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PRELIMINARY TESTS OF VULNERABILITY OF TYPICAL AIRCRAFT ELECTRONICS TO LIGHTNING-INDUCED VOLTAGES

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16. Abstract
This report describes the results of tests made on two pieces of typical aircraft electronics equipment to ascertain their vulnerability to simulated lightning-induced transient voltages representative of those which might occur in flight when the aircraft is struck by lightning. The test results demonstrated that such equipment can be interfered with or damaged by transient voltages as low as 21 volts peak. Greater voltages can cause failure of semiconductor components within the equipment. The results emphasize a need for establishment of coordinated system susceptibility and component vulnerability criteria to achieve lightning protection of aerospace electrical and electronic systems.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS - Continued

LIST OF TABLES

SUMMARY

Two pieces of modern aircraft electronics equipment which could be susceptible to transient voltages induced in interconnecting electrical circuits by lightning strikes to the airframe were tested to determine the levels of such voltages at which interference or damage occurs.

It was found that both pieces of equipment could sustain some transient over-voltages with no evidence of temporary interference or damage; however, at high voltage levels interference or damage occurred.

In the case of the turbine gas temperature indicator, momentary fluctuation began appearing in the analog and digital readings when a 6 x 18 microsecond transient voltage with a peak of 21.0 volts was applied across the thermocouple input. After application of a higher amplitude voltage with a peak of 370 volts, the analog and digital readouts of the turbine gas temperature indicator malfunctioned permanently. Subsequent examination of the instrument indicated a contactor on a printed circuit board had been damaged by the tests. After average handling of the indicator, it began to function properly again. Thus, no semiconductors had been permanently damaged by the tests.

When a 1 x 6 microsecond transient voltage of 1700 volts was applied to the microphone circuits of the aircraft passenger address amplifier, the voice input channels ceased to function. When a transient voltage of 2090 volts was injected into the music reproducer, the audible tones associated with the NO SMOKING and FASTEN SEAT BELTS signs also ceased functioning. Subsequent damage analysis of the failed amplifier revealed damage to some of the solid-state components of the circuits tested.

The voltages which resulted in interference or damage to either of these components are representative, in amplitude and waveshape, of those believed capable of being induced by lightning in typical interconnecting circuits within the aircraft.

INTRODUCTION

This report concerns the 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 (Ref. 1). There are also many incident reports of avionics equipment malfunction as a result of lightning strokes to aircraft (Ref. 2). The objective of the work reported in this report was to determine if typical induced voltages could in fact cause interference or damage to avionics equipment.

This work was part of a larger program directed toward solution of the lightning-induced voltage problem. The other objectives were to:

(a) Develop a test and measurement technique to determine the potential effect upon aircraft electrical systems of lightning currents passing through the skin and structural members of a complete aircraft (Ref. 3).

(b) Develop an analytical technique to calculate the possible lightning-induced voltages in aircraft structures while still on the drawing board, by relating the induced-voltages to the physical and electrical characteriestics of an airframe and its circuitry within (Ref. 4).

Incident reports show that the consequences of induced voltages due to a lightning stroke to an aircraft can apparently range from no noticeable effects to permanent damage. It has not been possible, however, to assess the severity of the potential problem, since it is not yet known what transient overvoltage levels can be safely withstood by most avionics equipment. This is partly because at present there exist no universal lightning-induced transient voltage withstand requirements for aircraft electronic equipment. Related specifications such as MIL-STD-704A (Ref. 5) apply only to aircraft and equipment power circuits and generally require that transient overvoltages of up to 600 volts be withstood by these circuits and connected equipment. These requirements are intended to assure that the equipment will not be damaged by aircraft power system transients resulting from system switching operations or other sources within the aircraft power systems. As such, they are not applied to signal and data circuits interconnecting various equipment within the aircraft. Voltages induced in some of these other circuits, which operate at the very low signal voltage levels characteristic of solid-state devices, may damage or interfere with the operation of such equipment to a considerably greater extent than would similar voltages induced in the circuit supplying aircraft power to the equipment.

To learn more about the manner in which lightning-induced voltages interact with electronics of the type utilized in aircraft, a preliminary evaluation was conducted in which two pieces of aircraft electronic equipment were tested by injecting simulated lightning-induced voltages into them. The resulting effects on the operation of the components during and after exposure to these transients was then determined.

The authors gratefully acknowledge the assistance of the Boeing Company, Commercial Airplane Group, and the General Electric Company, Aircraft Instrument and Control Systems Department, for loan and damage assessment of the electronic equipment tested in this program.

LABORATORY TESTS

General

Two operational pieces of electronic equipment typical of those found aboard modern commercial jet transport aircraft were obtained for use as the subject of these laboratory tests. These included a cabin public address system and a turbine gas temperature (TGT) instrument. These were chosen, of course, partly because they happened to be available at no direct cost to this limited program, but also because they are, indeed, equipments whose function is important to the safe conduct of the flight. Reliable communication between flight deck and cabin must be maintained during flight in thunderstorm weather conditions, for example, in which lightning and turbulence may occur together. Reliable indications of engine operating parameters must also be available to the flight crew if sustained safe flight is to be maintained.

Both of these units utilize solid state electronics operating at low steady-state voltage levels. This equipment is therefore representative of much of the electronics present in modern aircraft avionics and instrumentation.

The cabin P.A. system was loaned for these tests by the Boeing Co., Commercial Airplane Group. The TGT instrument was loaned by the General Electric Co., Aircraft Instrument and Control Systems Department. After the voltage injection tests, each of these organizations performed the inspection and failure analysis of its loaned unit, reported herein.

The turbine gas temperature indicator, when installed in an aircraft, is centrally located on the pilot's panel and presents an analog (pointer) and digital (counter) display of turbine gas temperature. The indicator receives a voltage proportional to the turbine gas temperature, from a thermocouple in the turbine. The circuit between the engine and the indicator is sufficiently long to make it susceptible to significant induced voltages. The instrument also requires an operating voltage of 115 VAC, 400 Hz, so it would be exposed to induced voltages appearing on the power distribution bus.

The cabin address system is also located in the flight deck and, in contrast to the turbine gas temperature indicator, the cabin address system uses 27.5 VDC for its operation. Induced voltages are known to appear on the DC busses as well as the AC distribution system. Additionally, the system has lengthy circuits extending throughout the cabin to passenger indicators and annunciators.

Induced voltages have been measured in every circuit inside an airframe as a result of simulated lightning strokes delivered to the aircraft in laboratory tests (References 1, 3 and 6). The induced voltages range in amplitude from several millivolts to several thousand volts, depending on the amplitude and waveshape of the exciting lightning current, as well as physical characteristics of the aircraft and particular circuit in question. The induced transient voltage surges were nearly as short in time duration as the lightning stroke current itself. This means they may last for times from a few microseconds to several hundred microseconds. As a general rule, they rise faster than they decay. Therefore, in this series of tests simulated lightning-induced voltage surges were injected into the terminals of the tested component, thus simulating the exposure to lightning-induced voltages it might experience when connected to circuits in an actual aircraft. The effect of these voltages on the operation of the component during and after exposure to these voltages was evaluated.

The waveshapes of the test voltages were selected to represent typical lightning-induced voltages. Since the vulnerability of many electronic devices to voltage transients is known to be a function not only of voltage amplitude but also time duration, the voltage waveshape is a significant parameter. However, due to the preliminary nature of this investigation, a thorough study of waveshape and amplitude effects was not made.

Basic Test Procedures

Since the impedances of solid state components are usually different while operating than when not, the voltage injection tests were applied with the units powered up and operating. A TIC Model 400A frequency converter power supply was used to operate the TGT instrument, and a Hyperion Model, HY-AL-32-10, 28 VDC power supply operated the cabin P.A. amplifier.

Simulated lightning-induced voltages were generated by a GE transient analyzer of the type utilized at the High Voltage Laboratory for other tests on power transformers. The units were set at their normal operating modes and simulated induced voltages were injected into various input-output circuits of the tested units. If the tested circuit was one already connected to some other external component, such as the thermocouple for the TGT instrument, the output of the transient analyzer was connected in parallel with this circuit.

Generally, tests were begun by applying one simulated induced voltage transient whose peak amplitude was expected to be withstood by the tested unit. If no indications of interference or damage to the tested component were noted, the test was repeated at successively higher peak amplitudes until some indication of an adverse effect was noted. When some damage to solid state electronics occurs, the impedance of the affected component usually undergoes a change. Since the test voltage generated by the transient analyzer has its own source impedance, changes in the tested electronics impedance also cause changes in the applied test voltage amplitude or waveshape. In other words, the test voltage is determined partly by the (load) impedance across the terminals of the component being tested. Thus, there are frequent cases where the first indication of component malfunction is an unexpected change in the injected voltage waveform. Sometimes damage results in a lower component impedance, thus reducing the amplitude of the voltage available from the transient analyzer. Thus, a situation may arise where an increased transient analyzer charging voltage setting causes a decrease in load impedance, and a decreased output voltage.

The following paragraphs present detailed descriptions of the tested components, tests applied and results obtained, including the post-exposure inspections made by Boeing and GE-AICSD on their respective components.

TURBINE GAS TEMPERATURE INDICATOR

Description

The turbine gas temperature indicator (TGT) is housed in a metal case about 2 inches square and 9 inches long. The indicator is made up of six major assemblies. The indicator and these assemblies are pictured in Figure 1. The assemblies are described briefly below:

Case Assembly

The metal case assembly houses the complete instrument and consists of a flange, case and tabs.

Electro-Mechanical Assembly

The electro-mechanical assembly contains the necessary mechanical and electrical components needed to provide analog and digital display. It consists of the following: lens-and-support assembly; lighting; analog and digital indicators; scaleplate; flag-and-frame assembly (failure indication); torque motor assembly; flexible cable; connector and transformer assembly; and printed circuit boards.

Lens-and Support Assembly

The lens-and-support assembly is at the front end of the electro-mechanical assembly. It permits access for replacement of lamps, lens, pointers, and scaleplate.

Torque Motor

The torque motor positions the analog pointer and contains a resistor assembly, magnet shaft assembly and coil assembly by which it is driven.

Flexible Cable, Connector and Transformer Assembly

This assembly secures the flexible cable(s), holds the printed circuit boards in place and connects all electrical transmission between the connector, transformer and printed circuit boards.

Face of Turbine Gas Temperature Indicator, showing analog (pointer) and digital indicators. It also has an amber warning light to indicate an over-temperature condition.

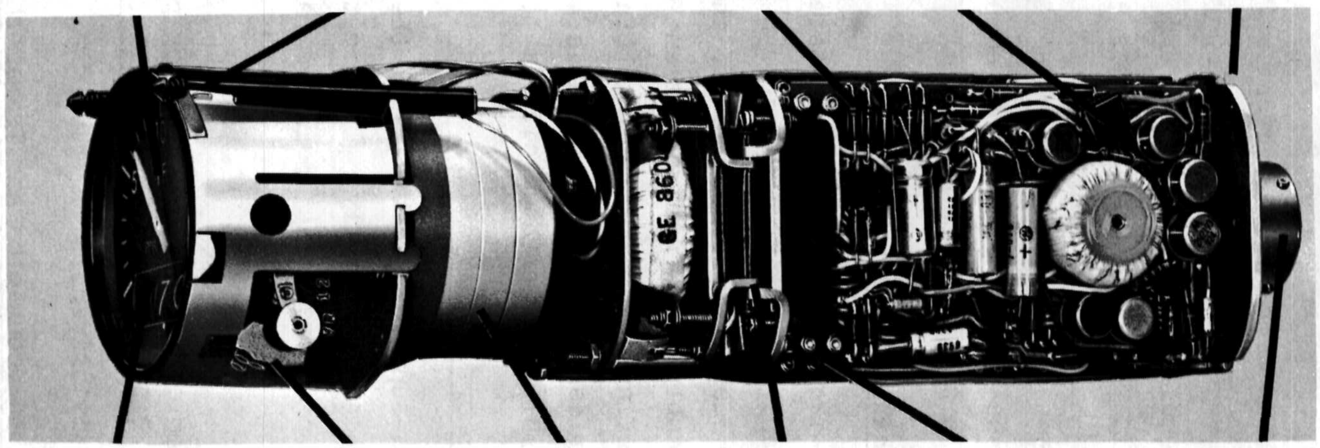


Figure 1. - Turbine Gas Temperature Indicator Showing Position of Circuitry.

Printed Circuit Board Assemblies

The printed circuit boards contain all the electronic components required for indicator operation.

The instrument displays turbine gas temperature in the range 0-1000 degrees Centigrade (°C). It has a maximum indication pointer (MIP) which moves upscale with the analog pointer above the redline mark at 850°C and remains there to register overtemperature conditions until reset to 850°C by application of a momentary 28 VDC signal. An overtemperature warning light on the front scaleplate comes on when the scale indication passes 780° ± 4°. There is also a failure warning flag which drops and obscures the digital counter when there is a power failure to or within the indicator. The TGT indicator also has an 0-5 VDC analog output to feed TGT information to the aircraft's Airborne Integrated Data System (AIDS).

Principles of Operation

Figure 2 is a block diagram of the turbine gas temperature measurement system. The alumel and chromel leads are continuous through the cabling system and connectors until termination is made within the indicator at a point co-located with the compensating resistors (subject to the same ambient temperature conditions). This point is inside the indicator on the connector mounting plate.

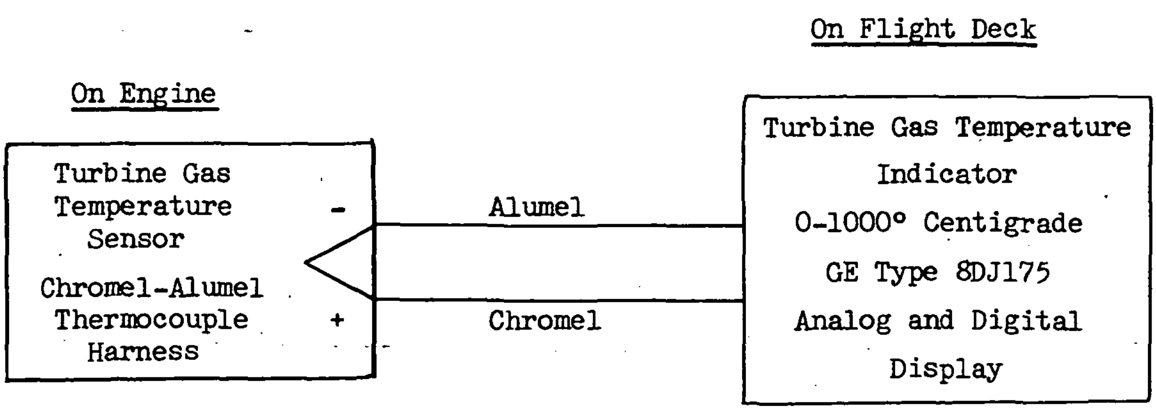


Figure 2 - Block Diagram of TGT Measurement System.

The indicator is also compensated in both the analog and digital channels for the inherent non-linearity reflected in the temperature-versus-millivolts curve for a thermocouple junction so that both displays are linear. The AIDS (Airborne Integrated Data System) output is not compensated, however, and is thus non-linear.

Figure 3 is an overall functional block diagram of the turbine gas temperature indicator. Its operation is as follows:

Analog Channel

The instrument receives a small voltage from the chromel-alumel thermocouple, proportional to turbine gas temperature. This voltage is brought into a measuring bridge circuit in the instrument, where an error signal is developed and processed in the signal processing channel and appears at the input to the torque amplifier.

This error signal is amplified and then causes a drive signal to be applied to the stator windings of a DC torque motor through the driver. The resulting torque counterbalances that developed by the spring return mechanism and moves the display pointer upscale. This movement would continue as long as an error signal persists at the input to the torque amplifier. However, as the pointer display moves upscale it moves the arm of the balancing potentiometer, which is integral with the torque amplifier and in opposition to the error signal developed in response to the input signal. When this feedback signal is equal to the error signal, the resultant signal in the torque amplifier is reduced to zero, and the servomechanism has then reached its null or balance point.

The servomechanism will remain in equilibrium until some change occurs in the error signal, which is proportional to gas temperature. If a decrease in gas temperature should occur, a proportional decrease in error signal at the torque amplifier would result. The counter torque supplied by the spring would then move the mechanism downscale until the feedback signal from the balancing potentiometer again equalled the error signal.

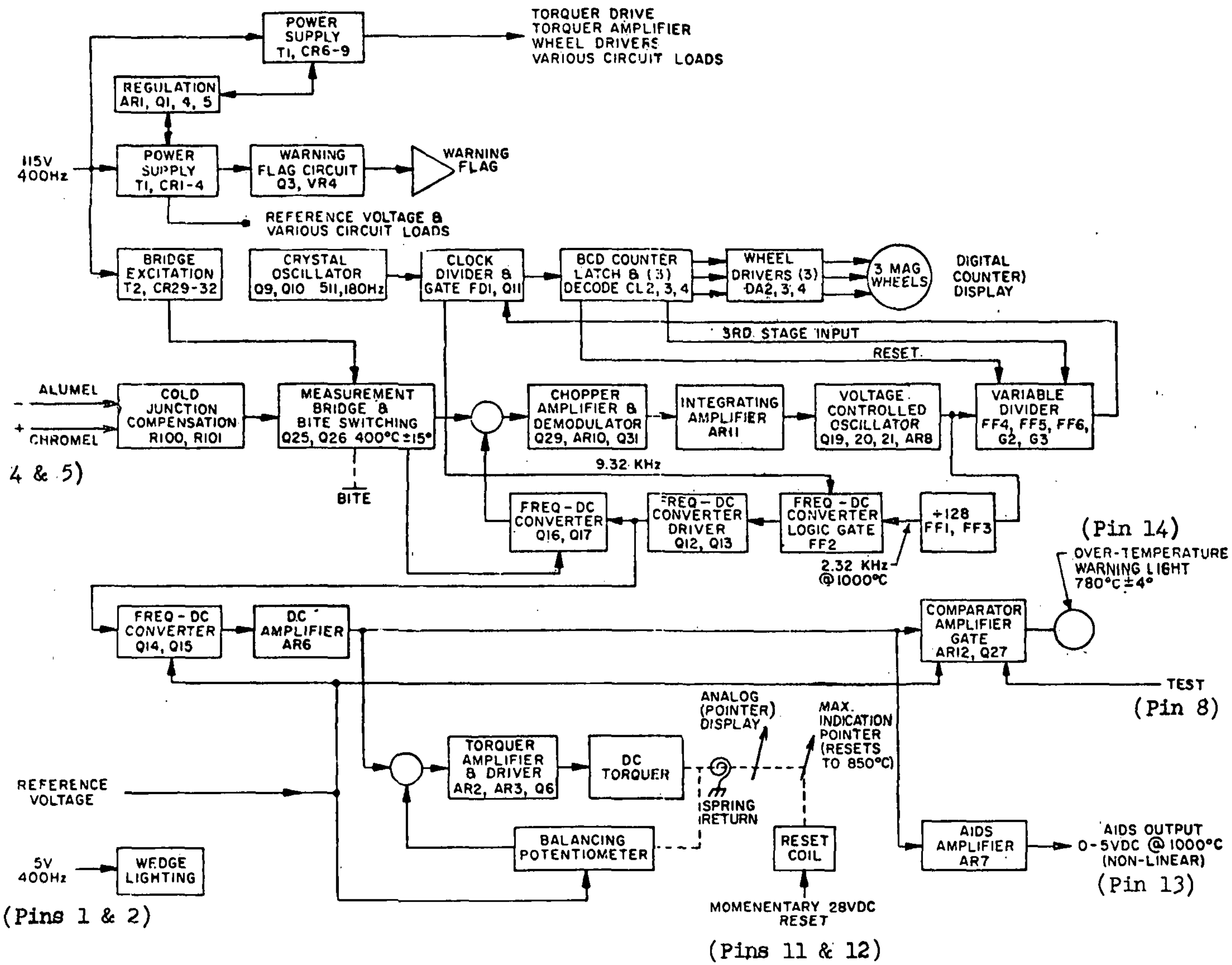


Figure 3 - Turbine Gas Temperature Indicator
Functional Block Diagram Showing Relationship of
Connector Pins to Internal Components.

Scale movement would cease and the pointer would then indicate the lower gas temperature in degrees Centigrade.

Digital Channel

Referring again to the overall block diagram, Figure 4, it can be seen that to develop the digital output counter drive for the indicator, the analog signal is connected to a variable frequency AC signal. Digital logic and sampling circuitry is then employed to count cycles proportional to gas temperature for a precise period. The resulting signal is then displayed by a set of magnetically driven wheels.

Test Circuit

Figure 4 shows a diagram of the test circuit. The 115 volt, 400 Hz, power supply was used to power the TGT instrument. The instrument was turned on, and to simulate the voltage signal that would come from the chromel-alumel thermocouple harness due to a hot turbine gas, a 1.5 volt battery in series with a variable resistance was substituted for the thermocouple. By varying this resistance it was possible to obtain all possible analog and digital readings. Figure 5 shows the face of the operating instrument with and without a voltage on the thermocouple input.

The simulated lightning-induced voltages were applied across the various pairs of pins on multipin connector J1, at the back of the TGT indicator. Applied voltages were measured with a Tektronix 545 oscilloscope connected across the tested pins. The tested pins are listed in Table I.

Table I

Tested Circuits in TGT Indicator

Functional Description	J1 Pin Numbers
Comparator Gate Amplifier	8 and 14
Comparator Amplifier Gate and AIDS Amplifier	8 and 13
AIDS Amplifier	9 and 13
Max. Indication Pointer Reset Coil	11 and 12
Wedge Light	1 and 2
Thermocouple Input	4 and 5

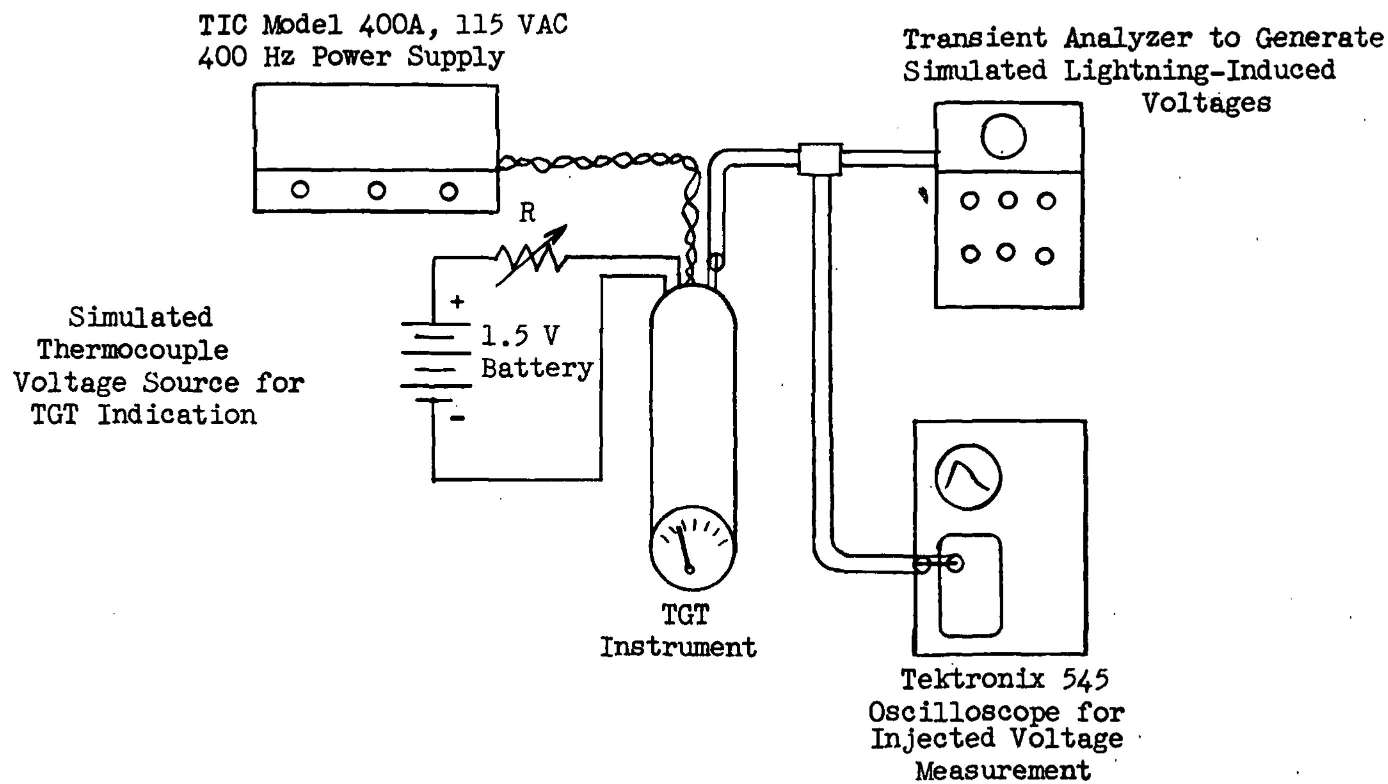
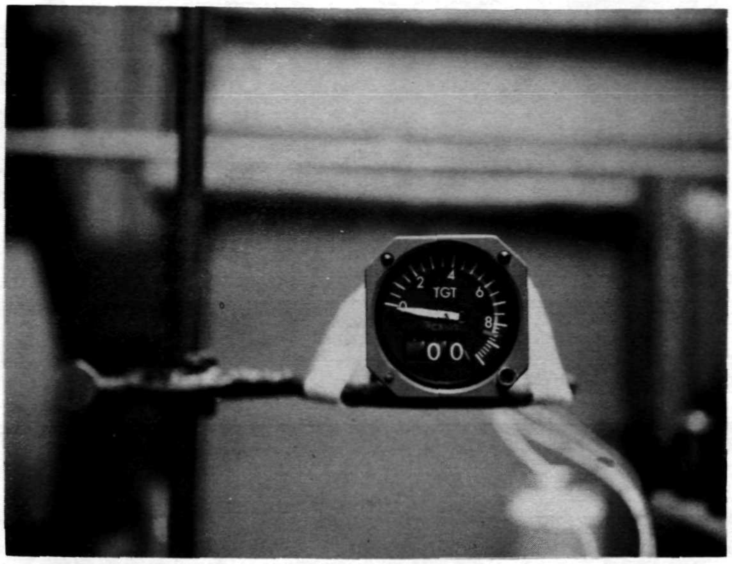


Figure 4 - Test Circuit for Voltage Injection Tests on Turbine Gas Temperature Indicator.



No Voltage on Thermocouple Input.
No indication on Analog or Digital Readout.

Battery Voltage on Thermocouple Input
Causing Analog and Digital Indications.
(565°C)

Figure 5 - Operating Turbine Gas Temperature Indicator With and Without Simulated Thermocouple Voltage.

In performing these tests, voltage injection testing was terminated at voltages judged to represent the maximum which each particular circuit would be susceptible to in the aircraft, even if no interference with instrument operation had yet been observed so as to preserve the instrument in operating condition for further tests on other portions of its circuitry. In general, the circuitry connected to the longest interconnecting aircraft wiring was judged to be susceptible to the highest voltages, so these circuits (such as the thermocouple input) were tested last for fear of permanently damaging the instrument before all desired tests had been run.

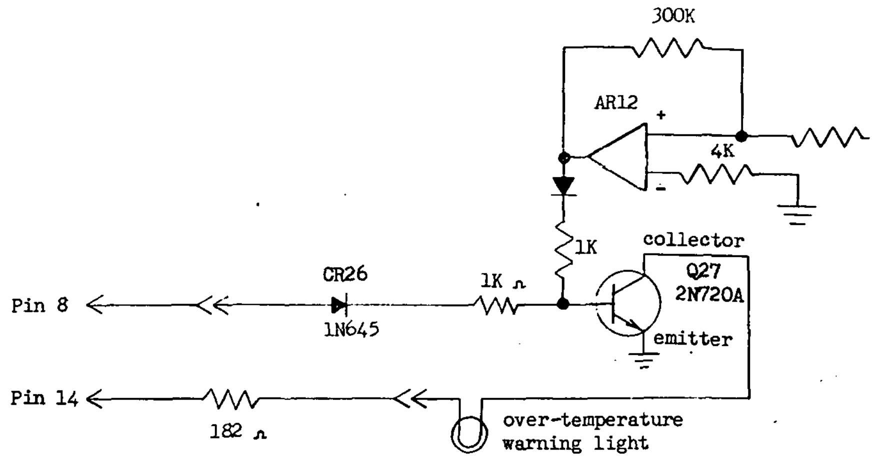
Test Results

Comparator Amplifier Gate (Pins 8 and 14)

Figure 6 shows the voltages injected into this portion of the TGT circuitry. Beginning at 3 volts peak, with pin 8 grounded, successive voltages up to 10 volts were applied with no apparent change in waveform or TGT performance. At 12 volts peak, a flattening of the injected voltage waveform was evident, although no change in indicator performance was noted. This continued up to a maximum voltage of 35 volts peak, at which level the tests were terminated. The injected voltage and ground connections were reversed and the test repeated, so that pin 14 was now grounded. This time no effects of any kind on instrument or waveform were noted, up to 180 volts, where the test was terminated. This level was judged to be the maximum induced voltage this circuit would be susceptible to in the aircraft.

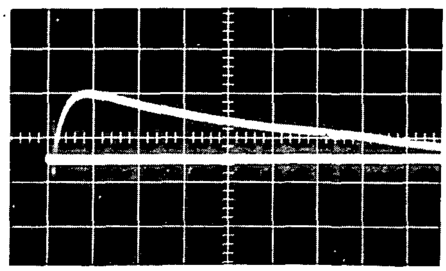
Comparator Amplifier Gate and AIDS Amplifier (Pins 8 and 13)

The immediate components associated with the circuit are shown on Figure 7 along with examples of the simulated induced voltages applied. Since the circuit between pins 8 and 13 is unbalanced with respect to ground, it was necessary to perform the tests first with one and then the other of these two pins grounded, since one side of the transient analyzer, measurement oscilloscope and TGT case were all at ground potential. With Pin 8 grounded injected test voltages up to 28 volts peak were withstood by the



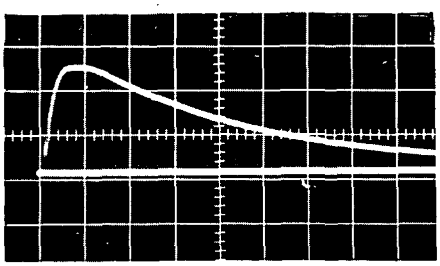
Pin 8 Grounded

Test #1



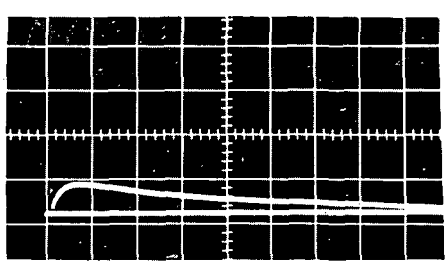
2 v/div. 10 μs/div.

Test #10



5 v/div. 10 μs/div.

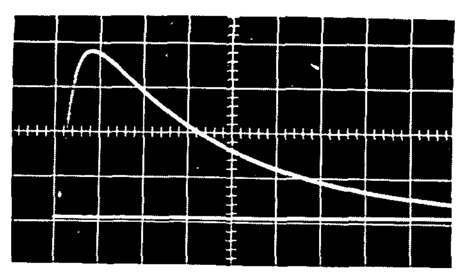
Test #21



50 v/div. 10 μs/div.

Pin 14 Grounded

Test #22



50 v/div. 10 μs/div.

Figure 6 - Simulated Induced Voltages Applied to Comparator Amplifier Gate.

In performing these tests, voltage injection testing was terminated at voltages judged to represent the maximum which each particular circuit would be susceptible to in the aircraft, even if no interference with instrument operation had yet been observed so as to preserve the instrument in operating condition for further tests on other portions of its circuitry. In general, the circuitry connected to the longest interconnecting aircraft wiring was judged to be susceptible to the highest voltages, so these circuits (such as the thermocouple input) were tested last for fear of permanently damaging the instrument before all desired tests had been run.

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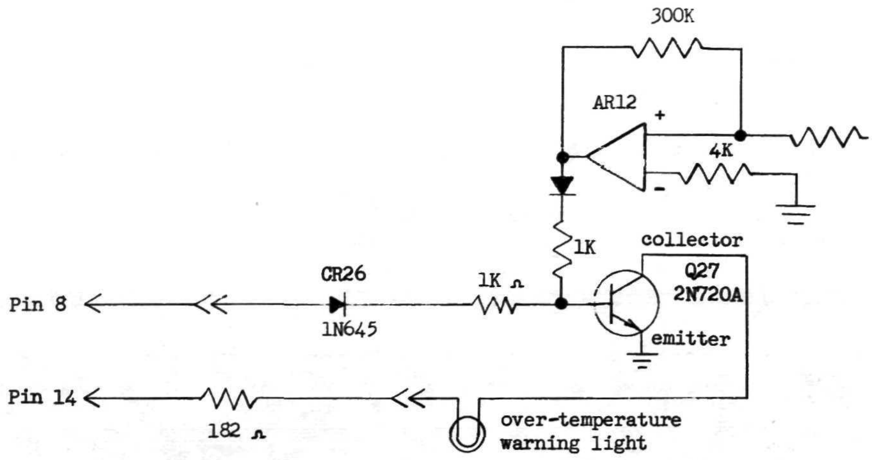
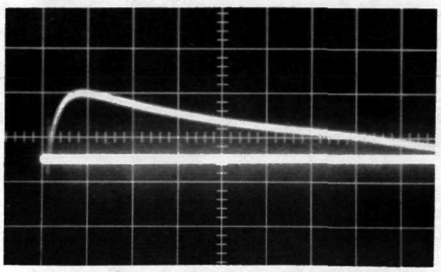


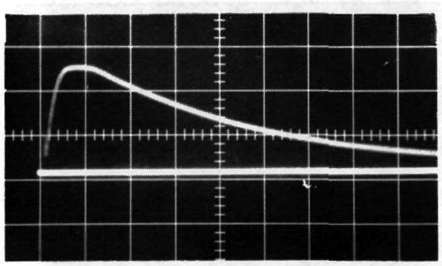
Pin 8 Grounded

Test #1



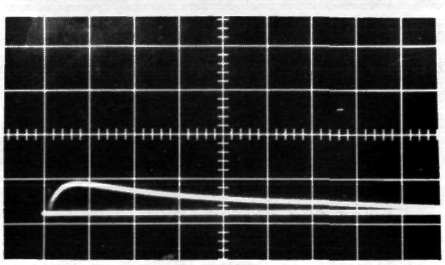
2 v/div. 10 µs/div.

Test #10



5 v/div. 10 µs/div.

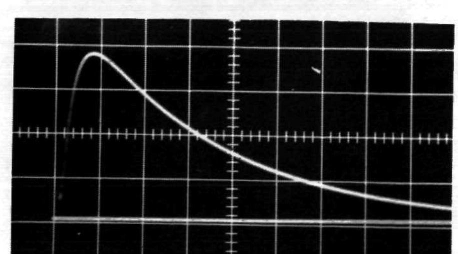
Test #21



50 v/div. 10 µs/div.

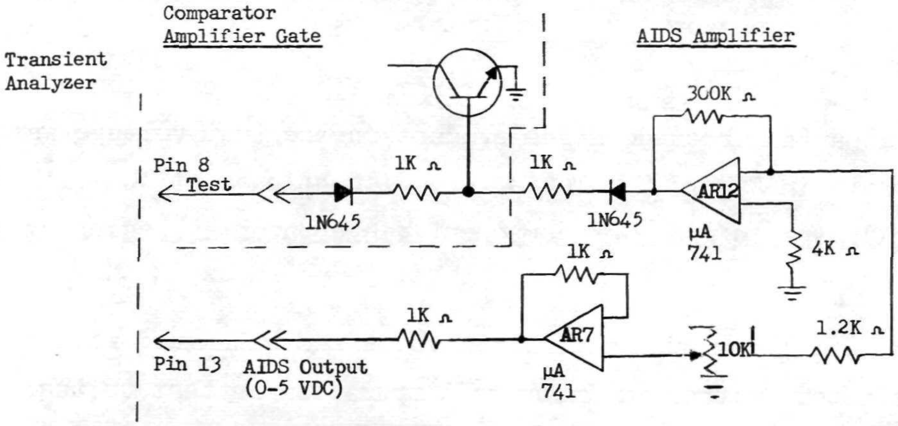
Pin 14 Grounded

Test #22



50 v/div. 10 µs/div.

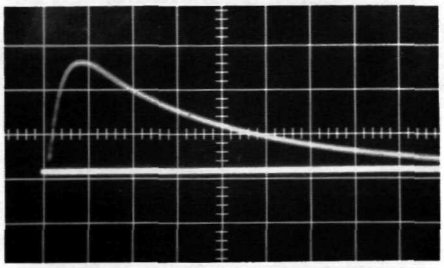
Figure 6 - Simulated Induced Voltages Applied to Comparator Amplifier Gate.



Pin 8 Grounded

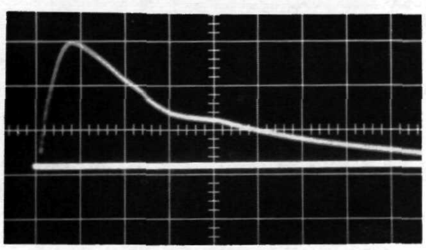
Pin 13 Grounded

Test #11



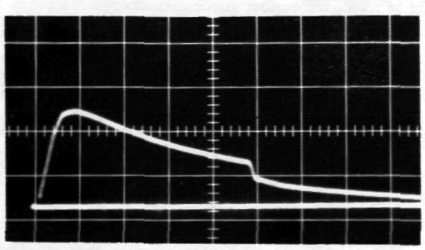
5 v/div. 10 μs/div.

Test #13



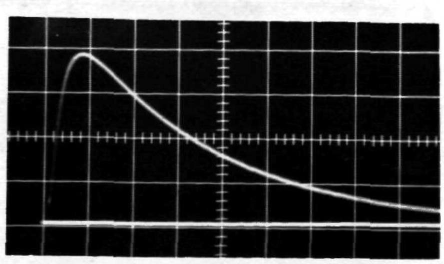
10 v/div. 10 μs/div.

Test #14



20 v/div. 10 μs/div.

Test #23



50 v/div. 10 μs/div.

Figure 7 - Simulated Induced Voltages Applied to Comparator Amplifier Gate and AIDS Amplifier Circuits.

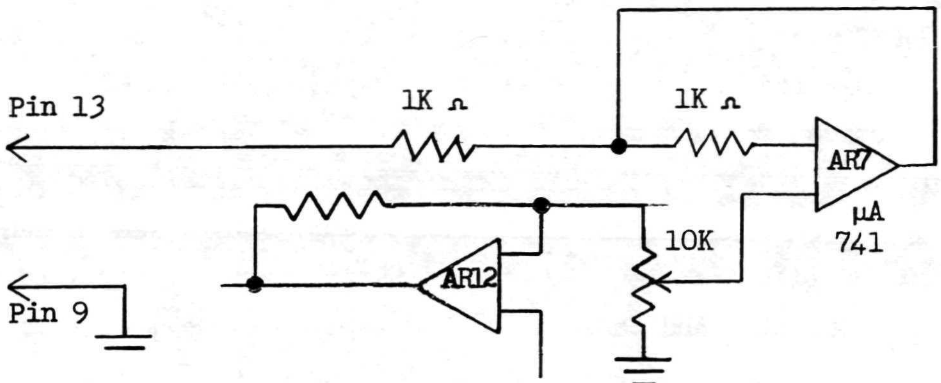
instrument with no indications of interference with its operation. Above 28 volts peak, a partial breakdown was evident on the test voltage waveform tail, as shown in Figure 7. Tests were discontinued at 40 volts to prevent further damage to whatever component was apparently beginning to break down.

With Pin 13 now the grounded pin, 190 volts was withstood with no adverse effects noted, either in instrument operation or test voltage waveform. The tests were discontinued at this level on this circuit since it was felt that 200 volts was greater than that which lightning would induce in the internal AIDS circuitry, which would be located predominantly in the flight deck area alone.

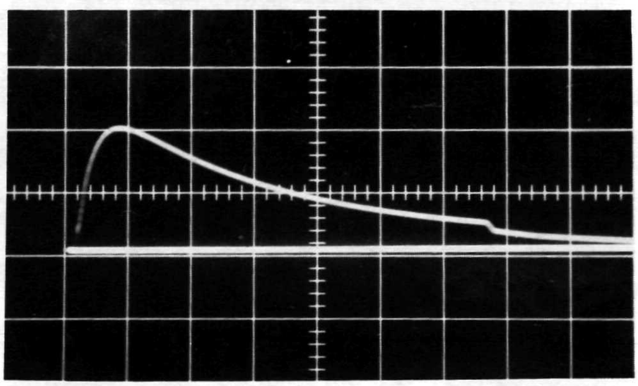
An analytical study of this portion of the TGT circuitry to explain the partial breakdown was not made; however, the IN645 diode requires at least 225 volts to conduct in the reverse direction, and the partial breakdown occurred at only 40 volts (peak). Thus, some other semiconductor may have been responsible for this event.

AIDS Amplifier (Pins 9 and 13)

Figure 8 shows the AIDS amplifier input circuitry and a representative oscillogram of test voltage injected into it. For this test, neither pin was grounded because both are above ground in the aircraft circuit. No adverse effects were observed on instrument operation or injected voltage waveform until a voltage whose peak was 100 volts was applied. A partial voltage breakdown was noted on the wave tail, as shown on Figure 8, but no interference with instrument operation was noted. This partial breakdown occurs after the wave peak has been reached, thereby indicating that it is related not only to voltage amplitude but also to time duration. This result is similar to the partial breakdown observed in test of comparator amplifier gate and AIDS amplifier circuitry (Figure 7, Pins 8 and 13) and pin 13 is common to both tests. Pin 13 is an input to an operational amplifier, so the partial breakdowns may be associated with a component in this amplifier. Testing of this circuit was discontinued after the 100 volt test on which the partial breakdown was noted.



Test #25



50 v/div. 10 µs/div.

Figure 8 - Simulated Lightning-Induced Voltage Applied to AIDS Amplifier.

Maximum Indication Pointer Reset Coil (Pins 11 and 12)

Pin 12 of this circuit was grounded internally to the instrument case so this pin was connected also to the ground side of the transient analyzer. The reset coil forms an electromagnet which moves the maximum indication pointer to 850°C when 28 volts is switched to this input. When the 160 volt transient was injected into the circuit no indications on waveform or indicator were noticed, as shown on Figure 9. When a slightly longer duration, 140 volt pulse was injected, the maximum indication pointer moved to zero from its previous setting at full scale. Apparently there was enough energy in the longer duration transient for the resulting magnetic force to overcome the pointer inertia and cause it to move, all the way to zero. A 140 volt induced voltage transient such as this is a possibility in an incoming 28 VDC circuit such as would be connected to these pins.

Wedge Lights (Pins 1 and 2)

The wedge lights illuminate the instrument face and are powered by 5 VAC, 400 hertz. The input to the wedge lights, except for its ground connection to the case, is not connected to any other part of the instrument circuit. Figure 10 shows a 170 volt waveform injected into this circuit. No effects were noted on the waveform or lights (they did not light-the transient was too short) but the analog pointer fluctuated momentarily from a preset value of 400°C. No positive cause for this is known, but some electrostatic or induced effect may be responsible.

Thermocouple Input (Pins 4 and 5)

Simulated induced voltage ranging in peak amplitude from a few volts to 390 volts were applied to the thermocouple input circuit shown on Figure 11. Waveshapes ranged from 4 x 40 μs to 4 x 80 μs. Momentary decreases in the ambient analog and digital indications on the instrument were noted after each applied voltage above 21 volts peak. The thermocouple input battery voltage (see Figure 4) had been set to provide an instrument

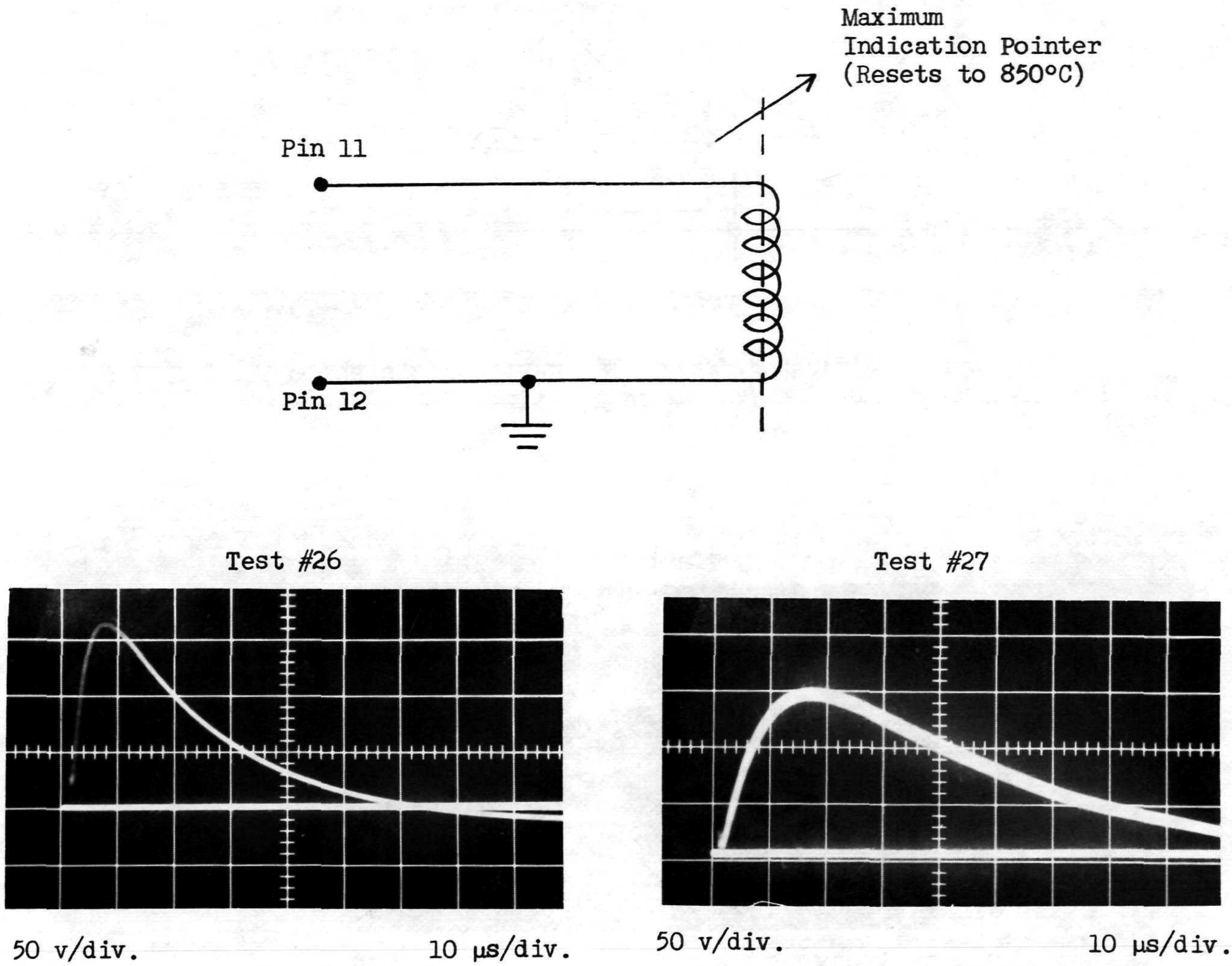
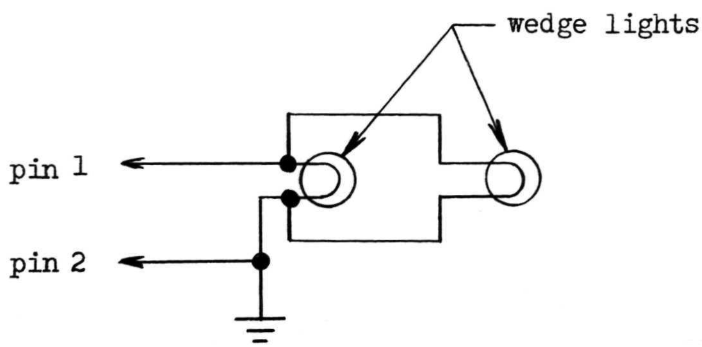
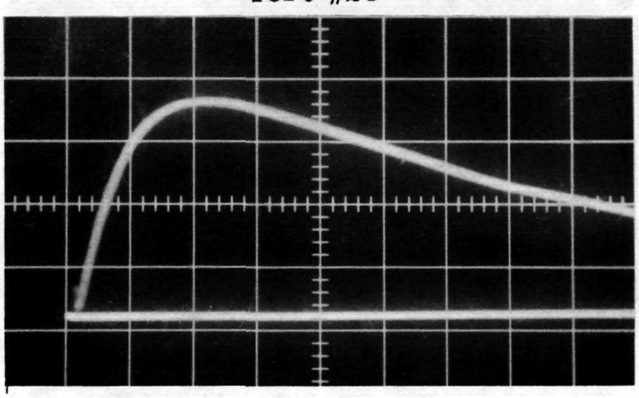


Figure 9 - Simulated Lightning-Induced Voltages Applied to Maximum Indication Pointer Reset Coil



pin 1 - 5 VAC, 400 Hz, 1.5 watts single phase
for wedge lighting

Test #28



50 v/div. 10 μs/div.

Figure 10 - Simulated Lightning-Induced Voltage Applied to Wedge Lights.

reading of 404°C (on both analog and digital indicators). When injected test voltages exceeded 21 volts, the indicators dipped momentarily but quickly recovered. The magnitude of the decreases bore no apparent relationship to the injected voltage level, and of course, the response time of both of these electromechanical devices is probably much longer than the duration of the injected voltage, so the instrument probably responded to the stimulus only, and not directly to the transient amplitude. The greatest deflections were nearly always in the analog indicator, and the maximum deflection noted was about 200°C. A total of 20 simulated lightning-induced voltage transients of successively higher amplitudes were injected into this circuit until a peak amplitude of 330 volts was reached, with the same results as described above.

At the next higher peak voltage level of 370 volts, an irregularity was noted for the first time on the tail of the injected voltage waveform, as shown in Figure 11 (Test #53). This indicates some change in the thermocouple input circuit impedance. Again the usual momentary deflection in instrument readings was noted. A repeat of the test at the same peak voltage gave the same result, with the waveform irregularity appearing 10 microseconds earlier on the wave tail. Another application of the same test resulted in an apparent breakdown or abrupt decrease in load impedance, on the wavefront. Upon this test both temperature indicators dropped to zero and remained there. No subsequent analog or digital deflections could be obtained. This was the last test performed on this instrument.

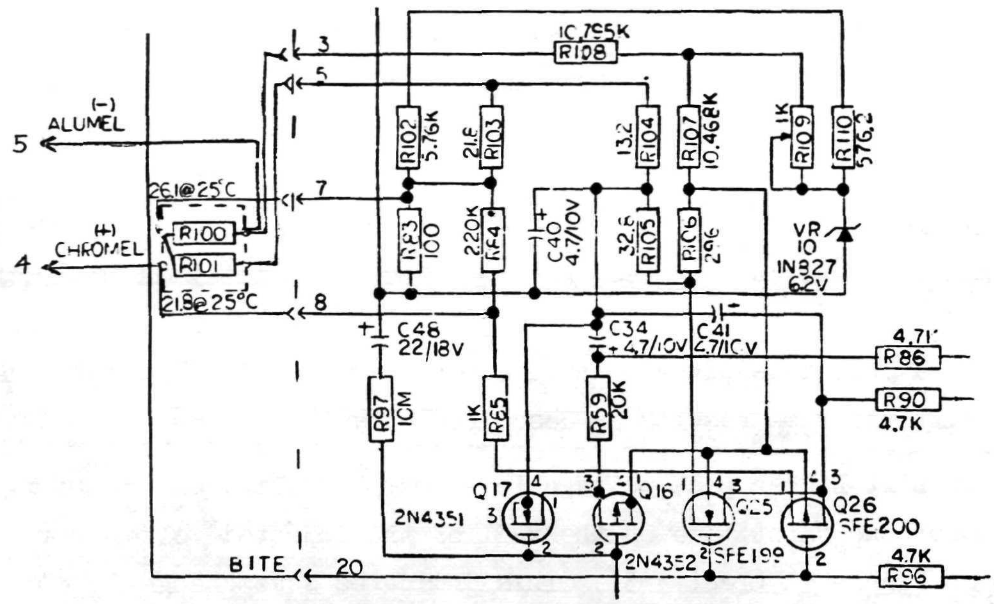
TGT Test Summary

Table II presents a summary of applied peak voltage levels and resulting effects noted during the tests on each of the TGT instrument circuits previously discussed. For all but the last test performed on the instrument, it remained functional and appeared to have sustained only temporary interference. The final test, with voltage injected into the thermocouple input circuit, permanently disabled the instrument when a transient of 370 volts (peak) was applied.

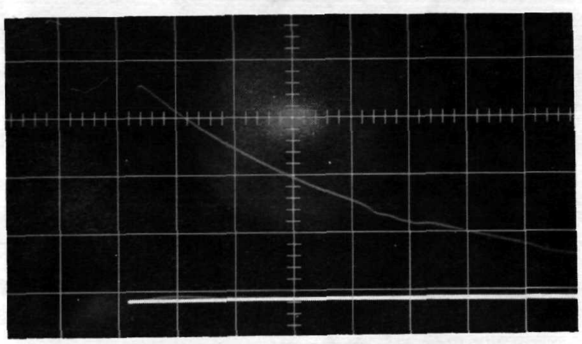
Diagnosis

The TGT indicator was returned to the General Electric Aerospace

Circuitry floating

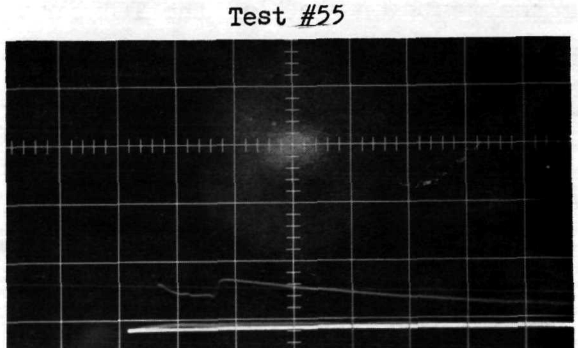


Test #53



100 v/div. 20 µs/div.

Test #55



100 v/div. 20 µs/div.

Figure 11 - Simulated Induced Voltages Applied to Thermocouple Input Circuit.

Table II

Summary of Results - Voltage Injection Tests on Turbine Gas Temperature Indicator

Circuit Function	J1 Pin Numbers	Test Voltage at Which Some Effect Was Noted (peak volts)	Effects: Waveform Variation	Effects: Instrument Operation
Comparator Gate Amplifier	8(gnd) and 14	35	slight flattening of waveform peak	none noted
" " "	8 and 14(gnd)	180	none	none noted
Comparators Amplifier Gate and AIDS Amplifier	8(gnd) and 13	28	change in waveform tail	none noted
" " "	8 and 13 (gnd)	190	none	none noted
AIDS Amplifier	9(gnd) and 13	100	partial breakdown on waveform tail	none noted
Maximum Indicator Pointer Reset Coil	11 and 12(gnd)	140	none noted	maximum indicator pointer went to zero and remained there
Wedge Lights	1 and 2(gnd)	170	none noted	momentary analog pointer fluctuations
Thermocouple Input	4 and 5 (floating neither grounded)	21	none noted	momentary downward deflections of up to 200°C from ambient 404°C level in analog and digital indicators
" "	"	370	irregularity on waveform tail	" "
Note: Up to this point, TGT Instrument appeared to have suffered no permanent damage				
" "	"	370	more complete breakdown on wavefront	Analog and Digital Indicators chopped to zero and remained there

Instrument and Control Systems Department, Wilmington, Mass. for diagnosis after the voltage injection tests had been completed. There, the indicator was connected to test equipment for performance checks and operational failure of the indicator was verified. However, after moving the indicator's printed circuit boards individually in their connectors, the instrument again operated. Apparently, whatever had malfunctioned had recovered as a result of movement of the circuit boards. Subsequent inspection of the boards indicated that the test voltage may have degraded an electrical connection in the E printed circuit board connector. This board contains the circuitry for the AIDS system and the frequency-to-DC converter system. Thus, the thermocouple input circuit itself safely withstood the simulated induced voltage. The indicator was next submitted to a normal acceptance test procedure. Its calibration was found to be slightly out of limits but this condition may have existed before the instrument was subjected to the voltage injection tests.

No semiconductor components of the TGT indicator were found to be damaged by the injected voltages.

CABIN ADDRESS SYSTEM

Description

Voltage injection tests were also performed on a Collins 346D-1B aircraft passenger address amplifier. This 60 watt amplifier provides audio power to an 83 ohm multiple loud-speaker in an aircraft cabin. It includes microphone inputs for use by the pilot and cabin attendants and two balanced inputs for use with tape reproducers for announcements and programmed music. The amplifier also has chimes for use by the pilot and passengers. The system circuitry extends the length of the passenger compartment, with the amplifier located in the cockpit.

The amplifier is housed in a metal case, with a total weight of 9.5 pounds. It accepts audio signals from transistorized microphones, carbon microphones, tape reproducers, automatic message annunciators, and other call/alert devices. The five inputs have individual level controls and solid-state priority switching.

The amplifier has two DC voltage regulators; one for 15 volts and the other, 10 volts. They receive their operating power directly from the aircraft's 27.5 volt DC supply. The address system accepts signals from the microphones and the tape reproducers through the five inputs. Every input passes through a voltage-controlled photo switch to eliminate key clicks and isolate the control circuit from the amplifier circuits. Each of the input controls, with the exception of No. 1, has a transistor that switches off its associated photo switch. Input control No. 1 has just a photo switch. Activation of an input control switches on its photo switch and switches off the photo switches of the audio inputs lower than it in priority. This permits only the audio signal of the controlling input to be amplified.

The four inputs to the chime trigger circuits are from the aircraft's 27.5 volt DC source. The output of the high trigger circuit is a positive pulse to the high chime switch. The output of the high/low trigger circuit is a positive pulse to the first high/low chime switch. The output of the low chime trigger circuits are pulses (positive and negative) to the low chime switch. The positive pulse triggers the low chime switch when a sign goes on, and the negative pulse triggers the low chime switch when a sign goes off.

The amplifier was loaned by the Boeing Company for these tests with the following additional equipment:

- Jensen speaker, Model C8-4
- Electrovoice microphone, Model 602TR
- Functional interconnection and test box

The test box interconnected all major components and enabled the voltage injections tests to be run with the amplifier operating. Also, the test box enabled activation of the chimes. 27.5 volts DC was supplied to the Collins amplifier by a Hyperion Model HY-A1-32-10 power supply.

Test Circuit

The test circuit is shown in Figure 12 and pictured in Figure 13. A low energy impulse voltage generator was used instead of the Transient Analyzer, to provide a higher output voltage than would be possible for some of the low impedance loads expected in this amplifier. As before, the amplifier was operating when subjected to the injected voltages and any resulting effects were noted. After each test the microphone and chimes were operated to determine if the amplifier was still working properly. Table III lists the amplifier circuits tested and the connector pins associated with each. All circuits were accessible through pins located in two jacks on the back of the amplifier. Figures 14 and 15 are sections of the wiring diagram of the amplifier showing the immediate circuitry connected to the pins that were tested.

Test Results

Pre-recorded Announcement
Reproducer Input

Voltage transients with peaks of from 26 volts to 540 volts with a waveshape of 7 x 23 microseconds as shown in Figure 16, were injected into

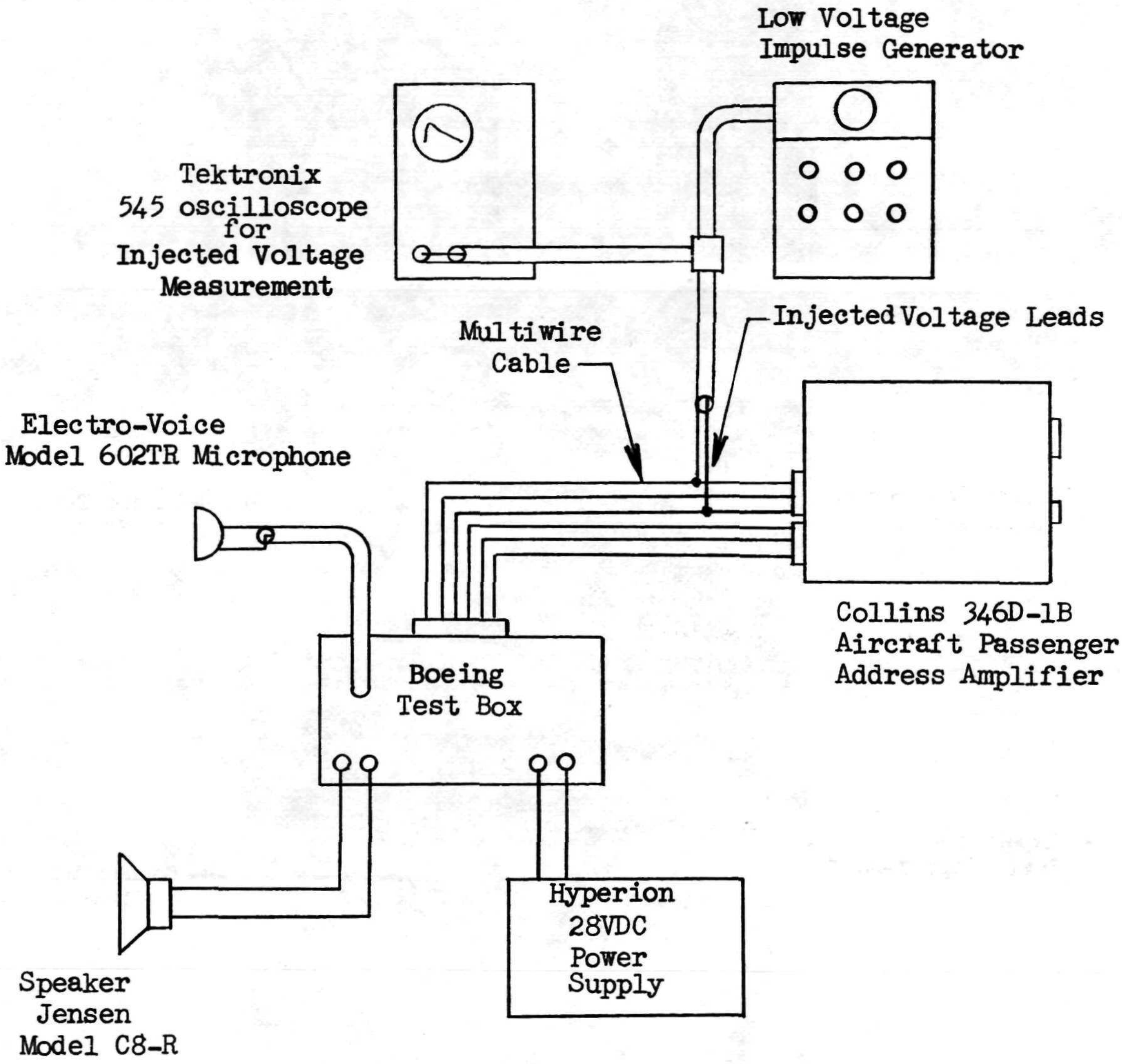


Figure 12 - Test Circuit for Voltage-Injection Tests on Collins 346D-1B Amplifier for Aircraft Passenger Address System

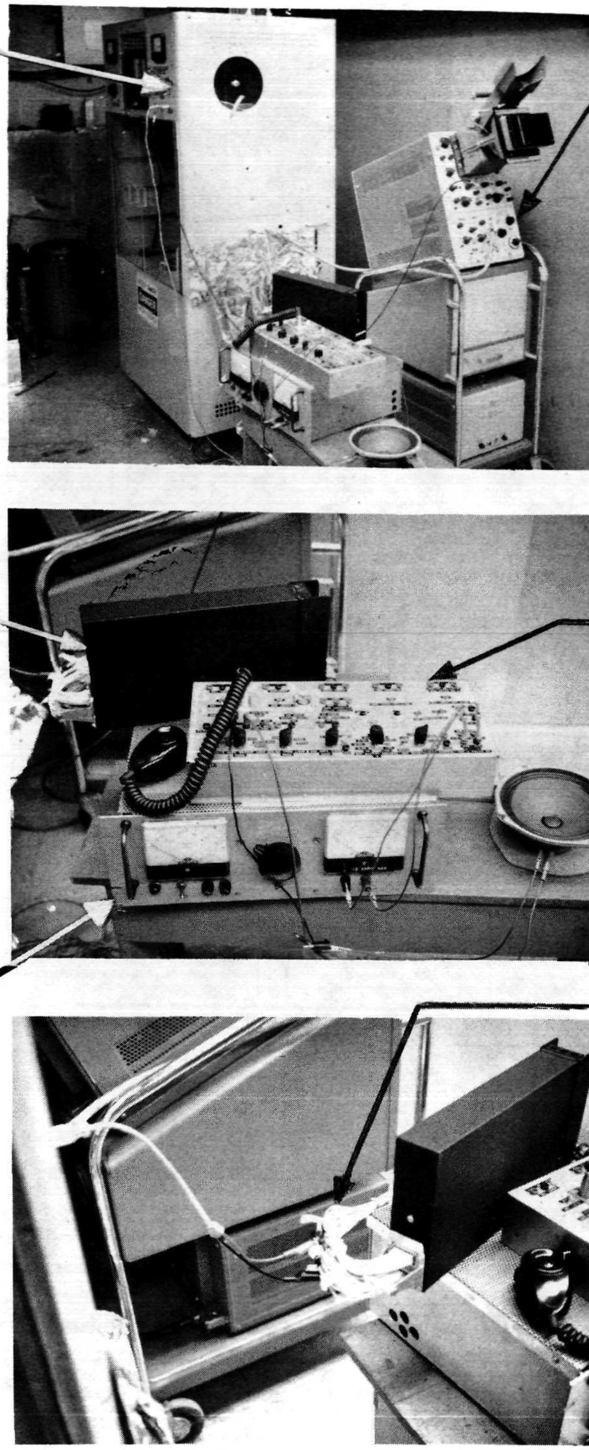


Figure 13 - Test Setup Showing Impulse Generator,
Collins 346-1B Amplifier, Boeing Test Box
and Connections to Passenger Address Circuit.

Table III

Tested Circuits in Passenger Address Amplifier

Functional Description	Connector and Pin Numbers	
Pre-recorded Announcement Reproducer Input	J2	3 and 4
Aft Cabin Microphone Input	J1	17 and 18
Aircraft Speaker Output	J1	14 and 22
Pilots' Microphone Input	J1	1 and 4
Music Reproducer Input	J1	21 and 28

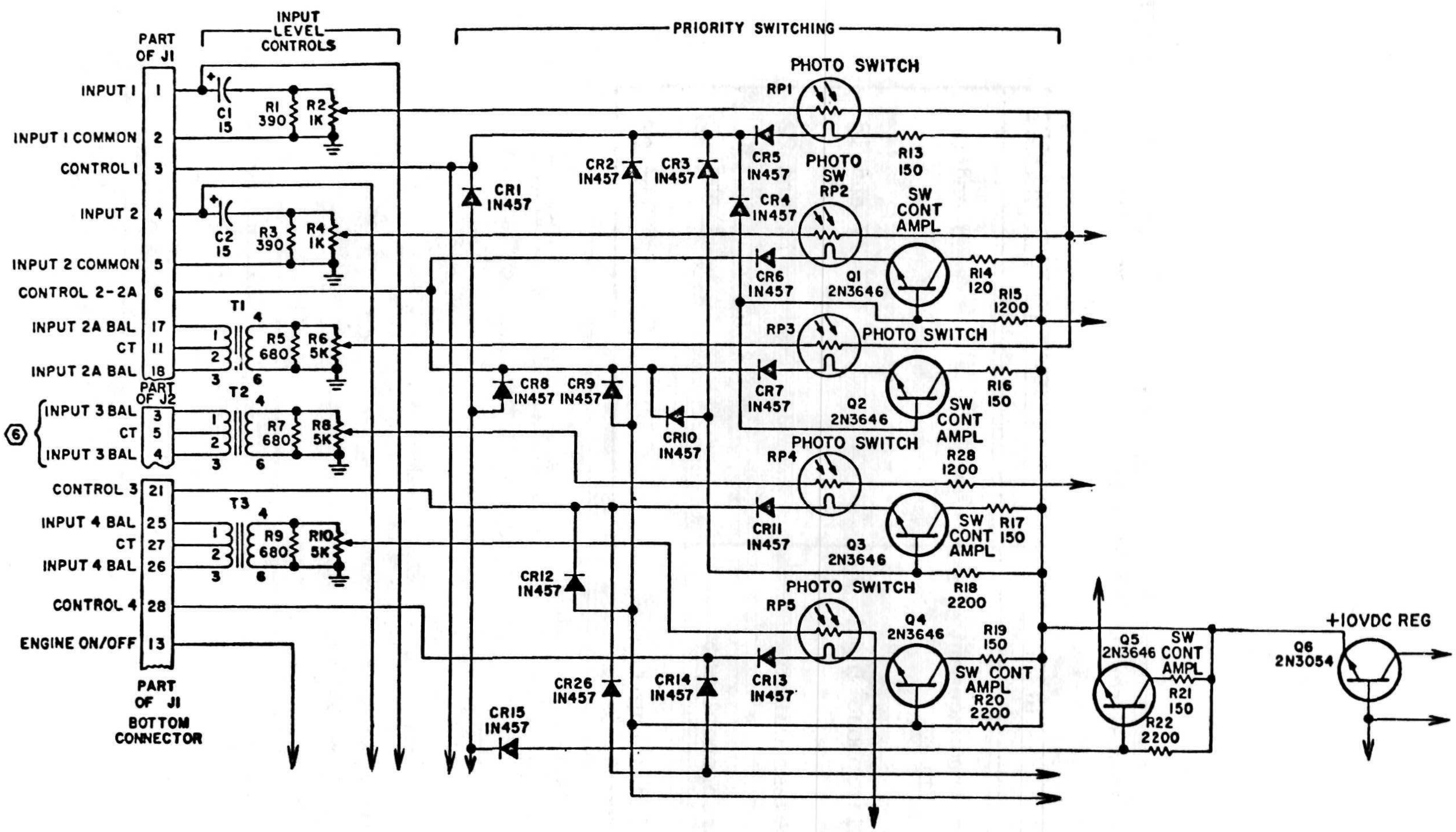


Figure 14 - Partial Wiring Diagram of Aircraft Passenger Address Amplifier Showing Tested Input Circuits on Connectors J1 and J2.

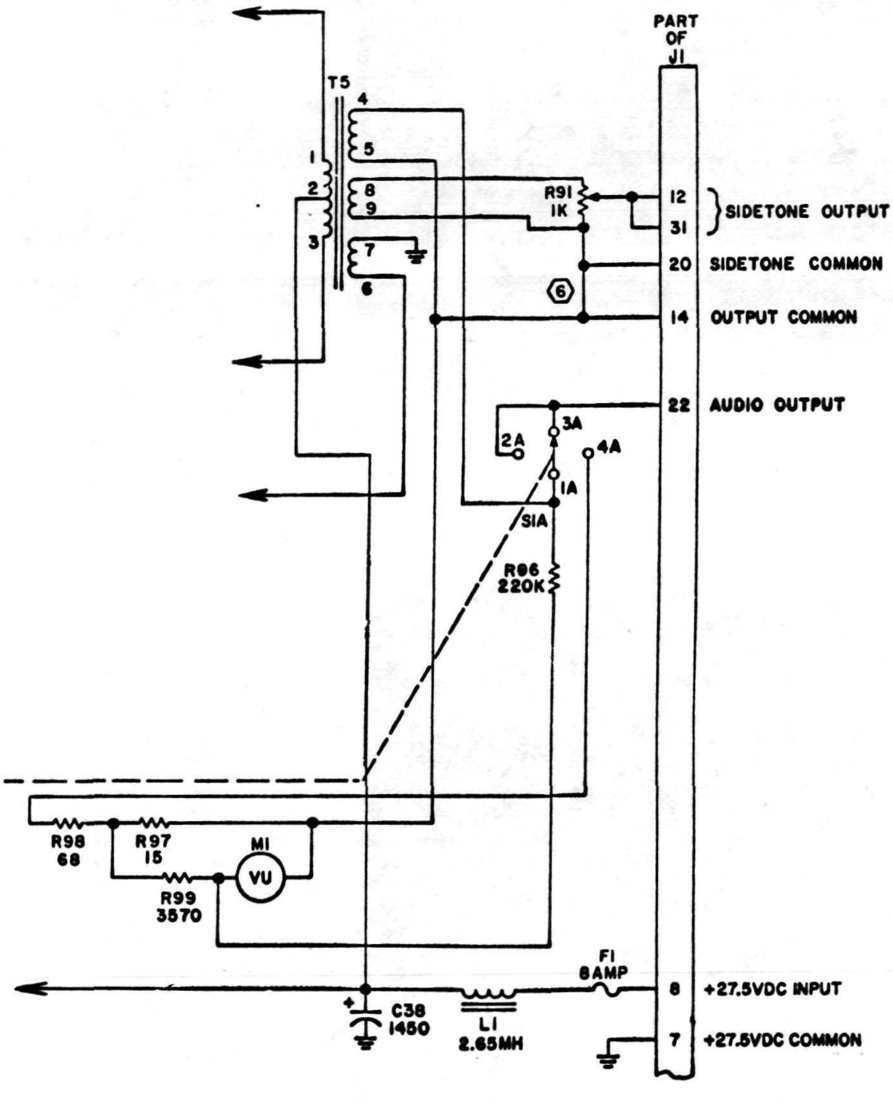
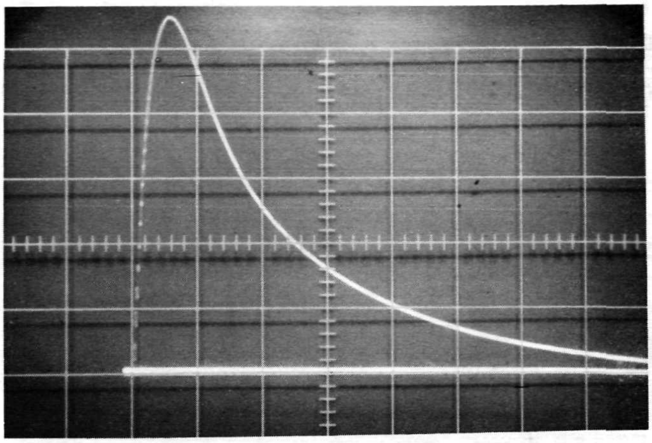


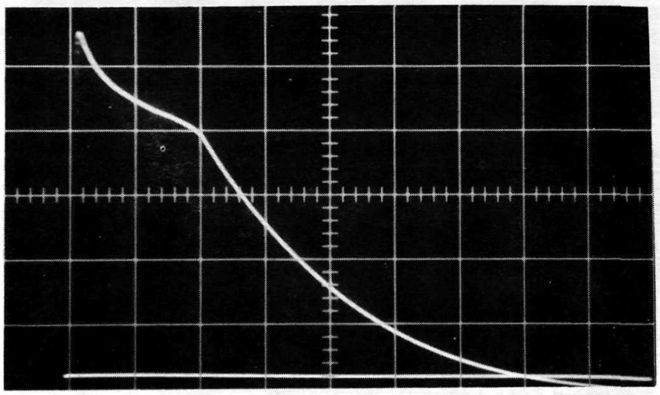
Figure 15 - Partial Wiring Diagram of Aircraft Passenger Address Amplifier Showing Audio Output Circuit, Pins 14 and 22, on Connector J1.



7 x 23 μs waveshape

540 volts peak

100 v/div. 10 μs/div.



1 x 55 μs waveshape

1060 volts peak

200 v/div. 20 μs/div.

Figure 16 - Simulated Lightning-Induced Voltages Injected into Pre-recorded Announcement Reproducer Input (Pins 3 and 4, Connector J2) of Aircraft Passenger Address Amplifier.

this input circuit via pins 3 and 4 of J2. There was no apparent change in the operation of the amplifier. The tests at this waveshape were terminated at the peak voltage of 540 volts since this was felt to be a reasonably high level. The applied waveshape was then expanded to a 1 x 55 microsecond wave as shown on Figure 16 and the tests repeated, beginning at a lower voltage of 390 volts and increasing to 1090 volts peak. Again no effect was noted on the amplifier performance. The somewhat irregular shape of the injected voltage waveform tail on the 1 x 55 μs waveform is attributable to the non-linear load presented by the input transformer.

Aft Cabin Microphone Input

This circuit is accessible via pins 17 and 18 on connector J1 on the amplifier. As shown on Figure 14 this circuit also feeds into an input transformer. Thus, the test results were expected to be similar to those of the prerecorded announcement reproducer input discussed above. The voltage injection tests were applied with the same waveforms and to approximately the same peak voltage levels; 550 volts for the 7 x 23 μs waveform and 1300 volts for the 1 x 55 μs waveform, where the tests were terminated. Again, no effects on amplifier operation were observed. Apparently the input transformers T1, T2, etc, shown on Figure 14, are effective in sufficiently attenuating even the fast rising injected voltages of over 1,000 volts peak to levels sufficiently low as to be harmless to the solid-state components beyond the transformers.

Aircraft Speaker Output

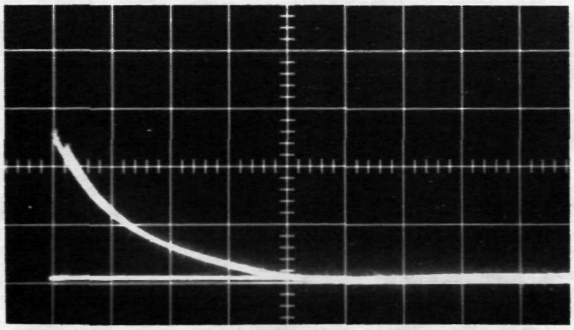
This is the cabin speaker output and therefore wiring would extend from it throughout the aircraft cabin to multiple speakers. It is accessible via pins 14 and 22 on the J1 connector on the amplifier, as shown on Figure 15. Tests were begun on this circuit with a 1 x 20 microsecond waveform injected with successively higher peak voltages ranging from 140 to 500 volts, with no noticeable effect on the amplifier. The 500 volt wave form is shown in Figure 17. A longer duration 1 x 50 microsecond waveform was applied beginning at 530 volts peak with no malfunction of the amplifier. This waveform is also shown in Figure 17. The amplitude of the test voltage was then increased in steps until a peak voltage of 1770 volts was attained. As the amplitude was increased, the wave tail time decreased due to circuit loading effects, until a 2 x 6 microsecond waveshape resulted at the maximum voltage of 1770 volts, where testing was terminated, still with no adverse effects on amplifier operation noted.

Pilots' Microphone Inputs

The crew's microphoneswere connected to pins 1 and 4 on the J1 connector, shown on Figure 14. While the short microphone cord itself is not expected to receive appreciable lightning-induced voltages, this input circuit is capacitively coupled, in contrast to the transformer coupled inputs tested earlier. Voltages with a waveshape of 2 x 12 microseconds up to an amplitude of 1610 volts were injected into this circuit. The 1610 volt waveform is shown on Figure 18. The amplifier remained operable at test voltages below 1610 volts but after being exposed to this level the voice amplifier stopped operating. The music and chimes portions of the amplifier remained functional, however.

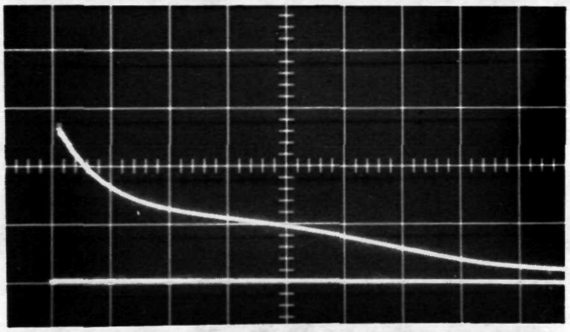
Music Reproducer Input

Since the non-voice sections of the amplifier were still operational after the microphone input tests, a similar test was applied to a music reproducer input circuit via pins 21 and 28 on the amplifier J1 connector. This time the same impulse generator charge utilized to obtain the 1610 volt 2 x 12 microsecond waveform delivered to the microphone inputs was pre-set. Due to the different load, a faster rising, higher amplitude voltage of 2090 volts was injected into the circuit and this voltage apparently caused some component(s) to break down as evidenced by the rapid



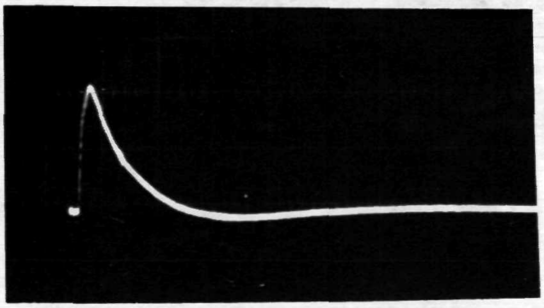
1 x 20 μsec waveshape
500 volts peak

200 v/div. 20 μs/div.



1 x 50 μsec waveshape
530 volts peak

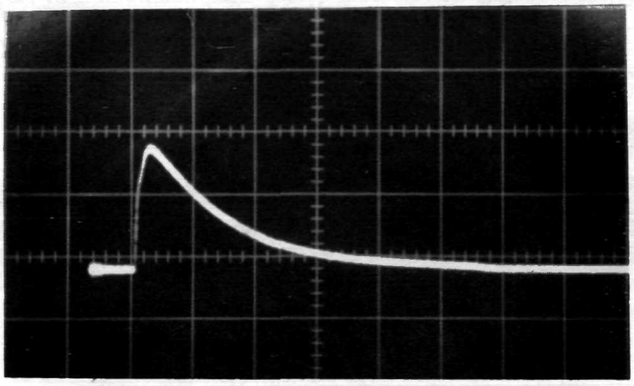
200 v/div. 20 μs/div.



1 x 6 μsec waveshape
1770 volts peak

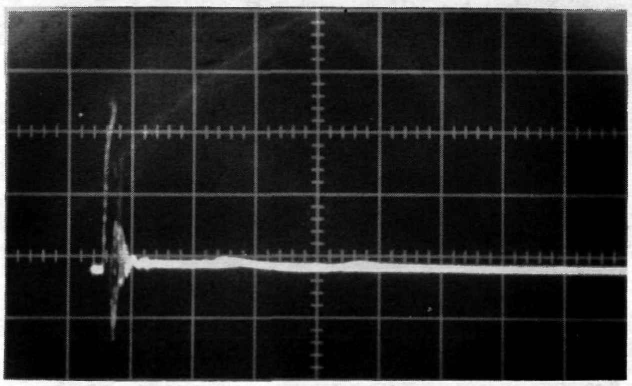
805 v/div. 10 μs/div.

Figure 17 - Simulated Lightning-Induced Voltages Applied to Aircraft Speaker Output (Pins 14 and 22, Connector J1) of Aircraft Passenger Address Amplifier.



Intercom Failure
Pins 1 and 4
2x12μsec waveshape
1610 volts peak

805 v/div. 10 μs/div.



Chimes Failure
Pins 21 and 28
2090 volts peak

805 v/div. 10 μs/div.

Figure 18 - Simulated Lightning-Induced Voltages Applied to Pins 1 and 4, 21 and 28, on Connector J1 of Aircraft Passenger Address Amplifier.

collapse of voltage, as shown on Figure 18. After this test the chimes associated with the NO SMOKING and FASTEN SEAT BELTS signs did not function. A further check of the amplifier showed that the test tone activated by the rotary switch on the front panel of the amplifier still functioned. The decibel meter check which usually read +1 or +2 dB now read -8 dB.

Amplifier Test Summary

Table IV presents a summary of applied peak voltage levels and resulting effects noted during the tests on each of the amplifier circuits previously discussed. For all but the final two tests performed on the amplifier, it remained functional. The amplifier was permanently disabled by the final two tests, after which it was returned to Boeing for diagnosis.

Diagnosis

Following the operational malfunction of the aircraft passenger address amplifier, the amplifier and associated test equipment was returned to the Boeing Company, Electronic Systems Group, where a damage analysis was made. The following are the findings of that analysis. Most of the damaged amplifier components, which are listed below, can be found in the partial wiring diagram of Figure 14.

Transistor Q4 - damage - open base to emitter
shorted base to collector (input #4 open)

The open circuit kept RP5 (photo switch) turned off. The short circuit let a 150 Ω load to be placed on the +10 volt line when base was pulled low with any priority switch.

Transistor Q5 - damage - open (high resistance) all terminals (no CAL function)

The high resistance (emitter to collector) kept RP7 turned off. This also caused oscillator output to go through bass circuit and be attenuated too much to give any indication on VU meter.

Transistor Q6 - damage - shorted collector to emitter (+10 volt line at +22 volts)

Short circuit of Q4 partially shorted this regulator transistor causing it to become a resistor. This also disabled the chime buffer, deactivator, and chime amplifier circuits.

Diodes CR1, CR9, CR26 - damage - shorted
and CR12 - damage - open

The damage to the diodes was discovered when trying to make RP7 turn on. CR9 allowed low signal to be switched through CR8 and CR15 to Q5 base when in CAL and TEST tone. Others were found by measuring all diodes in priority circuit. All other parts could have failed when, or subsequent to when the 2090 volt pulse was applied to pins 21 and 28 on J1.

Diodes CR2, CR8, CR14, and CR15

These diodes were strained, but did not short. All bad diodes had anodes connected to shorted transistors Q4 and Q5.

Table IV

Summary of Results - Voltage Injection Tests on Aircraft Passenger Address Amplifier

Circuit Function	Connector and Pin Numbers	Test Voltage at Which Some Effect Was Noted (peak volts)	Effects	
			Waveform Variation	Instrument Operation
Pre-recorded Announcement Reproducer Input	J2, 3 and 4	(1090 was highest voltage applied)	none noted	none noted
Aft Cabin Microphone Input	J1, 17 and 18	(1300 was highest voltage applied)	none noted	none noted
Aircraft Speaker Output	J1, 14 and 22	(1700 was highest voltage applied)	none noted	none noted
Pilots' Microphone Input	J1, 1 and 4	1610	none noted	voice amplifier became inoperative
Music Reproducer Input	J1, 21 and 28	2090	collapse of voltage at waveform crest	chime amplifier became inoperative

CONCLUSIONS

These tests showed that typical aircraft electronics equipment can be interfered with or damaged by voltage transients representative of those which can be induced by lightning in interconnecting electrical circuits. In these tests voltages as low as 21 volts caused temporary interference with the turbine gas temperature indicator, and permanent malfunction occurred when a 370 volt transient was injected into the instrument. The cabin address amplifier responded adversely to higher transients of 1600 volts peak or more. These voltage levels are quite within the range of lightning-induced voltages to be expected in some modern aircraft electrical wiring. Hence, the tests have demonstrated that the indirect effects of lightning can be damaging to on-board electronic equipment; although, these brief tests have not shown the extent to which this hazard exists in all aircraft electronics. Further, the range of vulnerability voltage levels determined in these tests is not necessarily inclusive of the possible or even most frequent vulnerability levels. In all probability, similar tests of additional types of equipment would extend this range on each end.

Perhaps more important than the actual equipment vulnerability levels associated with aircraft electronics is the question of protection philosophy. Clearly, protection against malfunction can be obtained either a) by controlling interconnecting wiring induced voltage susceptibility to voltage levels beneath the vulnerability levels of terminating equipments, or b) by designing hardening (vulnerability levels) of equipment to exceed the interconnecting circuit susceptibility levels. The first approach places the protection responsibility in the hands of the engineer who designs the interconnecting wiring, whereas the second approach places the responsibility on the electronics equipment designer. Either approach, if adopted completely, probably places an unreasonable burden of performance on the responsible party. In most cases, especially in the case of new designs, an optimum solution is probably a combination of both approaches, arrived at by establishment of "Transient Control Levels" (TCL's) applicable to equipment as well as interconnecting wiring. The TCL's would be standardized susceptibility and vulnerability voltage levels, applicable to each class of system or equipment, and properly coordinated so that an adequate margin of safety would exist between electronics vulnerability voltages and wiring susceptibility voltages. For such a set of TCL's to be established, the actual vulnerability voltages of many different types of electronic components must first be determined.

In assessing electronics vulnerability, attention must be given equally to mechanisms of interference as well as permanent damage. Interference might result in erroneous instrument readings or control errors, for example, with no warning to the flight crew that the equipment is in error. As found in these tests, such interference may occur at lower transient voltages than permanent damage. Thus, establishment of transient control levels should encompass interference as well as damage vulnerability levels.

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. Plumer, J.A., "Data from Airlines Lightning Strike Reporting Project", Summary Report 72-1, November, 1972, General Electric Report GPR-72-021.

3. Walko, L.C., "A Test Technique for Measuring Lightning-Induced Voltages on Aircraft Electric Circuits", Final Report, NASA Contract NAS3-14836, January, 1973, General Electric Report SRD-72-065, NASA CR-2348, 1973.

4. Plumer, J.A., "Analysis and Calculation of Lightning-Induced Voltages in Aircraft Electrical Circuits", Final Report, NASA Contract NAS3-14836, August, 1972, General Electric Report SRD-72-066, NASA CR-2349, 1973.

5. MIL-STD-704A, "Electric Power, Aircraft, Characteristics and Utilization of", August, 1966, Department of Defense.

6. Plumer, J.A. "Lightning Effects Relating to Aircraft, Part III - Measurements of Lightning-Induced Voltages in an F4H-1", Technical Report, USAF Contract F33615-70-C-1144/Project 4357, March, 1973, AFAL-TR-72-5.

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