skin	The shielding afforded by the aircraft skin and also the rate of diffusion of the current through the skin (skin effect).
composition of aircraft skin	All aluminum structures provide more shielding of electrical circuits than nonmetallic or semimetallic structures.
wave shape of lightning current impulse	Risetime and total duration of the lightning current are the main factors. Faster risetimes can induce larger voltages in some circuits.
amplitude of lightning current impulse	The larger the applied lightning current, the larger the induced voltage.
lightning attachment point relative to circuit position	If an electrical circuit is positioned close to the point where a lightning stroke attaches itself to an aircraft structure, the influence of the lightning current on that circuit is greater than if the lightning stroke is further away from the circuit.

POSITION #2
OUTBOARD LEADING EDGE



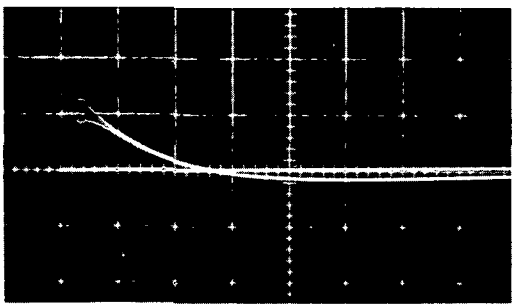
0.2 V/DIV. 0.54 VOLTS MAX. 5μs/DIV.

POSITION #3
TRAILING EDGE OF AILERON



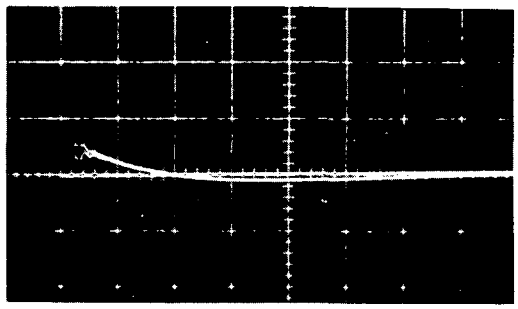
0.2V/DIV. 0.28 VOLTS MAX. 5μ s/DIV.

POSITION #4
CENTER OF WING SURFACE



0.2V/DIV. 0.22 VOLTS MAX 5μ s/DIV.

POSITION #5
INBOARD LEADING EDGE



0.2 V/DIV. 0.1 VOLTS MAX. 5μ s/DIV.

FIGURE 21 - OPEN CIRCUIT INDUCED VOLTAGES MEASURED ON CIRCUIT L.050 POSITION LIGHTS CONDUCTOR 2L10E18 USING FAST SIMULATED LIGHTNING CURRENT WAVE (7.4 x 20.5 μ SEC) INJECTED AT POINTS DESIGNATED ABOVE.

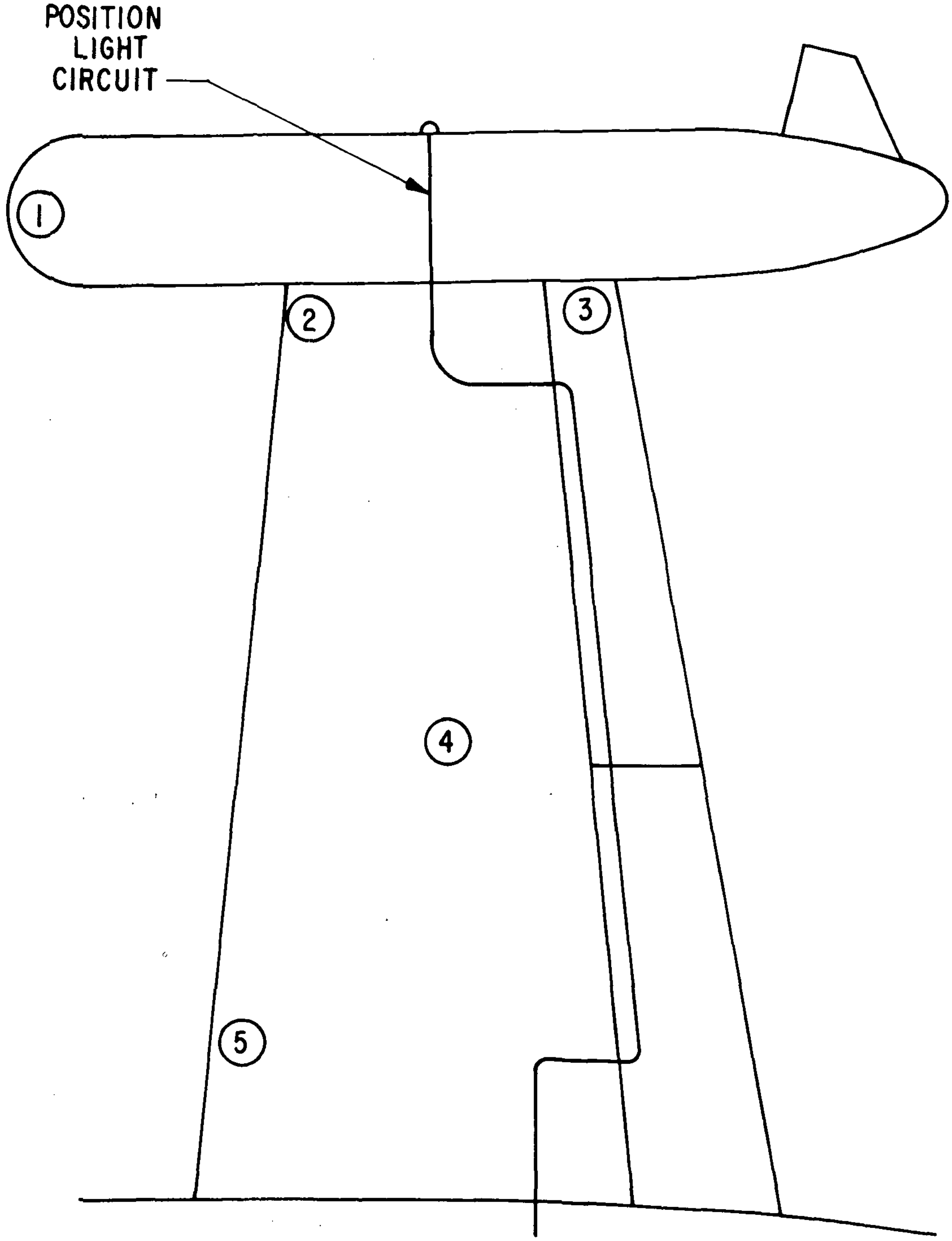


FIGURE 22 SIMULATED LIGHTNING STROKE LOCATIONS ON F89-J AIRCRAFT-CIRCLED NUMBERS INDICATE LOCATIONS SELECTED.

COMPARISON OF HIGH VOLTAGE LABORATORY RESULTS WITH CHINA LAKE RESULTS

For these comparison tests the simulated lightning current was injected onto the right wing of the F89-J aircraft at points similar to those used on the F89-J wing at the High Voltage Laboratory. The current was taken off the aircraft at the root end of the wing of the F89-J aircraft at China Lake.

Figure 23 shows oscillograms of simulated lightning currents applied to the forward end of the right wing tip tank of the F89-J wing in the High Voltage Laboratory outdoor area and the F89-J aircraft at China Lake Naval Weapons Center. The current was produced in both cases by the aircraft transient analyzer. It flowed off the aircraft at the root of the wing in both cases.

The maximum current injected in the wing at the High Voltage Laboratory outdoor area was 1832 amperes. The maximum current applied to the F89-J aircraft at China Lake was 1033 amperes. In terms of a proportionality, the High Voltage Laboratory current was 1.76 times greater than the China Lake current.

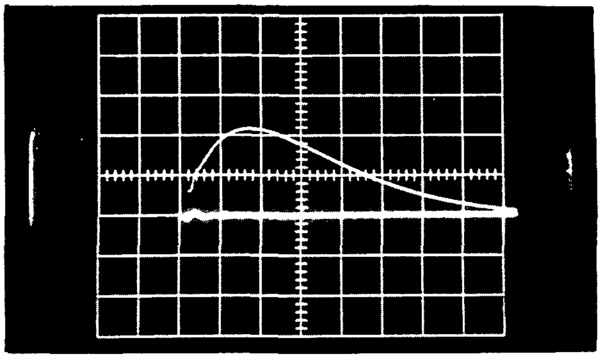
Figure 24 is composed of resultant open circuit voltages and short circuit currents measured on Circuit L.050, conductor 2L10E18, in the F89-J wing at the High Voltage Laboratory and at China Lake.

The polarity change observed between the oscillograms of the High Voltage Laboratory results and the China Lake results was due to reversed connections of the measurement leads into the oscilloscopes. The positive deflections are the correct polarity.

The maximum open circuit voltages measured are 6 volts on the wing at High Voltage Laboratory and 3 volts on the aircraft at China Lake. This gives a ratio of 2 to 1. The maximum short circuit currents measured are 0.8 amperes on the wing at High Voltage Laboratory and .45 amperes on the aircraft at China Lake. This gives a ratio of 1.78 to 1.

Comparing the induced voltage and current ratios to the ratio of applied lightning currents, a nearly linear relationship was observed between induced voltage amplitudes and applied current amplitudes.

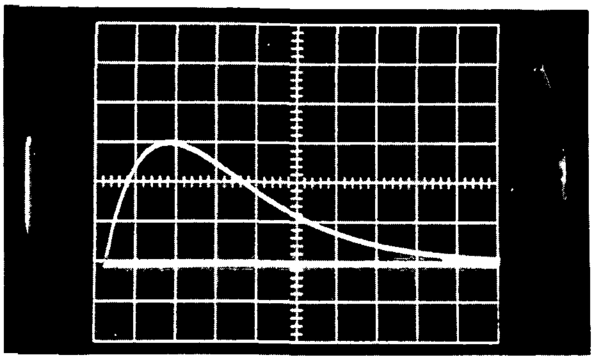
SIMULATED LIGHTNING CURRENT APPLIED TO F89-J WING
AT HIGH VOLTAGE LABORATORY



1832 AMPS MAX

833 AMPERES/DIV 5μSEC/DIV

SIMULATED LIGHTNING CURRENT APPLIED TO F89-J
WING AT CHINA LAKE



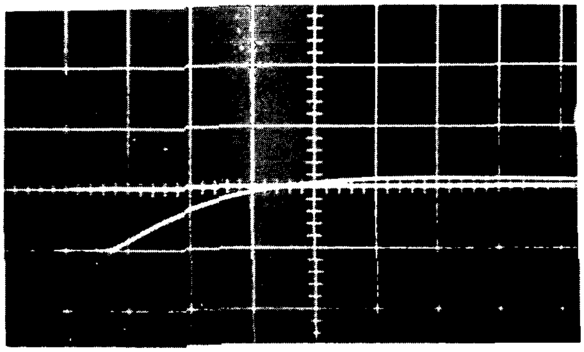
1033 AMPS MAX

333 AMPERES/DIV 5μSEC/DIV

FIGURE 23 - SIMULATED LIGHTNING CURRENT APPLIED TO THE RIGHT WING TIP TANK OF THE F89-J WING IN THE HIGH VOLTAGE LABORATORY OUTDOOR AREA AND THE F89-J AIRCRAFT AT CHINA LAKE

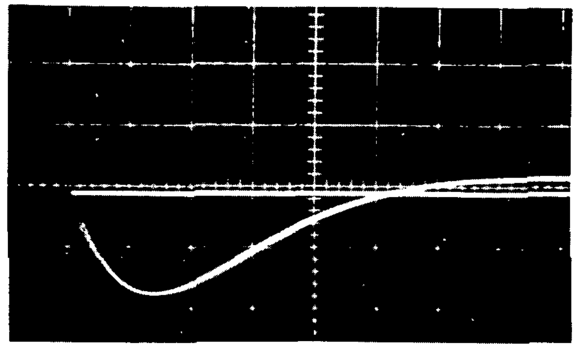
MEASURED ON WING AT HIGH VOLTAGE LABORATORY

OPEN CIRCUIT VOLTAGE, e_{oc}



5 VOLTS/DIV 5μ SEC/DIV

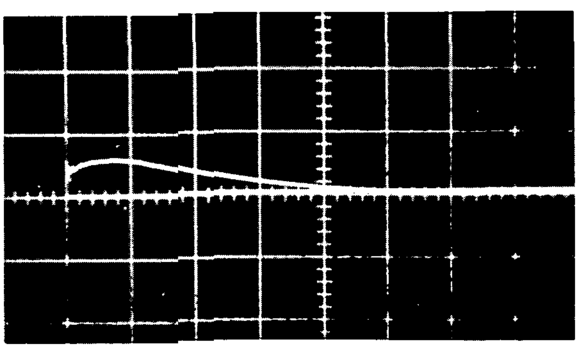
SHORT CIRCUIT CURRENT, i_{sc}



0.5 AMPERES/DIV 5μ SEC/DIV

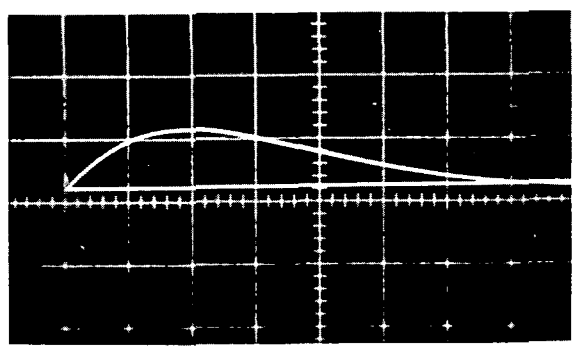
MEASURED ON F89-J AT CHINA LAKE

OPEN CIRCUIT VOLTAGE, e_{oc}



5 VOLTS/DIV 5μSEC/DIV

SHORT CIRCUIT CURRENT, i_{sc}



0.5 AMPERES/DIV 5μSEC/DIV

FIGURE 24 - COMPARISON OF OPEN CIRCUIT VOLTAGES AND SHORT CIRCUIT CURRENTS MEASURED ON CIRCUIT L.050, CONDUCTOR 2L10E18, IN THE F89-J WING AT THE HIGH VOLTAGE LABORATORY AND AT CHINA LAKE NAVAL WEAPONS CENTER

However, only this circuit gave a good comparison of data taken with the F89-J wing at the High Voltage Laboratory and the F89-J aircraft at China Lake. In comparing data obtained on other circuits, the voltages measured on the F89-J aircraft, using the aircraft transient analyzer as the simulated lightning current source, were higher or lower, depending on the circuit, when compared with the results of "full scale" tests on the F89-J wing at the High Voltage Laboratory. The full scale tests were performed under NASA contract NAS3-12019 and are described in Reference 1. Tables V through X, list the measurements made on the aircraft at China Lake. When possible, these results are compared with the measurements made at 40 kiloamperes applied lightning current in the High Voltage Laboratory.

In Table V the voltages measured on the circuit A.140 in the aircraft at China Lake are much larger than would be expected with a 40/1 reduction in applied lightning current magnitude.

In Table VI induced voltage measurements made on circuit F.0511, E-11 autopilot, were made on conductor XV70B16, which is located in the 115 volt AC circuit breaker panel in the cockpit and is connected to the autopilot circuit breaker. There is circuitry connected to the E-11 autopilot in both the right and left wing as shown in Figure 25. Therefore, in the case of the 6.7 x 18.2 microsecond waveshape the higher induced voltage measured on the circuit with a wing tip to wing tip current flow path is understandably larger due to the lightning current influencing more of the autopilot circuit than a wing tip to tail current flow path would.

The 1.5 x 150 microsecond wave gave opposite results, with higher induced voltages measured with a wing tip to tail current path. These results are unexplainable, although the fast rising, long duration, current wave shape may effect the circuit differently than a slower, short duration, current wave.

In Table VII in the case of the right wing position light circuit, all data taken on the right wing in the laboratory was taken at connector TK, which included conductor 2L10E18. Measurements made on the right wing position light circuit on the F89-J aircraft at China Lake were made at connector CU in the cockpit. This circuit not only includes conductor 2L10E18 but also includes the additional conductor 2L10D18 into the cockpit. Figures 26 and 27 show details of this circuit.

Voltages measured on circuit Q.0401, Table VIII, at the lower current level are much smaller than would be expected.

Table IX, with measurements made on circuit R.060, does not have any direct comparisons with "full scale" tests, but it is interesting to note that with access doors open in the vicinity of conductor RA35C the measured induced voltage is much greater than with the access door in place. This voltage increase could be due to external fields, created by the lightning current impulse affecting the induced voltage on the circuit.

In Table X conductor 2SF3819J20 becomes conductor SF3819G20 after it comes off of terminal board 28 (TB28), see Figure 28. The induced voltages on this conductor were measured at connector MJ19. Therefore, there can be a comparison of induced voltage measurements made on this conductor in the laboratory and at China Lake if it is stated that the China Lake measurement includes the additional length of conductor from connector MJ34 to MJ19. This explanation also holds true for comparison between results obtained on conductors SF3821B20 and 2SF3821J20.

TABLE V - MAXIMUM AMPLITUDES OF MEASURED INDUCED VOLTAGES

Circuit A.140, Right Armament Jettison
Conductor 2A925F16 and Airframe, MB-1 Pylon Attached
Open Circuit Voltage, e_{oc} (volts)

Stroke Location	i_L Wave Shape		
	7.4 x 20.5 μs	8.2 x 14 μs	1.5 x 150 μs
1 Forward End of Tip Tank	0.39	0.9	--
2 Outboard Leading Edge	0.22	0.78	--
3 Trailing Edge of Aileron	0.28	0.64	--
4 Center of Wing Surface	0.28	0.75	--
5 Inboard Leading Edge	--	1.0	--
Right Wing Tip to Tail	--	--	0.26
Tip of MB-1 Pylon to Tail	--	--	1.0

NOTE: 7.4 x 20.5 μs applied wave - 1000 amperes peak
*8.2 x 14 μs applied wave - 40 kiloampere peak
1.5 x 150 μs applied wave - 100 amperes peak

* applied to F89-J wing at High Voltage Laboratory

TABLE VI - MAXIMUM AMPLITUDE OF MEASURED INDUCED VOLTAGE

Circuit F.0511, E-11 Autopilot
Conductor XV70B16
Open Circuit Voltage, e_{oc} (volts)

Stroke Location	i_L Wave Shape	
	6.7 x 18.2 μs	1.5 x 150 μs
Right Wing Tip to Tail	1.0	3.5
Wing Tip to Wing Tip	4.0	0.4

NOTE: 6.7 x 18.2 μs wave - 1000 amperes peak
1.5 x 150 μs wave - 100 amperes peak

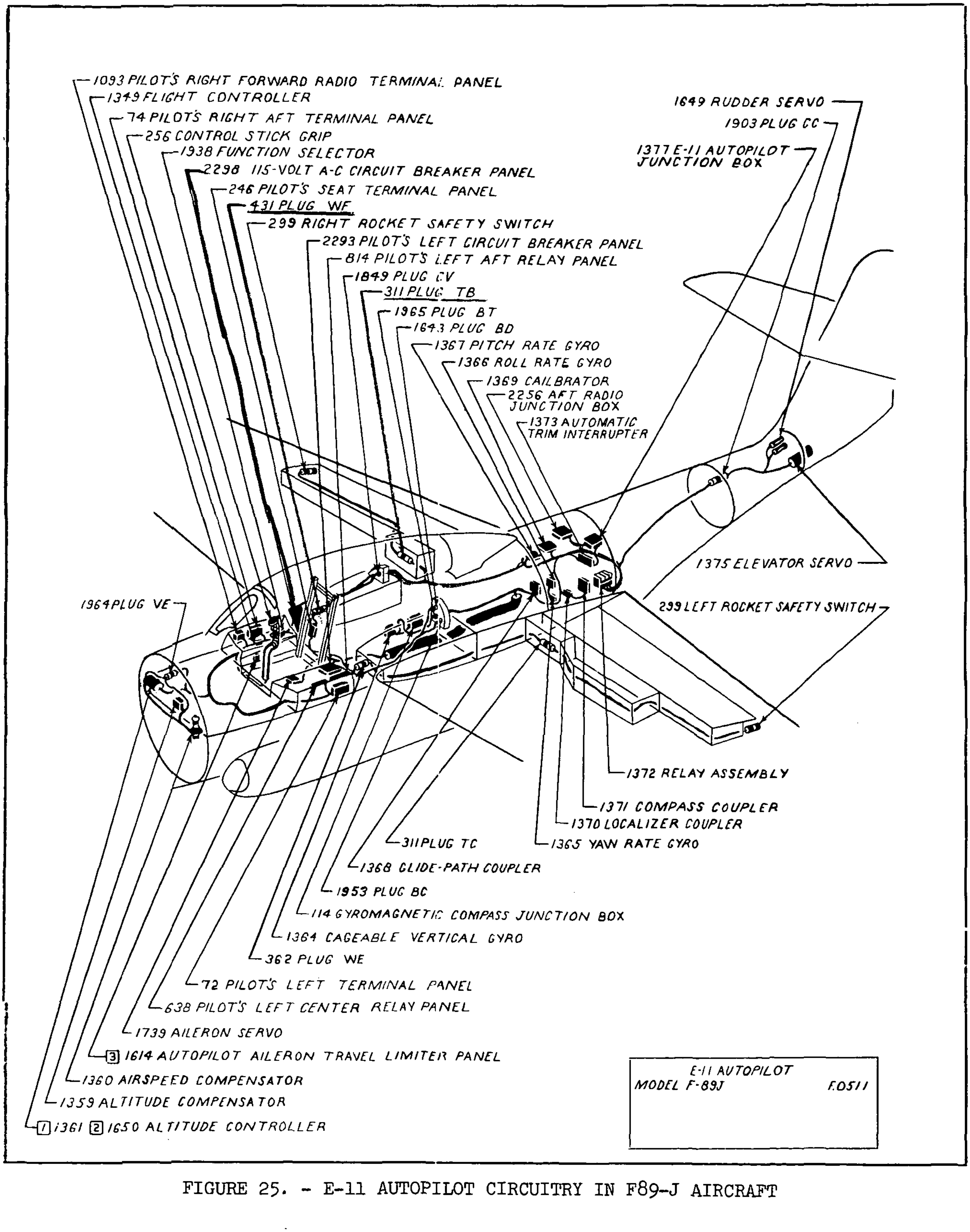


FIGURE 25. - E-11 AUTOPILOT CIRCUITRY IN F89-J AIRCRAFT

TABLE VII - MAXIMUM AMPLITUDE OF MEASURED INDUCED VOLTAGE

Circuit L.050 Position Lights
Open Circuit Voltage, e_{oc} (volts)

i_L Wave Shape:	24 x 70 μs	36 x 82 μs	7.4 x 20.5 μs	8.2 x 14 μs	6.7 x 18.2 μs				1.5 x 150 μs				
Stroke Location	2L10E18 to Airframe	2L10D18 to Airframe	2L10E18 to Airframe	2L10D18 to Airframe	2L10D18 & Airframe	1L10D18 & Airframe	L11D20 & Airframe	L10H20 & Airframe	2L10D18 & Airframe	1L10D18 & Airframe	L11D20 & Airframe	L10H20 & Airframe	Access Door #42 Open L10H20 & Airframe
1 Forward End of Tip Tank	**5.6, 1.4	40, 20	3.5, 0.38	96, 48	2.9	--	--	--	--	--	--	--	--
2 Outboard Leading Edge	0.24	6, 2.2	0.8	15, 4	--	--	--	--	--	--	--	--	--
3 Trailing Edge of Aileron	0.07	15, 3.8	5.0, 0.2	30, 12	--	--	--	--	--	--	--	--	--
4 Center of Wing Surface	5.0, .01	10, 2.4	1.8, 0.24	20, 2	--	--	--	--	--	--	--	--	--
5 Inboard Leading Edge	5.0, .01	10, 1.8	3.0, .08	17, 2.8	--	--	--	--	--	--	--	--	--
Right Wing Tip to Left Wing Tip	--	--	--	--	*2.7	*2.8	*2.4	*2.3	1.5	2.6	0.5	.07	--
Right Wing Tip to Tail	--	--	--	--	3.0	1.7	2.2	2.2	--	1.7	1.9	1.3	1.6

NOTE: 24 x 70 μs applied wave - 650 amperes peak
†36 x 82 μs applied wave - 40 kiloamperes peak
7.4 x 20.5 μs applied wave - 1000 amperes peak
† 8.2 x 14 μs applied wave - 40 kiloamperes peak
6.7 x 18.2 μs applied wave - 1000 amperes peak
1.5 x 150 μs applied wave - 93.5 amperes peak

*6 x 19 μs applied wave - 868 amperes peak

**First value is fast-rising, oscillatory peak voltage
Second value is slower rising peak voltage

†Applied to F89-J wing at High Voltage Laboratory

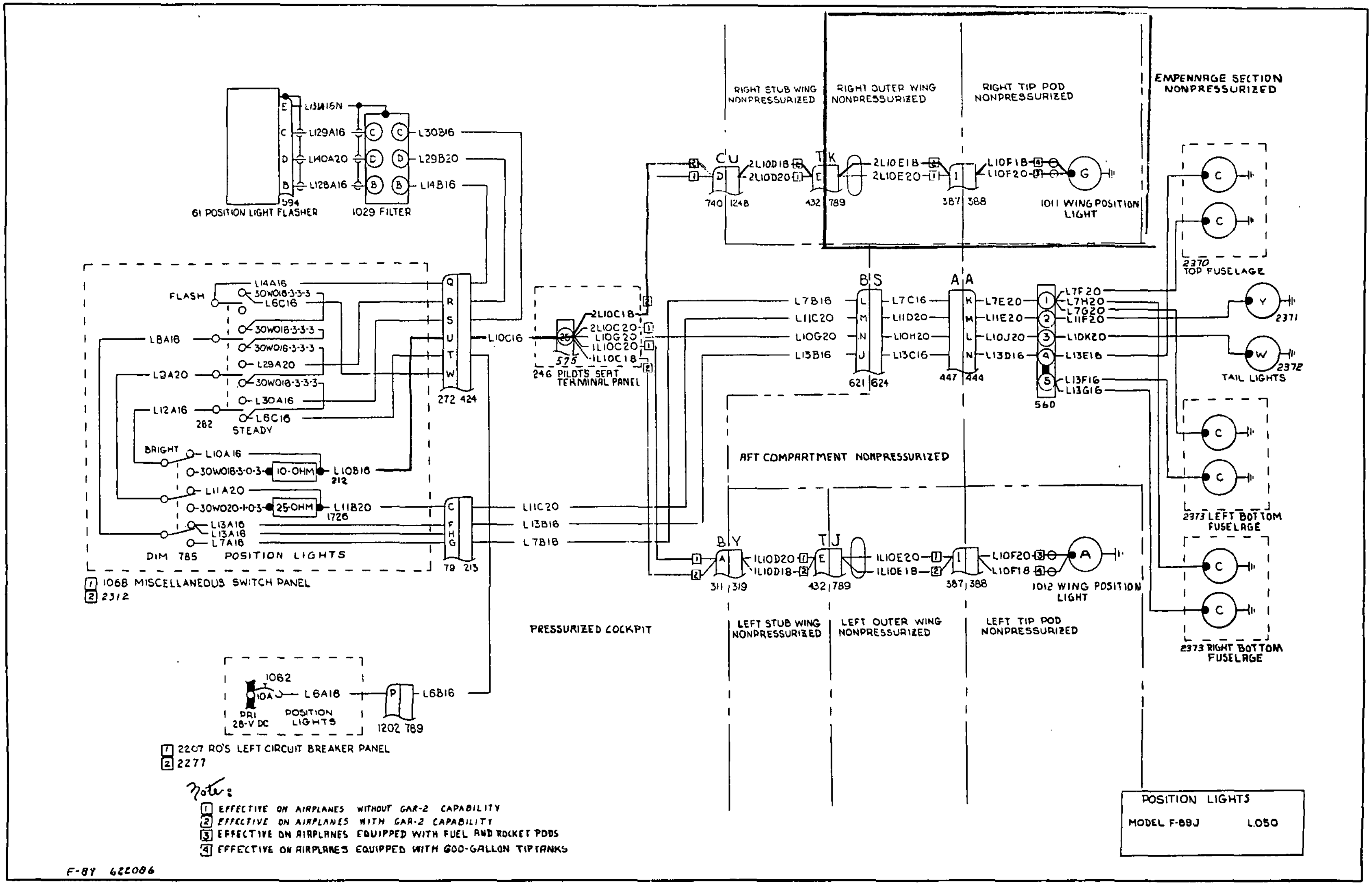
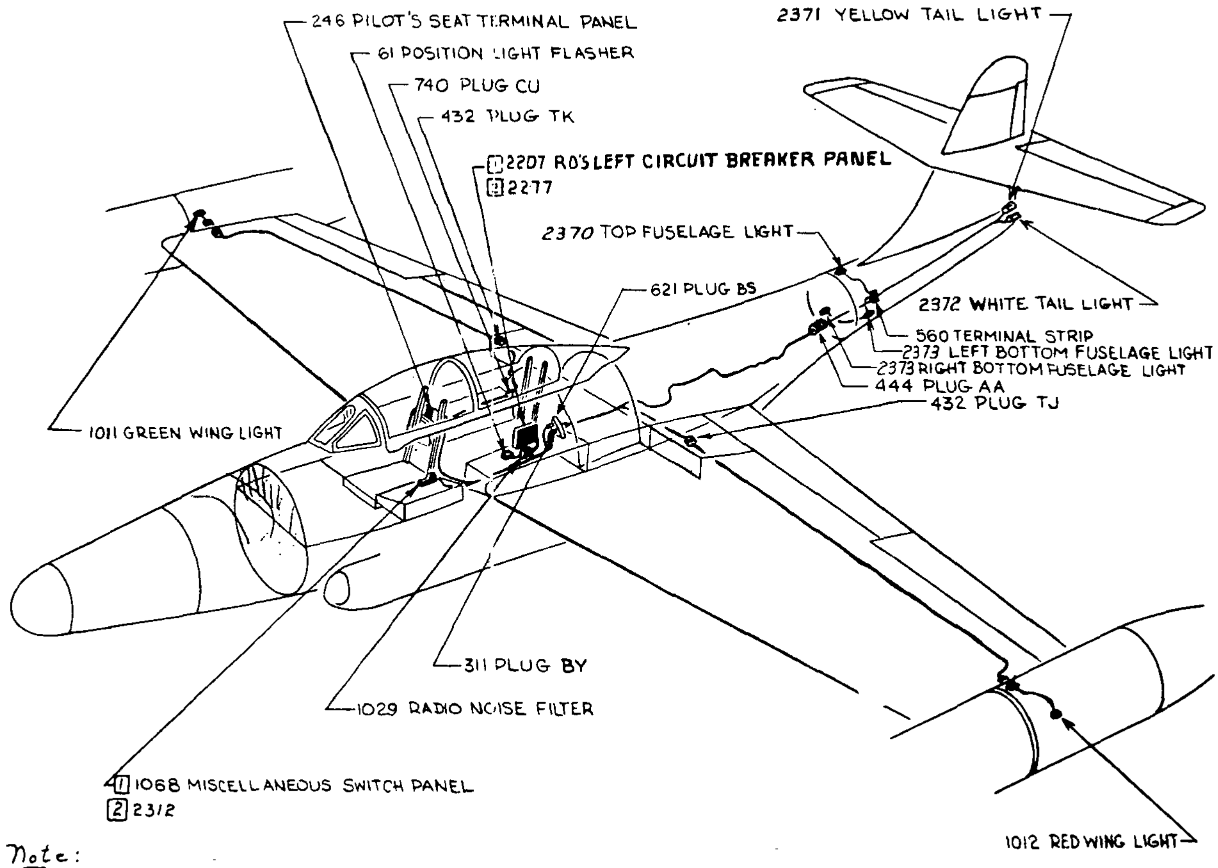


FIGURE 26. - POSITION LIGHTS, CIRCUIT L.050 SCHEMATIC

ITEM NO.	NAME OF PART AND DESCRIPTION	TYPE OR DWG NO. OR MFRS NAME AND NO.
61	POSITION LIGHT FLASHER	SPEC 32660
79	PLUG	AN3106A-24-28SX
575	TERMINAL STRIP	NAI 60P335-12-21
212	10-OHM RESISTOR	25 WATT ACKER 0200B
213	RECEPTACLE	AN3100A-24-28PX
246	PILOT'S SEAT TERMINAL PANEL	5105145
272	PLUG	AN3106A-24-28S
282	4PDT SWITCH	AN3227-1
311	PLUG BY	AN3106A-28-12S
319	RECEPTACLE BY	AN3100C-28-12P
387	PLUG	AN3106A-20-27S
388	RECEPTACLE	AN3100A-20-27P
424	RECEPTACLE	AN3100A-24-28P
432	PLUG TJ AND TK	AN3106A-28-11SW
444	PLUG AA	AN3106A-24-28P
447	RECEPTACLE AA	AN3100A-24-28S
560	TERMINAL STRIP	NAI 60P343-5-1
594	PLUG	AN3106A-16S-8S
621	PLUG BS	AN3106A-28-12PY
2277	RO'S LEFT CIRCUIT BREAKER PANEL	5145254 [2]

ITEM NO.	NAME OF PART AND DESCRIPTION	TYPE OR DWG NO. OR MFRS NAME AND NO.
624	RECEPTACLE BS	AN3100C-28-12SY
740	PLUG CU	AN3106A-28-12PW
785	3PDT SWITCH	AN3226-3
789	RECEPTACLE TJ AND TK	AN3100A-28-11PW
2370	POSITION LIGHT ASSEMBLY	AN3177-12
2371	YELLOW TAIL LIGHT	AN3158-5
2372	WHITE TAIL LIGHT	AN3158-4
1011	GREEN WING LIGHT	AN3033-8
1012	RED WING LIGHT	AN3033-7
1029	RADIO NOISE FILTER	4105522
1062	10-AMP CIRCUIT BREAKER	4986768-10
1068	MISCELLANEOUS SWITCH PANEL	5105762 [1]
2312	MISCELLANEOUS SWITCH PANEL	5145275 [2]
2373	POSITION LIGHT ASSEMBLY	AN3177-10
1202	PLUG	AN3108A-28-11SW
1248	RECEPTACLE CU	AN3100C-28-12SW
1726	25-OHM RESISTOR	20WATT OHMITE BROHI
2207	RO'S LEFT CIRCUIT BREAKER PANEL	5144039 [1]



Note:
[1] EFFECTIVE ON AIRPLANES WITHOUT GAR-2 CAPABILITY
[2] EFFECTIVE ON AIRPLANES WITH GAR-2 CAPABILITY

POSITION LIGHTS
MODEL F-89J L.050

F-89 622DR5

FIGURE 27. - POSITION LIGHTS, CIRCUIT L.050 IN AIRCRAFT

TABLE VIII - MAXIMUM AMPLITUDE OF MEASURED INDUCED VOLTAGE

Circuit Q.0401, Fuel Vent Valves
Conductor 2Q331B14 and Airframe
Open Circuit Voltage, e_{oc} (volts)

Stroke Location	i_L Wave Shape			
	24 x 70 μs	36 x 82 μs	7.4 x 20.5 μs	8.2 x 14 μs
1 Forward End of Tip Tank	0.034	2.8	0.01	6.5
2 Outboard Leading Edge	0.015	1.8	0.02	3.1
3 Trailing Edge of Aileron	0.01	1.8	0.02	1.6
4 Center of Wing Surface	0.01	2.2	0.02	1.9
5 Inboard Leading Edge	0.018	2.4	0.02	2.4

NOTE: 24 x 70 μs applied wave - 650 amperes peak
*36 x 82 μs applied wave - 40 kiloamperes peak
7.4 x 20.5 μs applied wave - 1000 amperes peak
* 8.2 x 14 μs applied wave - 40 kiloamperes peak

* applied to F89-J wing at High Voltage Laboratory

TABLE IX - MAXIMUM AMPLITUDE OF MEASURED INDUCED VOLTAGE

Circuit R.060, AN/ARN-18 Glide Path Radio Receiver
Conductor RA35C and Airframe
Open Circuit Voltage, e_{oc} (volts)

Stroke Location	i_L Wave Shape					
	6.7 x 18.2 μs Wave Shape			1.5 x 150 μs Wave Shape		
Right Wing Tip to Tail	Access panel door open RA35C to inner shield	Access panel door closed RA35C to inner shield outer shield grounded	Complete side access door removed. RA35C to inner shield outer shield grounded	Access door closed RA35C to inner shield	Access door open RA35C to inner shield	Access door open RA35C to inner shield. Foil off instrument leads.
	60.0	1.0	--	0.17	0.25	25.0
Right Wing Tip to Left Wing Tip	--	0.9	21.0	--	--	--
Left Wing Tip to Right Wing Tip	--	0.08	--	0.24	--	--
Right Wing Tip to Nose	--	0.70	--	0.40	--	--

NOTE: 6.7 x 18.2 μs applied wave - 1000 amperes peak
1.5 x 150 μs applied wave - 100 amperes peak

TABLE X - MAXIMUM AMPLITUDE OF MEASURED INDUCED VOLTAGE

Circuit S.220, Armament Power Supply
Open Circuit Voltage e_{oc} (volts)

Stroke Location	i_L Waveshape								
	24 x 70 µs		36 x 82 µs		7.4 x 20.5 µs				8.2 x 14 µs
	SF3819G20 and Airframe	SF3821G20 and Airframe	2SF3819J20 and Airframe	2SF3821J20 and Airframe	SF3885B20 and Airframe	SF3819G20 and Airframe	SF3821G20 and Airframe	SF3861B20 and Airframe	2SF3819J20 and Airframe
1 Forward End of Tip Tank	0.24	0.28	.045	.055	0.28	0.8	1.2	0.3	0.18
2 Outboard Leading Edge	0.2	--	.03	.04	0.56	1.0	0.34	0.5	--
3 Trailing Edge of Aileron	0.2	--	.025	.03	0.24	0.9	0.38	0.28	--
4 Center of Wing Surface	0.16	--	.02	.03	0.24	0.9	0.22	0.23	--
5 Inboard Leading Edge	0.16	0.2	.045	.06	0.08	0.8	1.1	0.26	.02
Tip of Pylon	0.16	0.24	--	--	--	0.9	1.1	--	--

NOTE: 24 70 µs applied wave - 650 amperes peak
*36 x 82 µs applied wave - 40 kiloamperes peak
7.4 x 20.5 µs applied wave - 1000 amperes peak
* 8.2 x 14 µs applied wave - 40 kiloamperes peak

* applied to F89-J wing at High Voltage Laboratory

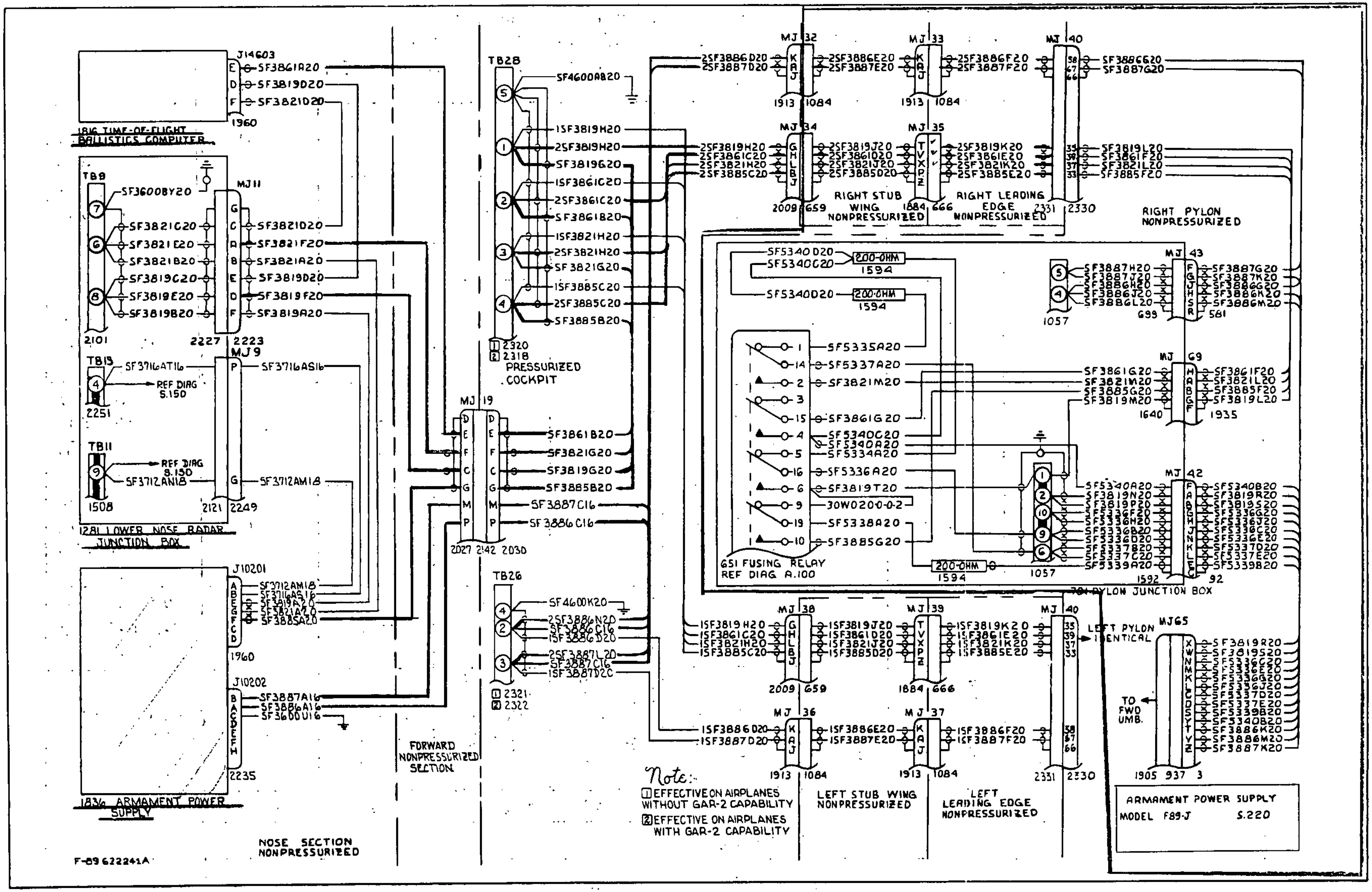


FIGURE 28. - ARMAMENT POWER SUPPLY, CIRCUIT S.220 SCHEMATIC

All connections for measurements performed on the F89-J aircraft at China Lake were made inside the cockpit. Since all measurements were made line-to-ground the structure of the aircraft completed the electrical circuit and thus, any bonds, such as wing root-to-fuselage would add series resistance to the circuit.

Therefore, even though the lightning current is pulled off the wing of the F89-J aircraft at China Lake at the same point (root end) as the F89-J wing in the High Voltage Laboratory, the added length of the circuit including the added resistance of the bond between the wing root and the fuselage increased the amount of induced voltage on the circuit.

When measurements were made with a given wave shape at different lightning current amplitudes on the same test configuration, a linear scaling relationship is much more evident. This is shown in Figure 29 for the Position Light Circuit, L.050. This data was taken on the F89-J wing at the High Voltage Laboratory outdoor facility using the aircraft transient analyzer.

To further stress the importance of the lightning current wave shape in regards to induced voltage, Figure 30 is presented as a reprint of a graph that appeared in NASA report CR-1744. By varying the front time to crest of the applied lightning current from 8 microseconds to 36 microseconds it was possible to vary the amount of induced voltage on a circuit from 20 volts to 44 volts. This was done while keeping the applied current amplitude constant at 40 kiloamperes. It is felt that the differences in applied current wave shapes used in the low current and high current tests on the F89-J wing in the laboratory and the F89-J aircraft at China Lake contributed to the "non-linearity" observed in the induced voltages measured on the aircraft circuits.

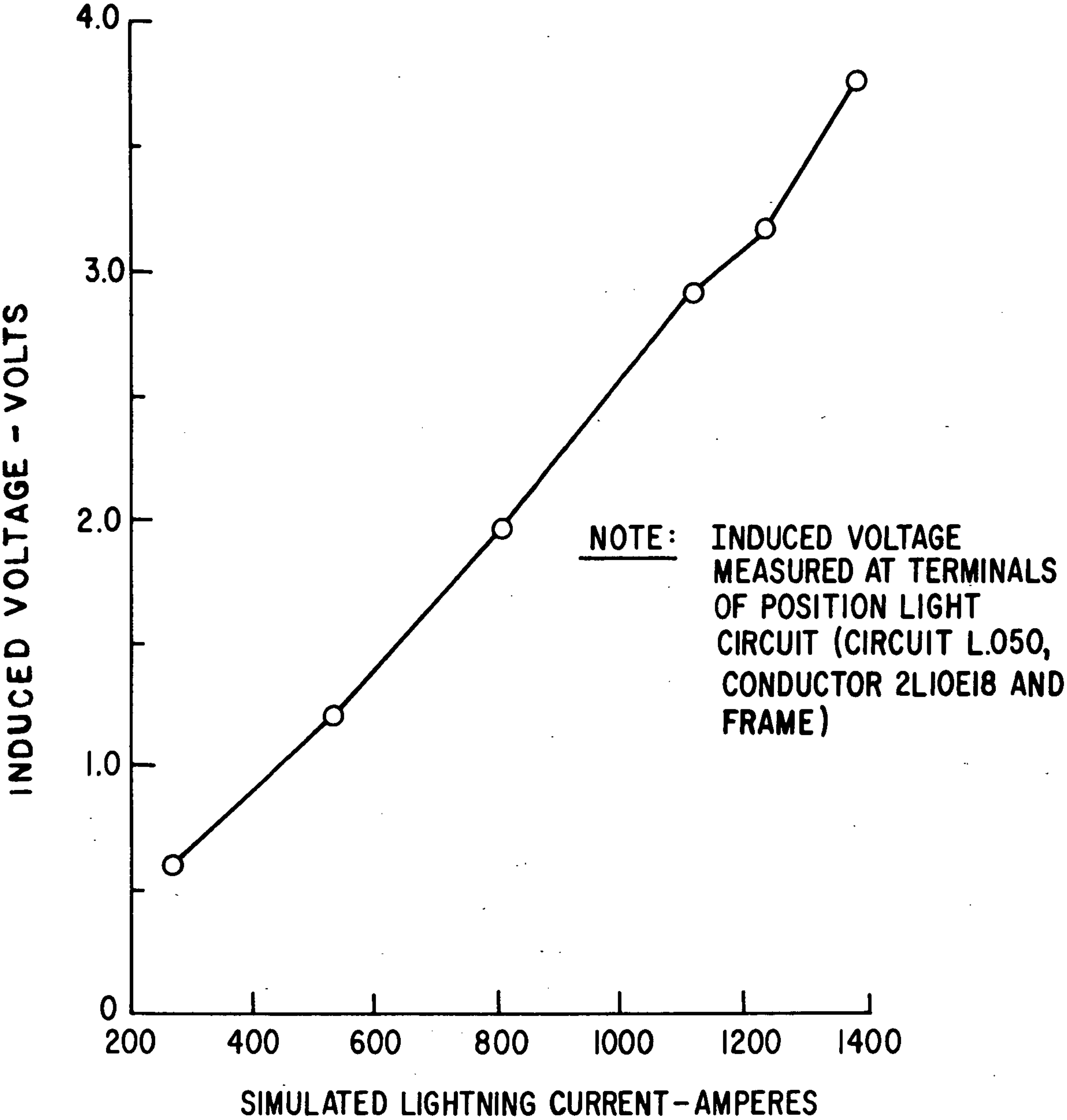


FIGURE 29- AMPLITUDE OF INDUCED VOLTAGE VERSUS AMPLITUDE OF SIMULATED 9 x 18 μSEC LIGHTNING CURRENT DISCHARGED TO LOCATION NO. 1 (FWD. END OF WING TIP FUEL TANK) OF F89-J WING AT HIGH VOLTAGE LABORATORY OUTDOOR TEST AREA USING AIRCRAFT TRANSIENT ANALYZER.

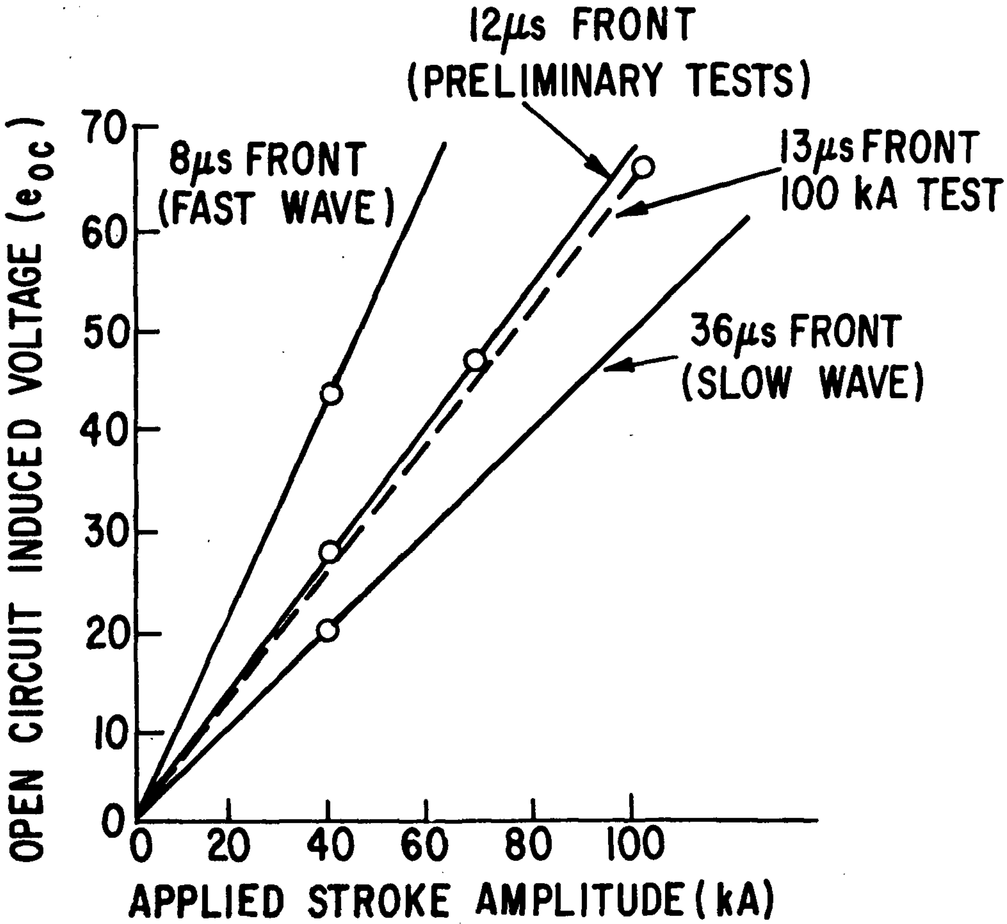


FIGURE 30 - AMPLITUDE OF INDUCED VOLTAGE VERSUS STROKE CURRENT AMPLITUDE

CONCLUDING DISCUSSION

This program is based on the development of a technique to be used for investigating the effect of lightning currents on aircraft electrical circuits. The development is amply documented in this report. Some conclusions pertaining to this program are now discussed.

This test technique can be used on any aircraft now flying today. Due to the low currents used to induce voltages in the aircraft circuitry there is no deterioration, either electrical or mechanical, of the aircraft under test.

The portability of the technique allows the convenience of choosing the location. All commercial and military airports can adequately provide the support facilities needed for this type of testing. 110 volts AC is the only power required for this test technique. No special step-up transformers or rectifiers are required to provide power to the aircraft transient analyzer and the measurement equipment, which are commercially available oscilloscopes.

The size of the test site is governed only by the size of the aircraft to be tested. Additional space is only needed for the enclosure housing the measurement instrumentation. The test site area would be completely enclosed by rope and warning signs to insure personnel safety.

The time from arrival on the test site to actual data acquisition is very short. Depending on the accessibility of the circuitry to be tested, a day of setup time is all that is needed. This involves no modifications, either electrical or mechanical to the aircraft. All measurement leads are clip-on type and, if needed, require only the use of masking tape to keep the leads in position.

During all testing the structure of the aircraft is solidly grounded. If need be, this permits personnel to be in contact with the aircraft and stay seated in the cockpit during the time that the lightning current is being applied to the aircraft.

The compactness of this test technique allows the use of only two people to run the tests. This includes the operation of the transient analyzer and the measurement oscilloscopes. This economy of use of personnel is reflected in savings in total costs.

The test technique allows for data that can be accumulated and analyzed immediately for significant problem areas and areas for further study.

Although transient voltage linearity was not observed on most of the cirćuits measured when compared with the results from applied currents of a few thousand amperes to 40 kiloamperes, the results obtained support the explanation that increased circuit resistance, due to the bond between wing and fuselage, created higher voltages on the circuits tested. Unfortunately, high current tests (40 kiloampere) were not done on a complete aircraft.

REFERENCES

1. Lloyd, K.J., Plumer, J.A., Walko, L.C., "Measurements and Analysis of Lightning-Induced Voltages in Aircraft Electrical Systems", Final Report, NASA Contract NAS3-12019, February, 1971, NASA Report CR-1744.

2. Peterson, B.J., Wood, A.R., "Measurements of Lightning Strikes to Aircraft", Final Report No. DS-68-1 Federal Aviation Administration, January, 1968.

3. Hagenguth, J.H., Anderson, J.G., "Lightning to the Empire State Building -- Part III", AIEE Trans., vol. 71, Part III (Power Apparatus and Systems), pp. 641-649, August, 1952.

4. Plumer, J.A., "Lightning-Induced Voltages in Electrical Circuits Associated with Aircraft Fuel Systems", Proceedings of FAA/Industry Fuel System Fire Safety Conference, May, 1970.

5. Jordan, E.C., "Electromagnetic Waves and Radiating Systems", Prentice-Hall, Inc. 1950.

6. Plumer, J.A., "Analytical Study of Relationships Between Lightning Current and Aircraft Physical Characteristics", Final Report, NASA Contract NAS3-14836, August, 1972, General Electric report SRD 72-066, NASA CR-2349, 1973.

BIBLIOGRAPHY

Technical papers and articles covering subjects related to the research desbribed in this report are listed below. Items listed below have not been utilized as specific references in this report.

General Lightning Characteristics

1. McEachron, K.B., "Lightning to the Empire State Building", The Journal of the Franklin Institute, vol 227, No. 2, pp.149-217, February, 1939.

2. McEachron, K.B., "Wave Shapes of Successive Lightning Current Peaks", Electrical World, vol. 113, pp. 56-58, 126-127, February 10, 1940.

3. Newman, M.M., Stahmann, J.R., Robb, J.D., "Experimental Study of Triggered Natural Lightning Discharges", FAA Report No. DS-67-3, March, 1967.

4. Schonland, Sir Basil: "Lightning and the Long Electric Spark", an address delivered to the August 31, 1962 meeting of the British Association for the Advancement of Science. Available as a preprint from The Advancement of Science XIX, 1962-63.

5. Wilson, C.T.R., "Some Thunderstorm Problems", The Journal of the Franklin Institute, vol. 2, p. 1, 1929.

6. Wilson, C.T.R., "Investigations on Lightning Discharges on the Electrical Field of Thunderstorms", Proceedings of the Royal Society, Series A, vol. 221, pp. 73-115, 1929.

7. Simpson, Sir George, "The Mechanism of a Thunderstorm", Proceedings of the Royal Society, Series A, vol. 114, p. 376, 1927.

8. Evans, E.A., McEachron, K.B., "The Thunderstorm", General Electric Review, pp. 413-425, September, 1936.

9. Simpson, G.C., "Lightning", Journal of the Institution of Electrical Engineers, vol. 67, No. 395, pp. 1269-1282, November, 1929.

10. Simpson, G.C., Scrace, F.J., "The Distribution of Electricity in Thunderclouds", Proceedings of the Royal Society, Series A, vol. 161, pp. 309-352, 1937.

11. Robertson, L.M., Lewis, W.W., Foust, C.M., "Lightning Investigations at High Altitudes in Colorado", AIEE Trans., vol. 61, pp. 201-208, April, 1942.

12. Lewis, W.W., "The Protection of Transmission Lines Against Lightning", Chapters 1 and 2, John Wiley, New York, N.Y., 1950.

13. Westinghouse Electric Corp., "Electrical Transmission and Distribution Reference Book", Chapter 16, East Pittsburgh, Pa., 1950.

14. Alexander, W.H., "Distribution of Thunderstorms in the United States", Monthly Weather Review, vol. 52, p. 337, 1924.

15. McCann, G.D., "The Measurement of Lightning Currents in Direct Strokes", AIEE Trans., vol. 63, pp. 1157-1164, 1944.

16. Berger, K., "Front Time (Rise Time) and Current Steepness of Lightning Strokes to the Earth", Central Electricity Generating Board, Central Electricity Research Laboratories, Leatherhead, England. International Conference, May, 1962. Gas Discharges and the Electricity Supply. Preprint Paper No. 27.

Effects of Lightning on Aircraft Electrical Systems

17. Conference Papers, Lightning and Static Electricity Conference, Dec. 3-5, 1968, Technical Report AFAL-TR-68-290, Part II, May, 1969.

18. "Protection of Nonmetallic Aircraft from Lightning - IV. Electrocution Hazards from Inductive Voltages", NACA ARR No. 4128, March, 1945.

19. Newman, M.M., Robb, J.D., Stahmann, J.R., "Electromagnetic Hazards Inside Aircraft - I", AFAL-TR-66-215, Part I, September, 1966.

NASA-Langley, 1974 E-7783