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A NEW APPROACH TO EQUIPMENT TESTING

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ABSTRACT

Considerable controversy has arisen during the recent discussions over the new version of the RTCA DO160C/ED 14C Section 22 document at the European Committee for Aviation Electronics. Section 22 is concerned with lightning waveform tests to equipment.Investigations of some of these controversies with circuit analysis and measurements indicate the impedance characteristics required of the transient generators and the possibility of testing to a voltage limit even for current waveforms.

1 INTRODUCTION

This paper is particularly concerned with calibration procedures and test methods for the lightning transient waveforms 1 and 2 for both bulk current injection and ground plane injection tests. Several of the working drafts have specified the source impedance of the generator, and its verification has been a requirement of the calibration procedure. The calibration procedure has also determined the generator charge level (power setting) required to produce a particular voltage level into a high impedance load. The ensuing test to the equipment/cable bundle assembly has required that the generator setting be increased until either the calibration setting is reached, or in the case of a bundle with a screen bonded at both ends to the aircraft structure, until a current limit is reached.

This paper discusses the relationship between the transients expected for such systems installed in aircraft and in equipment tests. It shows that the source impedance of any test generator should preferably be low ($<<5\Omega$). It also notes a definite relationship between the voltage that would be measured in an aircraft test on a high impedance circuit and the current that would be measured if the circuit was a very low impedance and predominantly inductive thus defining the voltage and current limits for equipment tests.

A test method is proposed where either the power setting of the generator is increased until the voltage applied to the circuit reaches the test limit if the cable length and installation is unknown, thus giving an induced voltage on screened wires that is independent of cable length, or either a voltage or a current limit if the installation is known and the proper cable length is used.

These ideas are illustrated with data from both aircraft and equipment tests.

2 RELATIONSHIP BETWEEN A/C TEST AND EQUIPMENT TEST

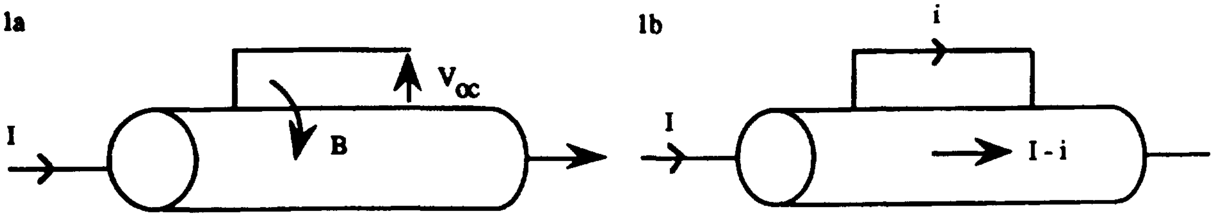
2.1 Predictions

The aim of an equipment test is to subject an item of equipment to transients that are representative of those that the equipment will experience when installed in an aircraft that is struck by lightning. The test may be in the form of a pin test where voltages and currents are applied between the individual pin inputs of the unit and the unit case or where a current is injected into a loop formed by the cable bundle connecting the equipment under test (EUT) and another item of equipment forming part of an avionics system and to the current return formed by either the test bench or the airframe. This paper is concerned with cable tests on simple equipment configurations such as those addressed by DO160C where the EUT and other items of equipment are connected together by a single cable loom. Often cable looms will be quite complex and have branch points; the current distribution in the cable harnesses that will occur in a lightning strike to the aircraft will be quite different from the distribution obtained by injection into single branches of a system on a test bench. This problem is not addressed in the paper but is being investigated in a further program of research.

Initially we consider aperture coupled voltages. Figure 1 shows a schematic representation of the mechanism for inducing voltage on an open circuit loop exposed to aperture flux in an aircraft and the current in the same loop if it is shorted to the airframe. If the shorted loop consists of a cable screen which has a negligible resistance then there will be no net magnetic flux threading the loop. Using the principle of superposition we can represent the shorted loop configuration as a sum of the two circuits shown in Figure 2.

FIGURE 1

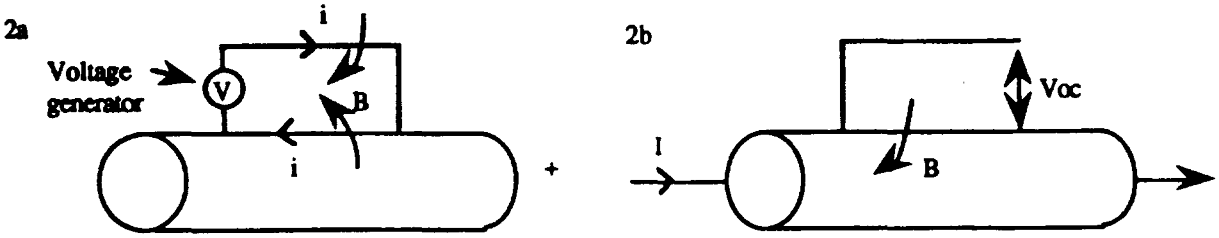
Schematic circuits for open circuit voltage and short circuit current measurements



I is lightning current passing through airframe.
V is voltage measured across open circuit loop.
i oc is current measured when the loop is shorted to the airframe.
B is the magnetic flux threading the loop

FIGURE 2

Representation of circuit 1b by sum of two circuit configurations



The second diagram is simply the lightning current flowing through the airframe when the cable loom is not connected. However the first diagram is a circuit that represents an equipment test where a voltage is injected into the loop formed by the EUT, the cable harness, another item of connected equipment and the airframe as a return conductor. In order that the net magnetic flux is zero and the current in the loop is i when the two configurations are summed, the voltage applied to circuit 2a will be equal to the Vo/c in 2b.

Hence an important parameter in an equipment test is the voltage applied across the loop under test which is equivalent to the Vo/c threat measured in an aircraft test or predicted by electromagnetic modelling.

Practically, for ground plane injection (GPI) tests the voltage can simply be measured by connecting a high impedance voltmeter across the loop under test and for cable injection tests by the voltage measured on a tightly wound monitor loop on the injection transformer.

What is the current flowing in the shorted loop in the equipment test or in the aircraft?

The open circuit voltage V_{OC} in Figure 2b, is given by:

$$V_{OC} = M_{TF} \frac{dI}{dt}$$

where M_{TF} is the mutual transfer inductance between the airframe and circuit.

Neglecting any resistance in the shorted loop, the voltage across the loop in Figure 2a causes a current to flow given by:

$$V = L \frac{di}{dt}$$

where L is the self inductance of the loop.

But we have already shown $V = V_{OC}$.

Therefore
$$\frac{di}{dt} = \frac{M_{TF}}{L} \frac{dI}{dt}.$$

Integrating
$$i = \frac{M_{TF}I}{L} = \frac{V_{oc}I}{L\,dI/_{dt}}. \qquad (1)$$

The differential and integral quantities in the equation can be mixed providing that each of the two differential and integral quantities are taken at the same time.

Hence the maximum current in the loop is defined by the waveform shape of the driving waveform, the $V_{o/c}$ and the inductance of the circuit loop. For the lightning current Component A waveform (see AC20-136 Reference 1) the maximum current I = 200kA (at t = 6µs) and the dI/dt = 140kA/µs (at t = 0+) hence the maximum loop current i is given by:

$$i = \frac{1.43\,\hat{V}}{L} \text{ where } \hat{V} \text{ is the maximum induced o / c voltage measured at t = 0+.}$$

where $\frac{I}{\frac{dI}{dt}}$ is 1.43µs and L is in µH. (For consistency of units M_{TF} is also in µH.)

Other factors will apply for other waveform shapes eg, Component D will have a factor of 0.71µs.

While for a particular geometry of cable installation there will be a fixed "voltage threat" which is due to the cables exposure to aperture flux, the "current threat" will depend also on the inductance and resistance of the cable harness/equipment loop.

Restricting the discussion to screened cables, the voltage at the equipment pin, which is what we are ultimately trying to achieve in the equipment test is given by:

$$V_{pin} = i\,Z_T$$

where Z_T is the total transfer impedance of the cable screen (strictly speaking this is a function of frequency but below about 1MHz is approximately equal to the screen resistance for coaxial screens).

Alternatively $V_{pin} = \frac{1.43\,\hat{V}Z_T}{L}$

But $Z_T = Z_0\ell$

and $L = L_0\ell$.

where Z_0 and L_0 are the transfer impedance (in ohms) and inductance (in µH) per unit length of the cable and ℓ is the total length through which current is flowing.

$$\text{Therefore } V_{pin} = \frac{1.43\,Z_0}{L_0}\hat{V}, \text{ which is independent of cable length.} \qquad (2)$$

$$= Z_o\,\ell\,i, \text{ which is dependent on cable length.} \qquad (3)$$

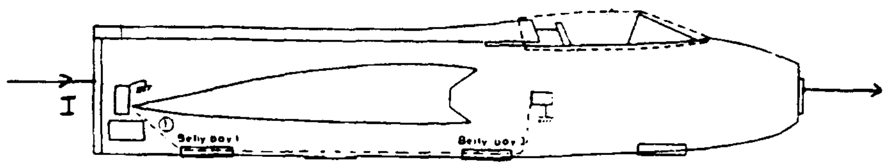
Hence if we do an equipment test and drive to a notional voltage limit, the voltage at the equipment pin is independent of cable length whereas, if the test is driven to a current limit the V_{pin} achieved is a function of length. It should be noted that in this analysis where the resistance of the cable is assumed negligible, the waveform of V will be the differential of the current waveform. These will follow waveforms 2 and 1 of AC20-136 respectively.

The magnitude of the pin voltage is simply related to current and the cable harness characteristics in equation 3 and thus driving to current limit represents an adequate method of achieving particular V_{pin} levels if the current flowing along the cable harness used in the test results in the same value of the product of current and cable length as in the aircraft.

The magnitude of maximum pin voltages can also be related to the maximum open circuit voltage using equation 2, this is independent of cable length but is dependent on cable inductance and as the pin voltage follows the cable screen current in form it is important that the voltage driving waveform in the equipment test follows waveform 2 well. The inductance of a cable above a return conductor is a logarithmic function and not very sensitive to separation above the conductor. However deviations from the waveform 2 shape have more important effects as will be shown in the next section.

2.2 Data

Measurements of $V_{o/c}$ and current in the shorted circuit were made using a 5m long cable installed in an aluminium fuselage with several apertures. A double exponential current waveform of 30kA was injected into the airframe. Using the same test set up, equipment tests were made using the GPI technique into the cable bundle. The set up is shown in Figure 3. The cable aircraft loop had a self inductance of about 3μH and a resistance of 37mΩ.



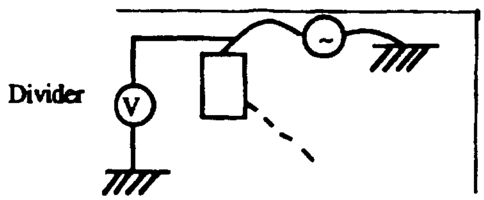


FIGURE 3

Test Set Up - Direct Injection
(insert - equipment test)

Waveforms of driving current and open circuit voltage for direct injection of current into the fuselage are shown in Figure 4. The open circuit voltage is complicated by air frame resonances, but the average value at time t=0+ can be evaluated. The open circuit voltage is 82 volts and the ratio of $I / \frac{dI}{dt}$ for the current waveform is 2.12μs.

The current when the loop was shorted was 37A and the shape was similar to the driving waveform (Figure 5). The maximum current occuring in the loop according to the prescription of equation 1 is 2.12 x 82/3 = 58A compared to 37A measured which is within 4dB.

We then performed an equipment test by disconnecting the EUT from the airframe and inserting our Waveform 1 current generator between the EUT and the airframe (see inset on Figure 1). The voltage is monitored on the high voltage potential divider and the current measurement used was the same current transformer as in the direct injection tests. The power level was increased until the monitored voltage value was near to 82V, the value obtained in the direct injection test. The waveforms of bundle current and monitored voltage waveforms are shown in Figure 6. For the same value of monitored voltage as open circuit voltage, the current is 85A (78.5 x 82/76). This value is considerably higher (7dB) than the value of 37A measured during the direct injection tests. As noted above we have to account for the different rise time of the voltage waveform of the equipment test. Reference to the Voc and monitored voltage waveforms in Figure 4b and 6 respectively reveals the voltage impulse of the equipment test is considerably slower. The rise times are about 100ns and 1000ns and zero cross times are about 7 and 12μs respectively. As the current is proportional to the integral of the voltage impulse we expect the equipment test to give a larger current for the same peak voltage. A circuit analysis program showed that the slower waveform of the equipment test gives a factor 2 larger current accounting for the observed difference between the peak current measured in aircraft and equipment test for the same open circuit voltage (Figure 7). Hence after the difference in voltage impulse shapes has been accounted for, the currents in both direct injection and equipment tests will be the same.

3 IMPLICATION ON GENERATORS FOR EQUIPMENT TESTS

The analysis of the configuration discussed above showed that the equipment test can be simulated by a voltage generator of zero source impedance (Figure 2a). This idealised generator will give either a voltage waveform 2 across a high impedance load or a waveform 1 current into a purely inductive load. For circuits with an L/R ratio intermediate between these two extremes an intermediate response will be obtained though in practice only for a small range of values of L/R ~ 1 will these intermediate responses be obtained. Generally the usual values of L/R give responses approximating either waveform 1 current or waveform 2 voltage.

Some of the earlier drafts of DO160C and indeed appendix IV of AC20-136 implies specific source impedances for the generator; 5Ω for waveform 2 and 4, and 25Ω for waveform 3. This section of the paper shows that these requirements are incompatible with the idealised response discussed above.

3.1 Waveforms 1, 2 and 3

One way of satisfying the 5Ω source impedance requirement is the generator indicated in the diagram below (Figure 8a):

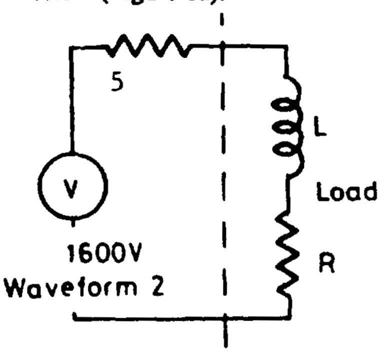


FIGURE 8a
Circuit diagram of 5Ω generator

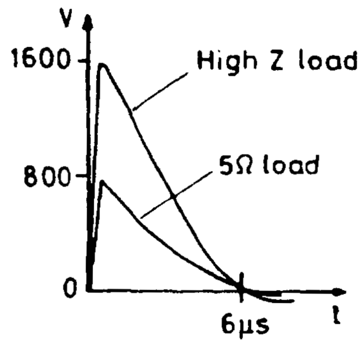


FIGURE 8b
Output response of circuit of Figure 8a on calibration loads

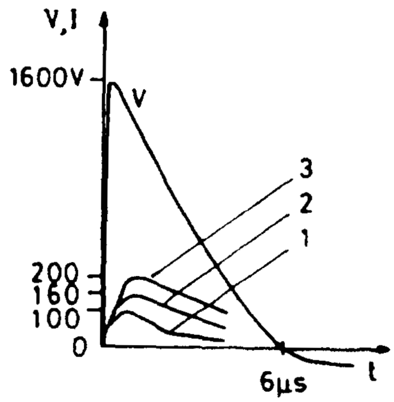


FIGURE 8c
Output of circuit of Figure 8a on a variety of loads

TABLE 1

			5Ω Generator			0Ω Generator		
R Ω	L μH	L/R μs	I Amps	t rise μs	Curve No. in Figure 8c	I Amps	t rise μs	Curve No. in Figure 9b
5	3	.6	100	0.8	1	200	1	1
1	3	3	160	1	2	400	2	2
37mΩ	3	81	200	1	3	760	6	3
37mΩ	1.5	41				1.54kA	6	4

The waveforms of the voltage obtained with such a generator across high impedance loads and a load of 5Ω are shown in Figure 8b. Using this generator into a variety of loads with different values of L/R gives responses as shown in Figure 8c. Corresponding waveforms that would be obtained with the ideal generator are shown in Figure 9 This does not satisfy the calibration requirement with a 5Ω load but gives the desired range of current waveforms, in the limit giving a waveform 1 current into a purely inductive load; on the other hand the 5Ω generator cannot achieve the correct waveshapes or levels for a particular value of monitored voltage. The magnitudes are compared in Table 1.

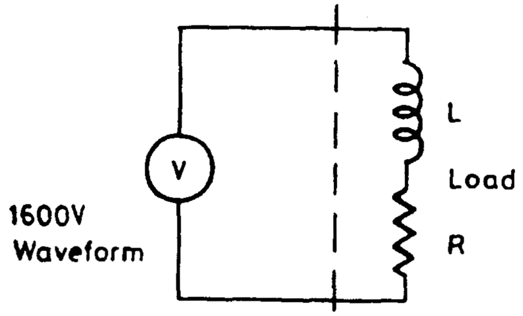


FIGURE 9a
Circuit diagram of 0Ω
source impedance generator

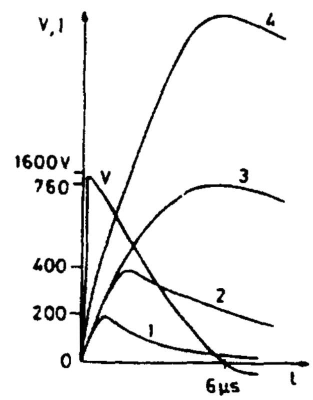


FIGURE 9b
Output of circuit of Figure 9a
on a variety of loads

While we do not address particular generator designs in this paper, we note that the generator design proposed in DO160C (published Reference 2) has a low source impedance and gives reasonable responses. The main point is that the waveform achieved into the load is the important consideration, not the generator source impedance. For example, a voltage waveform into 1000Ω impedance could be achieved with a generator with a source impedance of 50Ω.

At Culham for generating current waveforms, we have some particular generators with a high source impedance which drive the same shape current waveform regardless of the load impedance. For these generators, it is very important to monitor the voltage across the loop to prevent the loop being stressed too highly.

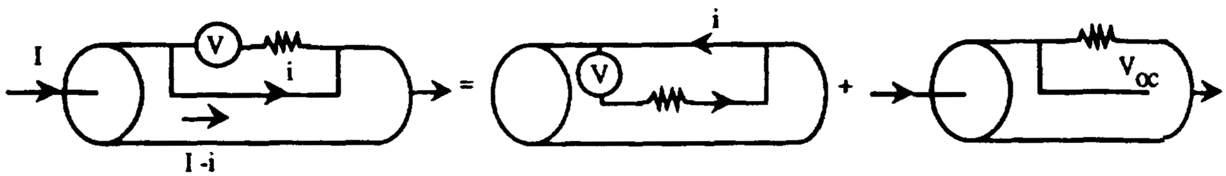
Waveform 3 which is also excited by aperture flux shows similar trends but the response is no longer purely inductive when the frequency is greater than or equal to the first cable resonance.

3.2 Waveform 4 and 5

For induced voltages in resistive structures such as those made from carbon fibre composite (CFC) the situation is complicated by current redistribution effects. In this case the driving voltage around a cable harness loop is due to resistive drop (waveform 4) generated in the CFC by lightning current flowing through the structure but this voltage will fall faster than the current as it redistributes from the resistive structure into the low resistance of the cable screen after peak dI/dt. The mathematical analysis is thus more complex but we can still use the same trick as in Section 2 by representing the configuration by the sum of two simpler ones as below in Figure 10.

FIGURE 10

Representation of resistive voltage mechanism by two circuits.



Hence the ideal waveform 4 generator will have a source impedance equal to the resistance of the structure between cable connection points. Typically this would be 10 →100mΩ. A circuit analysis program was used for a series of loads. Table 2 and Figure 11 show the results. We note that the characteristic waveform 5 shape is produced into a predominantly inductive load. A comparison of Table 1 and 2 and Figures 9b and 11 shows that for the same voltage level threat and same cable bundle, a waveform 4 voltage will produce a much larger waveform 5 current than waveform 2 voltage produces a waveform 1 current due to the relative width of the voltage impulse.

The current levels for waveform 1 and 5 chosen to correspond to the voltage levels of waveform 2 and 4 are indeterminate as they depend on cable inductance. The value will determine a value of inductance below which the current level will be reached first and above which the voltage level will be reached first.

TABLE 2

RΩ	I kA	t rise µs	Curve No.
1.5	1	6	1
150mΩ	8.4	40	2
37mΩ	23	60	3

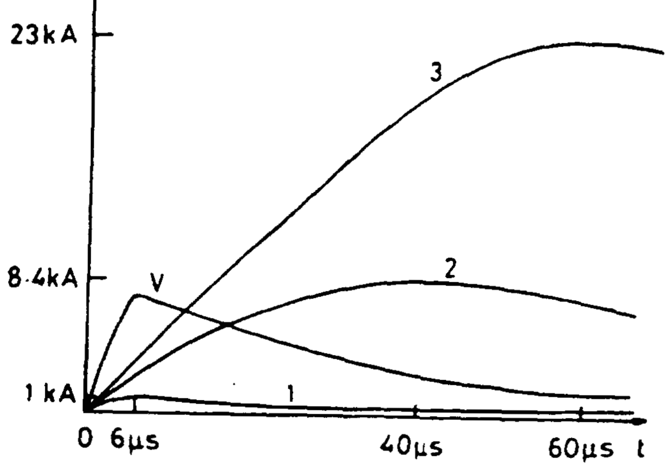


FIGURE 11
Response of a variety of circuits to a waveform 4 low source impedance generator

4 CONCLUSIONS

1. The open circuit voltage measured in an aircraft test is equivalent to the monitored voltage across the loop under test in an equipment test.
2. The current that would result in this loop when shorted to airframe return has a value which can be determined from the amplitude and shape of the driving waveform and the self inductance of the loop.
3. Circuit analysis has shown the impedance requirements of an ideal generator for achieving waveform 1/2 and 4/5 waveforms into any load. These requirements are not satisfied by the 5Ω values implicit to Appendix 4 of AC20-136. The current levels suggested by AC20-136 are thus also misleading. Actual current levels associated with the voltage levels are dependant on cable resistance and inductance.
4. For simple cable configurations adequate test levels at the equipment pin can be achieved with a test to a known Voc voltage limit if the monitored voltage waveform follows accurately the waveform 2 shape or with a test to a known current test level if the product of current and cable transfer impedance is the same as in the aircraft.

5 REFERENCES

1. FAA AC 20-136, Protection of Aircraft Electrical/Electronic Systems against the Indirect Effects of Lightning, 1991.
2. RTCA DO160C/ED 14C, Environmental Conditions and Test Procedures for Airborne Equipment, Section 22. 14th February 1990.

6 ACKNOWLEDGEMENTS

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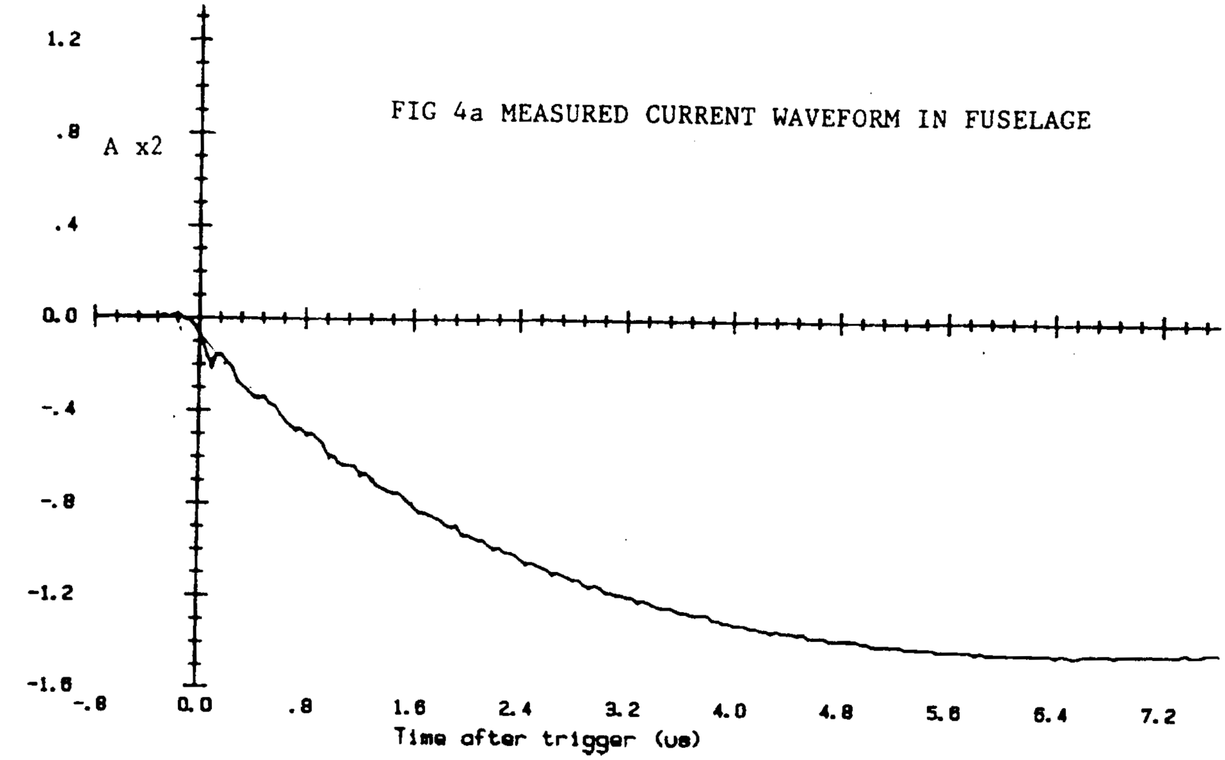

FIG 4a MEASURED CURRENT WAVEFORM IN FUSELAGE

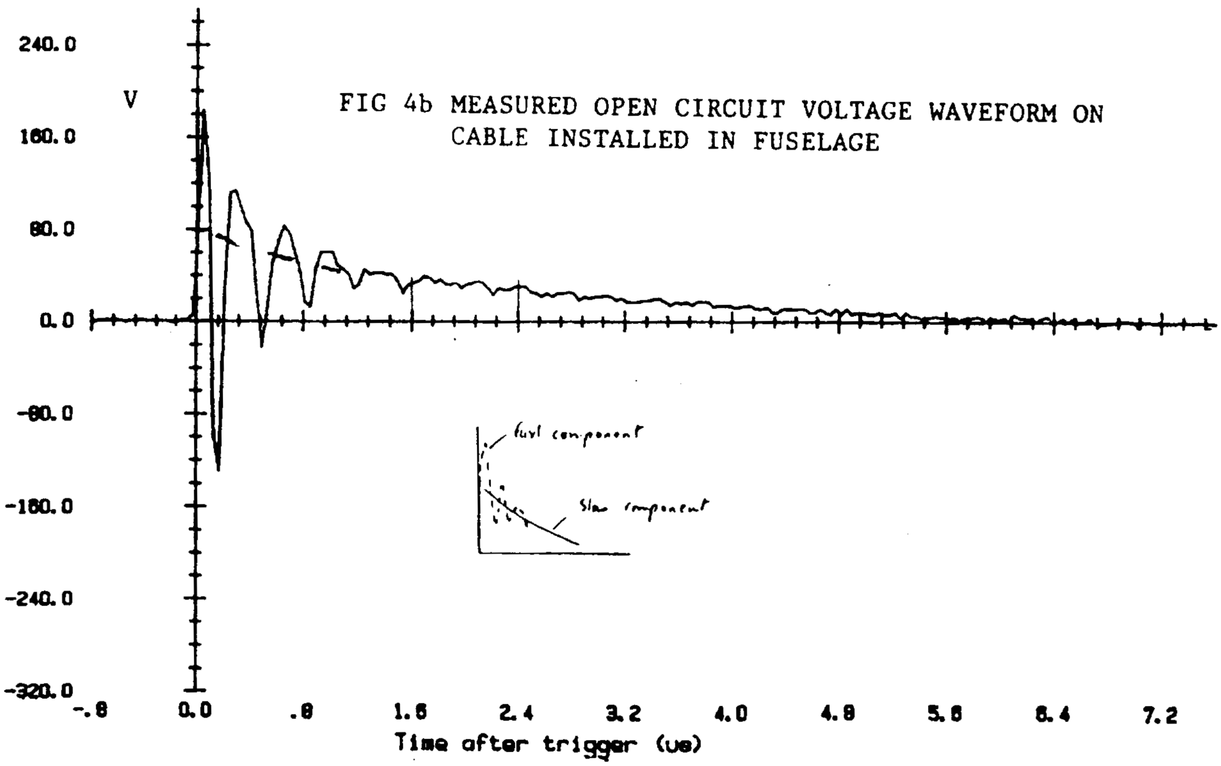

FIG 4b MEASURED OPEN CIRCUIT VOLTAGE WAVEFORM ON CABLE INSTALLED IN FUSELAGE

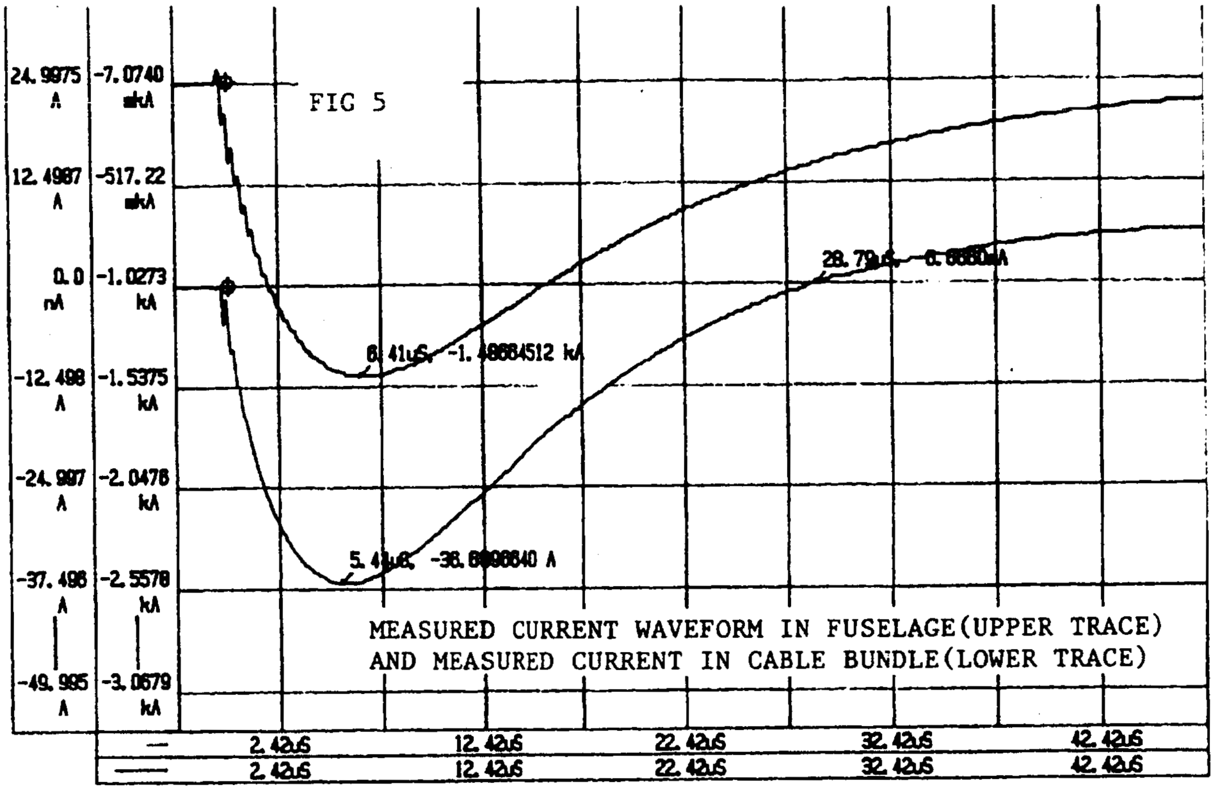
FIG 5
24.9975 A
12.4987 A
0.0 nA
-12.498 A
-24.997 A
-37.496 A
-49.995 A
-7.0740 mkA
-517.22 mkA
-1.0273 kA
-1.5375 kA
-2.0478 kA
-2.5578 kA
-3.0679 kA
8.41uS, -1.48884512 kA
28.79uS, -0.0880mA
5.41uS, -38.8008840 A
MEASURED CURRENT WAVEFORM IN FUSELAGE(UPPER TRACE)
AND MEASURED CURRENT IN CABLE BUNDLE(LOWER TRACE)
2.42uS
12.42uS
22.42uS
32.42uS
42.42uS

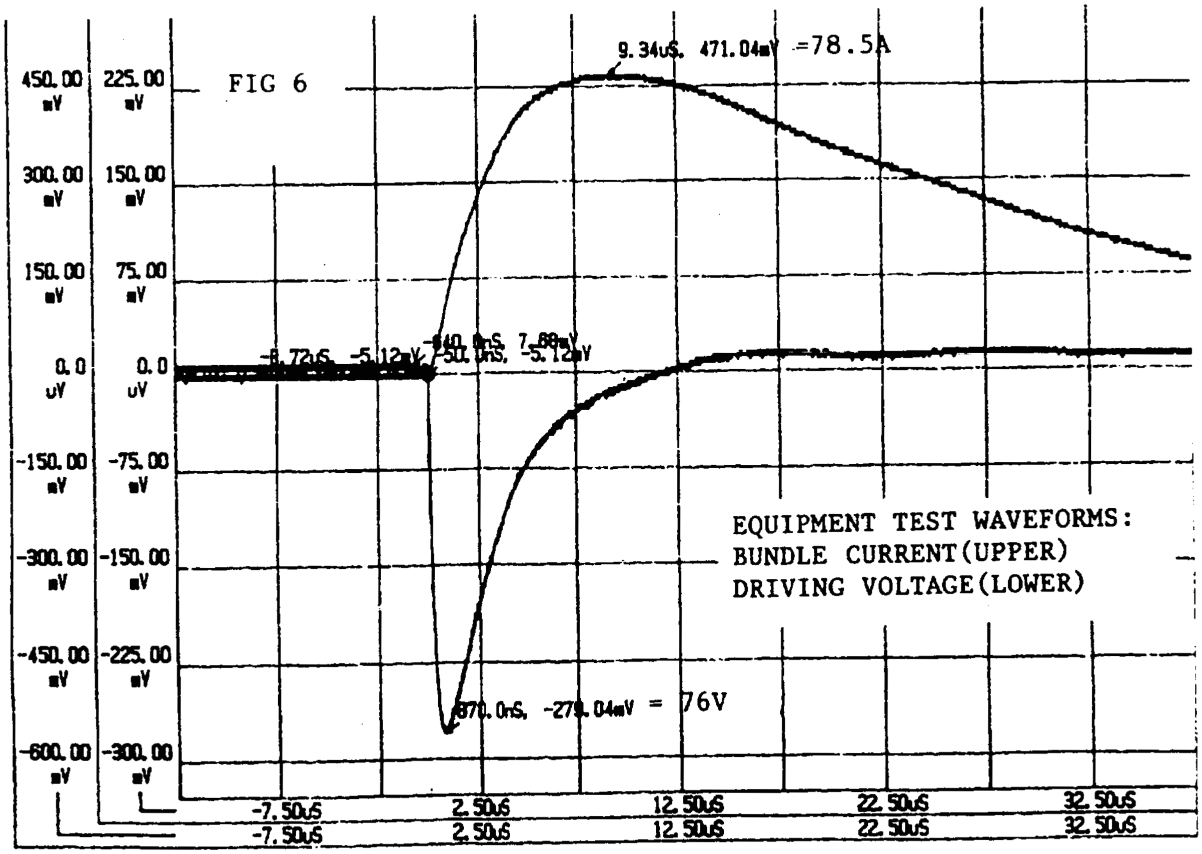
FIG 6
450.00 mV
300.00 mV
150.00 mV
0.0 uV
-150.00 mV
-300.00 mV
-450.00 mV
-600.00 mV
225.00 mV
150.00 mV
75.00 mV
0.0 uV
-75.00 mV
-150.00 mV
-225.00 mV
-300.00 mV
9.34uS, 471.04mV =78.5A
870.0nS, -279.04mV = 76V
EQUIPMENT TEST WAVEFORMS:
BUNDLE CURRENT(UPPER)
DRIVING VOLTAGE(LOWER)
-7.50uS
2.50uS
12.50uS
22.50uS
32.50uS

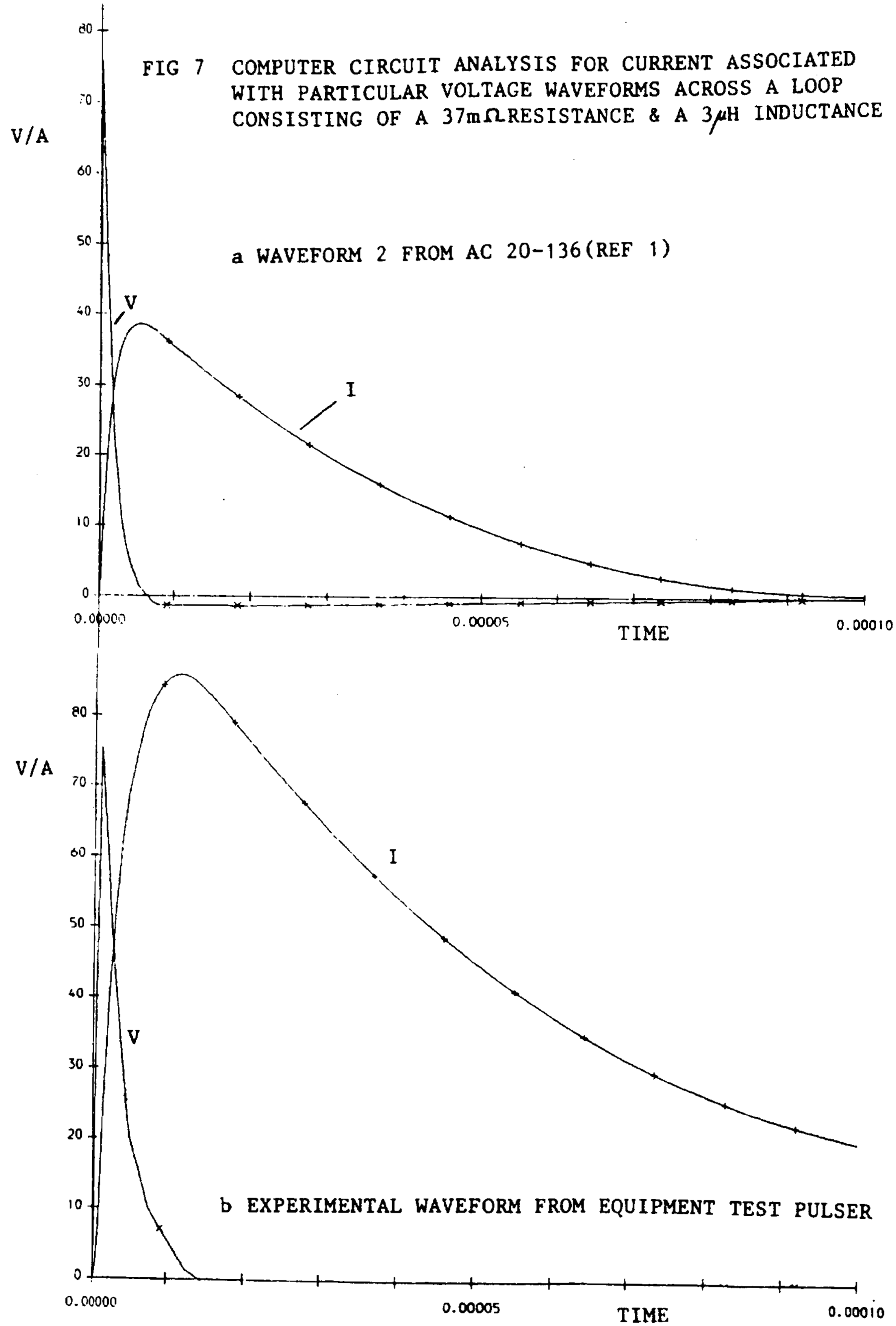

FIG 7 COMPUTER CIRCUIT ANALYSIS FOR CURRENT ASSOCIATED WITH PARTICULAR VOLTAGE WAVEFORMS ACROSS A LOOP CONSISTING OF A 37mΩ RESISTANCE & A 3μH INDUCTANCE

a WAVEFORM 2 FROM AC 20-136(REF 1)

b EXPERIMENTAL WAVEFORM FROM EQUIPMENT TEST PULSER