FULL-SYSTEM TESTS USING THE SANDIA LIGHTNING SIMULATOR

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ABSTRACT

Direct-stroke, very high-level natural lightning is simulated
with a developmental lightning simulator, which has been used to
apply fast-rising, high-current, high-energy outputs to full-scale
operational systems. Samples of the wide range in output capabili-
ties of this high-voltage, multiple-pulse simulator are described.
Circuit considerations related to its use for testing physically
large test items are discussed. The simulator is primarily used
for conducting internal Sandia National Laboratories test programs,
but example waveforms from direct-strike lightning simulation tests
made for the Navy with functional F-14 and F/A-18 aircraft are also
presented.

LIGHTNING SIMULATION TESTING of full-scale, fully operational systems at pulse levels corresponding to low-probability, maximum-threat conditions is a subject of relatively widespread interest. Severe-threat current levels as high as 200 kA peak are being specified for an increasing number of systems. High rates of rise in current are more frequently being associated with hazards to equipment from natural lightning. Simulation test current rate of rise (di/dt) as high as 2×10^{11} A/s is also being specified more frequently.

The need for high-current lightning simulators has been described in numerous previous publications and conferences, and much has been written concerning natural lightning and subjects related to it. The 1982 IEEE Transactions on Electromagnetic Compatibility(1)* contains many papers and their references which describe and summarize much of what is known about lightning and its interaction with aircraft. It includes a paper by Uman and Krider(2) that provides a good review of lightning subjects and also a comprehensive bibliography of literature related to lightning measurements and models.

This paper discusses some aspects of lightning simulation testing of items ranging in size up to that of full-scale operational military aircraft. A partial discussion of the Sandia National Laboratories, Albuquerque (SNLA) lightning simulator itself and some of its capabilities are included. Bushnell and Kostas(3) provide a more detailed description of the simulator elsewhere in this conference. Several different output pulse voltage and current waveforms related to use of the simulator for lightning simulation testing are discussed below. No attempt is made in this paper to discuss instrumentation or test item responses.

Natural lightning encompasses such a wide distribution of high-voltage, high-current characteristics that the task of simulating it is made easier by using some of the high-voltage, pulsed-power technology that has developed over the years in several of the national laboratories. A little of that technology, as related to the Marx generators and megavolt switches used in this simulator, is also mentioned.

Some of the discussion in subsequent sections is intended to support the concept that severe (high-level) lightning can be more easily simulated with physically small objects or systems having low-impedance than with large, high-impedance test items. The great majority of lightning simulation testing with this simulator is done with test systems smaller than full-scale fighter aircraft, so it is easier to do. The versatile nature of this

* Numbers in parenthesis designate references at the end of the paper.

developmental simulator is made more apparent by describing some of the large-item high-level tests that have been made.

LIGHTNING SIMULATION

CROWBARRED MARX LIGHTNING SIMULATOR – Underdamped RLC capacitor discharge circuits using the crowbar technique to clamp or short out the capacitor when peak current is reached have been used for pulse stretching here for more than 25 years and also at several of the other national laboratories. This method can provide fast-rising, long-duration, unidirectional pulses. Use of crowbarred Marx surge generators was strongly supported by F. W. Neilson(4) in 1977 for simulation of very high-level lightning currents. How to crowbar megavolt or higher voltage circuits was an important factor related to the success of such a simulator. Testing described by Parker(5) confirmed and demonstrated the feasibility of using a gas-dielectric, triggered-spark gap as a 1-MV crowbar switch.

Utilization and developmental operation of this new lightning simulator facility during the past year or so has confirmed the performance characteristics and capabilities predicted and described by Neilson. Once the capability of using the simulator for lightning studies was demonstrated, the request for tests became so great that continued development efforts had to be greatly curtailed. Since then, nearly constant test operation of the simulator has displaced its continued development to brief intervals between test programs.

The advantages of a crowbar-switched Marx circuit over other approaches for a simulator were described by Neilson(4) along with the important transient circuit parametric relationships for several approaches. The underdamped crowbar switched RLC circuit approach to generating a severe threat current pulse is many times more efficient than using an overdamped bank.

APPLICABLE TEST CRITERIA – The type of test and the test levels to be used need to be carefully considered relative to the nature of the item being tested. Simulation of low-occurrence-probability, severe-threat, very high-level lightning places stringent demands on lightning simulator performance and on the item being tested. The need for a high-level simulator may be very important if critical systems must be tested with severe simulated lightning environments. Very high-level testing may then be the only way of obtaining the required information.

Operational survivability or safety needed for other test items, on the other hand, may be much less critical, and/or exposure probabilities may be low. It may be important not to overdesign or overtest, especially when the relative consequences of lightning damage or service disruption are minimal. Very large,

unjustified costs and large design and performance penalties for normal nonlightning environments may result from providing unnecesaary overprotection.

Simulation of all of the more important characteristics of natural lightning requires a versatile system with a broad range of capabilities. Simulation of simplified versions of the extreme-level high-current pulaes is a smaller task but still not easy. A number of sources such as Cianos and Pierce(6), the SAE committee AE4L report(7) or MIL-STD-1757(8) propose or establish simplified pulse criteria for lightning simulation. Natural lightning characteristics and summaries of proposed or established simulation specifications are provided in many references. The papers in the proceedings of the Culham Laboratory, England 1975 Conference on Lightning and Static Electricity, including those of Pierce(9) and of Phillpott(10) give good summaries and discussion of lightning test criteria.

Even after simplification to bare essentials, a single, severe-level, return-stroke, simulated pulse is not easy to show in its entirety in a simple plot. A simulation pulse shown in Fig. 1 has an amplitude that ranges over three orders of magnitude and a time duration that ranges over seven orders of magnitude.

Simulation of just one pulse may not be enough to satisfy some test requirements. Over a decade ago, Cianos and Pierce proposed a three-pulse "Applied Model" for aimulation of severe lightning. Since natural lightning often has many return strikes, several pulses are a better simulation than just one. Their severe lightning applied model has three. The first has a 200-kA peak and the two subsequent strokes each have 100 kA. More recent proposals and criteria have been in general agreement and propose two pulses with the same 200-kA and 100-kA levels. MIL-STD-1757, entitled "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware," specifies a 250-ms to 1-second interval between pulies.

DOUBLE PULSE WITH FULL-SCALE AIRCRAFT - The majority of items tested at this facility require double-pulse simulation with continuing current at some point during the test process. Fig. 2 shows the current waveform record from one such test with the Navy F/A-18 Hornet jet airplane made during August 1982. This record was obtained using one of the lightning facility Tektronix 7612 digitizers, which provides a split time base capability. The horizontal timebase shown is divided into five separate time intervals. Approximately 16 ms was the time interval between pulses. Time separations between pulses have been selected between 10 ms and 800 ms for other tests.

This test also included continuing current in the several hundred ampere range between pulses and continuing well past the second pulse. Time of rise for each of the two pulses was 2 μs.

Double-pulse lightning simulation with continuing current was applied several times to the F/A-18 and was also used in June 1982 for lightning testing of the Navy F-14 Tomcat jet airplane. Additional description of the use of the lightning simulator for the Navy airplane tests has been treated by Ewing(11) and by Perala and Easterbrook(12).

MULTIPLE PULSE SIMULATOR ARRANGEMENT - Several different combinations of impulse generators have been used in the two main tanks of this simulator system. Using multiple sources allows multiple-stroke lightning simulation. Output pulse characteristics can also be more easily adapted to different specific test requirements using multiple sources with different inductive circuit elements to suit the test requirements. Fig. 3 shows multiple isolation spark gaps arranged to allow multiple sequential pulses during a single test. Use of the isolation gaps allows time separation between pulses to be set to any interval from microseconds to 1 second.

Most of the testing with the simulator has been done using only one crowbar spark-gap switch (G_{CR}) and one isolation spark gap in each of the two simulator tanks. Sometimes one crowbar switch is used with a single-impulse generator, and at other times, two generators are crowbarred simultaneously with a single switch. Make-up inductors (L_{MU}) are used between a crowbarred Marx generator and its test load to provide the desired wave shape. Different inductance values are built into these coils for different generators or different combinations of generators. The product of total loop inductance and source capacitance are adjusted to make $(\pi/2)\sqrt{LC}$ equal to the desired time to peak. Most of the tests have had a nominal 2-μs time to peak (t_p).

The very simplified diagram of Fig. 3 is not intended to be comprehensive. Many things are not shown in the diagram, including the continuing-current generator system. It is used to provide sustained current flow for durations out to about 1 s. The continuing-current system is also connected to the output for those tests requiring it. Since it is a lower voltage system, it is located outside of the simulator tanks. Low-level current from the continuing-current system is started with the first high-amplitude, return-stroke, current pulse and continues until the arc extinguishes between 0.5 and 1 s. The continuing-current component starts around 1 kA and slowly decays to about 300 A.

The oil-insulated, coaxial interconnection between simulator tanks provides a connection path to the load but also acts as a short transmission line that affects the detailed features of the output pulse. During tests with series spark gaps in the test-load circuit, the capacitance of the oil line acts somewhat like a peaking capacitor and briefly increases the initial rate of rise in current. Different kinds of terminal arrangements and

return-circuit arrangements are used to connect to the test item.

The maximum stored energy of 650 kJ from all four impulse generators combined could deliver at most 2×10^6 $A^2 \cdot s$ action integral to a total load circuit resistance not exceeding 0.3 ohms. MIL-STD-1757 specifies a single-pulse action integral of 2×10^6 $A^2 \cdot s$ for the initial 200-kA high-peak current component A of qualification tests for full-size hardware subject to direct-stroke attachment.

TEST SETUP PHYSICAL LAYOUT - Since the SNLA lightning simulator was originally developed to test relatively small systems, physical layouts of the facility were not oriented toward testing full-size, operational aircraft. Smaller test items are generally located indoors between the two main simulator tanks. They may be vertically supported above a vertical-axis, high-voltage terminal or may be located near it but displaced to one side. A horizontal-axis high-voltage bushing can be used as an alternate terminal arrangement. It mounts on the side of an oil-filled, cross transition that allows switching to an oil-insulated dummy-load coil mounted in a horizontal cylindrical container on the opposite side.

The arrangement of the simulator tanks is shown in Fig. 4 with the cross, horizontal bushing and oil-insulated load coil. The dummy-load coil allows the simulator to be fully checked out with a representative load just prior to a subsequent shot into the real load. An Air-Launched Cruise Missile, ALCM, with its return circuit, is shown connected to the simulator output. Lightning simulation tests with the ALCM are scheduled during 1983.

The relative locations of the four separate Marx surge generators used in the simulator are also shown in the diagram. Other components used in the oil-filled simulator tanks to trigger, crowbar, waveshape, etc., are not shown in this figure.

When the full-size aircraft were tested, there was not room within the building for them. An oil-insulated, coaxial transmission line was constructed so that the horizontal high-voltage bushing shown in Fig. 4 could be located outside of the building. The ALCM tests require that portions of the missile and its return circuit be outside in an adjoining temporary addition.

RETURN CIRCUITS - Current returning to the simulator from the test object is usually routed back to the output terminal ground through multiple conductors. The conductors are positioned to provide the minimum practical value of total-load-circuit inductance and still not greatly disturb the surface currents in the test item. The return circuits are often made coaxial unless it is either impractical or no particular need to do so exists.

The return circuit needs to be adequately spaced from the test item so that unintended flashovers between them do not occur. A series spark gap is shown in the previous figure near the tail of the missile. The test circuit is completed by breakdown of this gap between the ALCM and its return circuit. At least a small air gap is always used in any test requiring continuing current. However, it can be located at either end of the test item. Instead of using a short free-air spark gap to complete the test circuit, some setups employ a long-spark in conjunction with high-peak current tests.

The return circuit for the F/A-18 is sketched in Fig. 5, which shows the aircraft surrounded by cables. The wheels were down for both airplane tests and supported on high-voltage insulators. Twenty cables were arranged around the plane in a nearly coaxial array for both aircraft tests. The cables were supported by wooden stands and routed both to the tail and, with a branching array, to the left wing. Both the F-14 and the F/A-18 lightning tests were conducted for the Naval Air Systems Command. The overall return circuit structures and systems for both airplanes were of similar design. The return circuits were furnished and fabricated on site by Electro Magnetic Applications, Inc.(12) An overview of the tests is provided by Perala(12) in another paper in this conference.

The inductance value of the test item and its return circuit becomes relatively high when something as large as an airplane is being tested. The simulator must have high voltage to drive high-peak currents with high-rising di/dt through the load. This is discussed further in later sections.

IMPULSE GENERATORS - The design of the four Marx generators used in this lightning simulator was adapted from a 3.2-MV design used in a number of nonlightning SNLA pulsed power applications.(13) The basic 3.2-MV arrangement was designed over a decade ago, and a number of working variations have evolved from it since then.

The physical arrangement of this multiply folded impulse generator design is shown in Fig. 6. Each generator has 32 separate energy-storage capacitors arranged in a dual- polarity Marx circuit. Sixteen field- distortion, midplane, triggered spark gaps are used to switch the capacitors in series after the bipolar charging is complete. Each of the capacitors is charged to a maximum of 100 kA. Most of the lightning simulator tests have been made with less than full-charge voltage. At full-charge voltage, each sulphur hexafluoride (SF_6) insulated spark gap holds off 200 kV. Each of the four impulse generators used in the lightning simulator are of the same design and physical size. Each has 32 of the 100-kV capacitors, but two different values of capacitance are used. The capacitors in the lower capacity generators are a little over 0.7 μF, and the higher capacitance units in the same size container are each nearly 1.35 μF. This provides the higher capacitance Marx generators with nearly twice the energy of the lower

capacitance units

The Marx circuit was devised by E. Marx in Germany in 1924, and many variations have been adpated from it in the nearly 6 decades that have passed. The dual polarity charged Marx is one of several that has been used extensively at SNLA. This bipolar design has demonstrated high reliability in PBFA-I(14) where 36 separate 116-kJ units are simultaneously erected to a circuit-driving voltage near their design rating of 3.2 MV.(15) The resultant 4-MJ-parallel output pulse of the PBFA-I accelerator is used for research in the Particle Beam Fusion program at SNLA. A somewhat larger 6-MV, 400-kJ generator has been designed and tested for the 14-MJ PBFA-II accelerator where 36 of them will again be used in parallel.

The impulse generators in the lightning simulator and all of the others mentioned are oil-insulated. Multiply folded, oil-insulated, bipolar generators have a desirably low source circuit inductance and furnish much higher voltage to inductance ratios than are generally possible with air-insulated impulse generators.

The bipolar Marx circuit has a number of advantages in high-energy pulsed-power applications, even though it requires both positive and negative equal-charging voltages. A simplified schematic is shown in Fig. 7 for a four-capacitor, two-spark gap circuit. Because only one-half as many spark gaps are required, maintenance is reduced and reliability improved. It is relatively easy to fold into compact, low-inductance configurations. It does not need an isolation gap between its output and the test load (for single pulses) although one may be used. The output polarity of this type generator can usually be reversed quite easily.

The basic 3.2-MV PBFA Marx generator has more voltage than was needed for lightning simulation testing with low-inductance loads. Therefore, when this 3.2-MV design was adapted for use with the lightning simulator, it was split in two. The two resultant, normally series-connected halves were then joined in parallel to make a unit with four times the capacitance and twice the current capability but with only a 1.6-MV output, i.e., one-half of the original design voltage. Fig. 8 shows the discharge circuit for this lower voltage Marx generator.

All four of the simulator generators had the same electrical design parameters for the first year of operation, which included the periods during which both of the Navy airplanes were tested. Erected, series, output capacitance for each of the generators was 88 nF. The highest level peak currents were applied to the aircraft by combining the outputs from parallel impulse generators into a single pulse. Two of the Marx generators have since been rebuilt to furnish more energy from the same size units. Replacement of the capacitors provided an output capacitance of about 165 nF. One high-C Marx can now supply about the same output as two of the original generators. Low-level tests can still be furnished by using the two generators that retained their original capacitors.

CROWBAR SWITCH AND ITS TRIGGER - The performance of the simulator is very dependent upon the crowbar switch and its operating characteristics. It must reliably hold off the full-output voltage of the erected Marx, but almost immediately thereafter, it must be capable of being triggered near the time that the voltage across it passes through zero. It must pass very high currents that are even higher than that through the load. Crowbar switch current, as shown later, is the composite of load current and any Marx generator current oscillation that occurs. The switch electrodes must survive the high current and charge through it for some reasonable number of discharges.

The switch used with the lightning simulator facility was also adapted from PBFA-I and related pulsed-power technology. The PBFA switch is a 3-MV, gas-dielectric, triggered-spark-gap trigatron used for pulse forming. Electrical triggering with the switch dielectric gas composed entirely of sulphur hexafluoride is used in PBFA and most of the other pulsed-power applications of the switch. It is a larger version of an earlier (1972) 3-MV, SNLA-developed trigatron described by Tucker. (16) Thirty-six separate switches, each holding off 2.5 MV, are simultaneously triggered within about 10 ns in the PBF accelerator to dump 36 separate water-dielectric capacitors. These same switches do not have stringent timing requirements, as used in the lightning simulator, but they must be capable of being triggered at low voltage.

Crowbar switching right at peak current is difficult because switch voltage at that time is very near zero. Crowbar switching within $\pm 30°$ (or within $(\pi/6)\sqrt{LC}$) of peak current I_p, still provides 0.866 I_p. For an undamped LC oscillation, voltage at 60° or 120° is 0.5 of the initial voltage. The problem then becomes one of triggering the crowbar switch at instantaneous main-electrode voltages that do not exceed 50% of the initial peak voltage. The minimum main-gap voltage at which a specified trigger mechanism will ensure reliable operation has for many years been called cutoff voltage. Cutoff voltage differs for different trigger mechanisms and also is dependent upon other dynamic conditions related to use of the gap. Low ratios of cutoff voltage to holdoff voltage (or to operating voltage) allow generation of better pulses from the simulator. Good pulses can be provided when crowbar switching occurs either before or after peak current. Switching after peak has been used for much of the development testing. Switching before peak has been investigated more recently, and it better satisfies some requirements.

Electrical triggering and SF_6 gas were used with the unmodified trigatron during early

developmental operation of the simulator, and good output pulse results were obtained. It switched near peak current and permitted full 100-kV charging of the capacitors and open-circuit erection voltages near 1.6 MV. When problems were encountered with the electrical-trigger pulse generator, other crowbar triggering approaches of interest were explored.

Infrared (IR) laser triggering has been used for much of the development testing during the past year. The trigatron configuration was modified by removing the trigger pin and shaping the hole though the main electrode to allow focus of the laser beam within the main gap. The modified laser triggered switch has been used with lower dielectric strength gas compositions containing 50% nitrogen, 40% argon, and 10% SF_6. Many tests have been made with the IR laser triggering, and it has been moderately successful. Good triggering is obtained using the mixed gas, but the gas dielectric strength is much lower than it is for pure SF_6. Even with increased gas pressure, maximum holdoff voltage is reduced. Marx output and charging voltages have been limited to about 80% to avoid exceeding pressure limitations of the spark-gap housing. The lowered voltage reduces maximum stored energy in the impulse generators to about 64% of rated energy.

Work with ultraviolet (UV) laser triggering is in progress. This will permit use of 100% SF_6 in the crowbar switch so that full-rated, 100-kV charge voltage can be used. The UV laser trigger is expected to provide very good performance and will probably be used with both simulator tanks. As time permits, any other triggering methods, such as electrical triggering, that appear to offer lower operating complexity, lower cost, or improved reliability may also be investigated.

A new oil tank for developmental testing with an additional Marx generator is located near the two main simulator tanks. It is expected to be operational soon, which will then allow crowbar and triggering studies and other development activities to proceed in parallel with scheduled simulation tests. Crowbar switch and triggering development that leads to an improved cutoff-to-holdoff ratio should have a good payoff in terms of increased system versatility and reliability. Since the Marx generators are connected to provide only one-half of their normal design voltage, crowbar switch operational characteristics remain as one of the main temporary constraints to operating the simulator at higher voltages.

FAST-RISING, HIGH-CURRENT, WIDE PULSE - The simulator has the capability of providing very fast-rising, very high-amplitude, long-duration current waveforms. Waveforms of current and action ($\int i^2 dt$) are shown in Fig. 9 for a 1- by 380-μs very high-amplitude pulse delivered into a low-impedance load during development test series conducted with the simulator in the spring of 1982. Crowbar was above 200 kA and the 200-kA pulse level was

sustained for over 20 μs with a slow decay to half value of nearly 400 μs. This pulse achieved an action integral of 1.1×10^7 ($A^2 \cdot s$) and delivered a unidirectional charge of greater than 300 C. This pulse would be too severe for most test items, but it illustrates possible capabilities of the simulator. Since this test series was made, two of the impulse generators are being converted to even higher energy units.

Both inductance and resistance are added to the test circuit for most tests. Inductance is usually added to slow down the current rise and provide a time-to-current peak of about 2 μs. Added resistance can be used to speed up the decay and shorten the tail of the waveform to about 50 μs at half amplitude. Usually any special pulse-shaping components that need to be added to the circuit are located within the simulator tanks below the oil fill level. This provides them with adequate high-voltage oil insulation and prevents voltage flashovers that might otherwise occur in air.

LOW-CURRENT TESTS - A broad range of output current waveforms is made possible by the arrangement of the simulator. Lower current pulses are provided by selecting only one impulse generator and lowering its charge voltage to about half of rated value. Currents down to about 50 kA peak can be provided without significant changes in circuit components. Even lower peak current was desired for the early portion of both airplane test series. Current waveforms with peaks of 10 to 15 kA were provided by shunting the inductance of the test load with an even lower inductance added to the circuit and located within the simulator tank. A schematic of this arrangement with the F-14 Tomcat is shown in Fig. 10. A bypass inductor (L_B) with an inductance value about one-fourth that of the downstream load shunted about three-fourths of the simulator current to ground. The remaining fourth of the output current provided the desired low-current pulse.

WIDE RANGE OF CURRENT PULSES - As a part of the tests with the F-14A and the F/A-18 Navy aircraft, different current levels were desired. Initial tests were commenced at relatively low currents of 10 to 15 kA peak. The test levels were increased as confidence in the instrumentation and recorded results was acquired. This is a fairly common sequence of events for most test items. The relatively high inductances of the airplanes and their return circuits constituted higher than normal load impedances for the simulator. Even so, the tests went quite well.(11)

The two example simulator pulses shown in Fig. 11 were recorded during the F/A-18 test series. The simulated lightning pulse was injected nose-to-wing in both of these tests. These particular tests did not use long-spark gaps to complete the test circuit to the aircraft. Nose-to-tail injection was also used in many of the tests. Long-spark air gaps were used to complete the test connections for a

portion of both the nose-tail and nose-wing tests. These were called E-field tests, and they allowed the field on the surface of the aircraft to build up until breakdown of the long-spark gap occurred. Charging of the oil-transmission line plus the aircraft itself acted somewhat as a peaking capacitor. Start of initial current was delayed until spark-channel breakdown, and then current rose very rapidly during the discharge of the locally stored dielectric energy. During E-field tests, local currents generated at the aircraft would not pass through the simulator injected current monitors and would not be recorded. Since the two waveforms in Fig. 11 are not E-field-type tests, the early portions of the current rise are smoother. These sample waveforms into the F/18A show that a 10-to-1 range in peak current is available for a given test load circuit configuration.

LONG-SPARK, HIGH-CURRENT TESTING - When long-spark gaps in free air are used to establish connections to the test load, such as in the previously described airplane tests, portions of the circuit are subjected to very high voltages. Production of open-load-circuit voltages sufficient to break down the gaps requires that comparable high voltages also be present in the simulator. Some simulators, particularly those used primarily for generating controlled specified voltage waveforms, have sufficient voltage but are not designed to also deliver high current. Partly for this reason, combination of long sparks and high current into a single test has not been considered practical at some other facilities.

This simulator emphasizes the value of using high voltage and low inductance, but the greater emphasis is put on high voltage. This makes it quite practical to combine long sparks and high current into the same test.

One of the reasons stated for long-spark tests is to furnish high-voltage shock-excitation or fast E-field changes at the test system. Long 150- to 300-mm air gaps were used for some of the tests with both Navy airplanes. This was intended to allow charging of the aircraft and then to furnish a subsequent high dV/dt when the detach arc commenced. This quite likely did occur at least for portions of the airplane. However, for aircraft surfaces near the simulator terminal, the average rate-of-change in voltage was greater both in duration and in value during voltage rise than during voltage fall.

Rapid, large drops in test-item voltage occur with the long spark if subsequent L di/dt voltages are low either from low L, or from low di/dt. When breakdown current begins and the L di/dt voltage has a high value, it may approach the voltage that was required to break down the long spark path. In that case, the voltage appearing between the point of current injection and the nearest point of the return circuit may not be greatly different whether or not a long series spark path was used in the

downstream circuit. When the long-spark breakdown occurs, terminal voltage cannot fall very far before it equals the high L di/dt voltage of the load circuit.

For fast pulses and high-inductance loads, the rising voltage at the start of the pulse reaches a very high peak value with or without either long or short series spark gaps. With spark gaps, all or a portion of the voltage is applied to the gap until it breaks down. However, that may or may not exceed the subsequent L di/dt voltage, depending on gap length.

For predominately inductive loads, simulator tests in the 100-kA peak current range can produce voltage rises to 1 MV in 100 to 200 ns. This corresponds to dV/dt rates-of-rise in voltage of 0.5×10^{13} to 1.0×10^{13}. Local maximum values of available instantaneous current, together with local distributed capacitance, control the maximum possible value since dV/dt = i/C. Sometimes this also can be treated as a case of pulse reflection at the junction of mismatched transmission lines.

COMBINED HIGH-VOLTAGE AND HIGH-CURRENT TESTS - Discussion in previous sections makes it apparent that fast-rising, high-current tests have much high voltage associated with them. Combined high voltage and high current have been provided in some tests, and for most test items up to several microhenrys such combinations are not greatly constrained by simulator limits.

The voltage waveform shown in Fig. 12 is one example of the terminal voltage developed during a 100-kA peak current nose-to-wing injection into the F/A-18. The voltage spike at the front results from the oil-filled transmission line being terminated in a predominately inductive load. Most of the oil-line extension from the simulator to the airplane has a characteristic impedance of about 40 ohms. The pulse applied to the transmission line reflects and increases when it arrives at the output terminal. This explanation is somewhat oversimplified because there are other distributed circuit parameters also involved in the process. The waveform shown consists basically of L di/dt voltage components. The sharp change that occurs a little more than 3 µs into the pulse is related to crowbar switching.

The voltage waveforms appearing at the input to the airplane during high-current E-field, long-spark tests are not much different from the voltage shown in Fig. 12 for a test without the long-spark gap. Depending on the spark path length, the voltage in a long-spark test may go somewhat higher and last a little longer before the drop due to breakdown occurs, but the fast decrease only goes down to the appropriate L di/dt voltage level related to the test. Consistent results were obtained with computer circuit analysis simulations of the circuit. When a long-spark test is combined with a low-current (and/or low-di/dt) test, then the sharp voltage change related to

gap breakdown can be large.

The voltage waveform shown in Fig. 12, is composed of the sum of incremental series voltage drops along the surface of the airplane and of those developed along the return conductors. For a true cylindrical coaxial return, almost all of the voltage dr would be associated with the length and t e per-unit-length inductance only of the central conductor.

Whatever the diameter of an object struck by natural lightning, its diameter is likely to be small compared to the effective diameter of the natural system return path. Inductive voltage drop along the length of a solid metal conductor or vehicle surface subjected to a di/dt of 2×10^{11} can be on the order of 200 to 300 kV/m.

Several tests were made with the F-18 in which a primary objective was to develop voltages sufficient to cause sparkover across an insulating surface. The simulator was set up to furnish a noncrowbarred damped oscillatory pulse with about one-half of critical damping resistance.

The first test developed the voltage waveform shown in the upper part of Fig. 13. This waveform resulted when a 0.7-m-long flashover occurred between the output terminal and a return circuit cable. The local return circuit spacing was increased and the simulator voltage was lowered to produce the intended test load breakdown in the next shot. The voltage waveform in the lower half of the figure was recorded on that test. Also, some adjustment may have been made to the sparkover length of test item surface.

Peak currents for these tests are shown in Fig. 14 for the first and second tests, respectively. Nearly 90 kA was delivered in the first test with most if not all of it into the return circuit flashover. The subsequent 55-kA pulse was all delivered to the test aircraft. The difference in circuit inductance between the two tests is evidenced by the nearly 1-μs difference in pulse periods.

The simulator system described here has been used primarily to simulate current waveforms. The majority of the tests have been with low-impedance loads, or at least they become low once current through an isolation gap is established. Load inductances are often only a few microhenrys. MIL-STD-1757 and other test criteria specifications describe both current waveforms and voltage waveforms. Very little voltage testing has been done with this simulator. Major circuit components needed for voltage simulation may be similar to that needed for current simulation. There appears to be no major reason why this simulator system cannot be also used for some types of voltage simulation if the need for it becomes more important in the future.

COMPUTER SIMULATION OF CIRCUIT RESPONSE - Understanding and predicting what is going on in a simulator circuit is aided by simplified diagrams of the setup. Good rough estimates of performance can be obtained by paper-and-pencil application of basic relationships. However, the task of analyzing and predicting circuit performance becomes large when there are many variations of interest or the actual circuit becomes complex.

Actual circuits may have a number of stray or second-order elements that modify or affect performance. Stray capacities, stray-inductances, sections of changing characteristic impedance transmission lines, and other such factors that can contribute to superimposed oscillations may be present. Deliberately added shunt or damping resistors may have been added to various portions of the circuit to eliminate or minimize such oscillations. The number of circuit parameter combinations can become very large when test loads and test levels or conditions are varied. Computer simulation and analysis becomes valuable when simple methods become unwieldy or ineffective in treating a complete representation of the circuit.

The Air Force SCEPTRE(17)(18) program is one of several transient circuit analysis aids that has been used frequently at SNLA. It has been quite valuable for simulating many circuit variations related to use of the lightning simulator. SCEPTRE is a general transient analysis program that was developed about 15 years ago by IBM on contract to the Air Force Weapons Laboratory (AFWL).

An example current waveform computed by SCEPTRE for selected values of simulator parameters is shown in Fig. 15. Crowbar occurs 3.4 μs after peak current in this waveform. All other waveforms in the circuit being analyzed can be examined with plots available from SCEPTRE. Such examination and study can yield valuable insight and information concerning simulator operation.

The computed voltage waveform in the lower portion of Fig. 15 is that appearing across a 3-μH load inductance as a result of the upper current waveform. The synthesized simulator circuit for these two waveforms included distributed parameter elements representing the oil lines between tanks and the load terminal stray capacitance in addition to other physical elements that have been included in the simulator tanks. The initial spike on the voltage waveform is due to the peaking capacitor effect of the unmatched oil transmission line and terminal capacitance. The sharp change in voltage at crowbar switch time occurring at 3.4 μs is like that of measured simulator records. Undamped ringing similar to that appearing on the voltage waveform also appeared on the current waveforms prior to the addition of minor circuit elements. Such parasitic element oscillations have been reduced on output current waveforms by adding damping elements at various locations in the circuit. Some ringing still shows up on some of the more sensitive L di/dt waveforms. Even though natural lightning current has much unpredict-

able noise on it, clean current pulses are often preferred for simulation purposes because the responses of the system-under-test can be more easily interpreted.

A composite of three computed simulator current waveforms is shown in Fig. 16. The upper solid trace, I_L, is load current. The middle trace, I_M, is Marx current, which continues to oscillate from energy trapped in inductance and capacitance of the Marx/crowbar shorted loop. Crowbar current, I_C, is then the combination of load current and the oscillating Marx current. Load current and Marx current do not exactly coincide before crowbar time because a physical resistor has been placed in the real circuit across the crowbar switch to help damp-out noise appearing on the Marx terminal voltage that is applied to the crowbar switch.

The large oscillation of Marx current after crowbar can also be damped out with minimal reduction of initial peak current by additional series resistance placed in the Marx portion of the crowbar loop. This is shown in the lower portion of Fig. 16 for the same circuit parameters and the same voltage with only two changes. Crowbar timing was moved to an earlier time at 1.5 µs so that it occurred on the front side of peak current. Also, an additional series resistance was added on the Marx generator side of the crowbar switch. The added resistance rapidly damps out the oscillation in the low surge impedance, $(\sqrt{L/C})$, Marx/crowbar loop because it is a large fraction of critical damping resistance in that loop. The added 1 ohm has little effect on load peak current because in the load circuit loop, it is a small fraction of critical damping resistance, $Rc = 2\sqrt{L/C}$.

SIMULATION CIRCUIT CONSIDERATION

This section discusses some elementary considerations related to simulation and natural lightning circuit parameters such as resistance, inductance, action, energy, etc. It is not intended to be comprehensive. Clifford, Crouch, and Schulte(19) review much additional information on lightning simulation and testing.

HIGH RATE OF RISE IN CURRENT - Many natural lightning events have very fast-rising currents even though inductance of an established channel can be very high. Current pulses with di/dt values of 1 or 2 x 10^{11} A/s have been specified for some simulation testing. Clifford, Krider, and Uman(20) propose that even faster rising simulator pulses be considered for some studies.

Achieving high rates of rise in current from a lightning simulator can become a difficult development task unless the means for providing a high V/L ratio is available. Obviously, two ways are possible: the inductance must be kept low or the voltage made very high. Making inductance as low as practical

appears desirable, but with a crowbarred Marx generator simulator, increasing the driving voltage (or maximum erection voltage of impulse generator) is a better way of achieving the requisite high V/L ratios, providing that a suitable crowbar switch is available. Load/source interaction is reduced and the simulator becomes more versatile because it can furnish the required pulses for a greater variety of test item characteristics. If total loop inductance is made too low, the maximum permissible load circuit resistance must also be low if a long L/R decay time on the tail of the waveform is needed.

If the inductance of the impulse generator is permitted to constitute a significant fraction of the total inductance then a proportional fraction of $Li^2/2$ magnetic energy is trapped in the Marx/crowbar circuit loop. The trapped energy is unavailable to the load and oscillates back and forth between inductance and capacitance of the Marx/crowbar loop. The SNLA pulsed-power Marx, as modified for this simulator, has a very low value of source inductance, so this is not generally a problem. Each 1.6-MV impulse generator has a source inductance of about 1 µH.

The underdamped RLC circuit clamped or crowbarred near peak furnishes an energy-efficient way to furnish the needed high V/L ratio. With a 1.6-MV full erection voltage, di/dt of 2 x 10^{11} is attainable with a total loop inductance up to 8 µH.

HIGHER RESISTANCE LOADS - The probability of whether or not any particular natural lightning event will be high current or low current is relatively independent of the electrical impedance of any small-dimension object (airplane, building, tree, etc.) that may be encountered in the path. A given high-current natural lightning event (with its low probability of occurring at all) could well encounter either a low-impedance or a high-impedance object in its path.

Tremendous local energy deposition and damage might occur with a high-resistance object such as a tree; whereas, an event with similar electrical characteristics may have only slight effect on a heavy, low-resistance, copper grounding conductor. The tree or a moderate resistance object may shatter or disassemble with explosive violence as a result of the natural lightning stroke. Thermal damage in a good conductor would result if the stroke action integral exceeded the melting action value or the vaporization action value related to its cross section.

The greater energy deposition in high-resistance materials as compared to metals was described by Plumer and Robb(21). They indicate an energy deposition in graphite composite 2,000 times greater than in aluminum in accordance with their relative resistance values.

Fortunately, test loads of interest for this simulator have had a low resistance. They generally have been all metal. Even with the

airplanes and series spark gaps, the total load circuit resistance has been low. Greater stored energy and higher load circuit inductance would be required if it became necessary for a simulator to deliver 200 kA with a half-amplitude pulse width of 50 μs into a significantly greater load circuit resistance.

Load circuit loop inductance must be made higher for high values of load resistance if pulse width is to be maintained. Over 70 μH of inductance would be required for a total load circuit loop inductance of only 1 ohm. Magnetic energy stored in 70 μH of circuit inductance at 200 kA would be 1.4 MJ. This energy would have to be initially supplied from energy stored in the impulse generators. Even with the high-efficiency crowbarred Marx system, this requires more stored energy than is presently available with this simulator.

This may be an appropriate place to note the obvious. When 1.4 MJ of magnetic energy stored in load circuit inductance is released to a total load circuit resistance of 1 ohm, the resultant action is 1.4×10^6 $A^2 \cdot s$. If both the desired pulse action integral and effective load resistance are known, their product yields a quick estimate of the minimum $Li^2/2$ magnetic stored energy required of a simulator.

LOAD SCALING AND SIMULATOR TYPES - Manmade objects or systems that may encounter lightning are generally dimensionally small compared to the dimensions of a system producing natural lightning. The small relative size of the system struck prevents its resistance or inductance from having any significant effect on the action integral or other pulse parameters of the natural stroke main current path.

The dimensions of a natural lightning system can be extremely large. As a part of lightning studies being made in connection with the NASA Shuttle program, B. Vonnegut(22), with the State University of New York, has obtained photographic records of lightning with horizontal dimensions of 60 km or more. This was from a not particularly large winter storm over Brazil in June or July of 1982. NASA astronauts have visually observed single lightning events apparently spreading over several hundred kilometers.

Natural lightning is a "stiff" high-current source that is little affected by the impedance of some local object intercepted by it. This is a result of natural lightning having extremely high driving voltages and very high circuit inductances. Inductances of the cloud-to-ground portion of the current path may range from about 0.5 to 5 μH. Capacitances related to a single return stroke portion of the wave may be on the order of 10,000 nF.

Very large quantities of energy are stored in a natural lightning stroke, at peak current, in the form of $Li^2/2$ magnetic energy. One hundred MJ of magnetic energy would be stored in a 5-μH channel (on the order of 1 km long)

of a severe stroke having a peak current of 200 kA.

Total circuit electrical parameters of a lightning simulator may be significantly changed by a high-impedance load or test item. For a lightning simulator to be quite insensitive to load or test item impedance or resistance requires a "stiff" source having high voltage and the capability of driving high current through a high total circuit inductance. Such a system would provide good current waveform regulation and have charge and action integrals that were relatively independent of successively varied test item parameters.

A simulator circuit with a stiff source or a high (V)(L) product becomes increasingly important when high values of test object impedance are considered. However, practical laboratory physical constraints preclude simulating more than a tiny fraction of the high (V)(L) product of natural lightning. That is partly why different kinds of simulators have been used to simulate different aspects of natural lightning.

Low-voltage, low-impedance simulators can be used to produce high current into metal or near-short-circuit test items. Even at high current, little energy is deposited in the test item so the high current can be produced through it with modest or low driving voltages. Melting and vaporization can not be adequately studied, however, because of the rapid increases in resistance that occur.

High-voltage, low-current (low-energy) simulators can be used to evaluate breakdown characteristics of insulators or high-resistance test items if energy dissipation occurring during the transition period that occurs at breakdown can be ignored. If the breakdown is likely to occur around the item through a medium such as air, this may still be a fair test. Combinations such as these may allow many kinds of things to be tested without the need for high-energy simulators.

The requirements on a simulator are much more demanding if it is to be used for producing high currents through high-resistance and/or high-inductance test items. If the test item can be either low impedance, high impedance, or anything in between, then the simulator system must be much more versatile. Circuit-driving voltage usually must then exceed the maximum voltage drop to be developed across the load and high energy must be available to the load.

Total circuit inductance is often the most important controlling consideration in simulator selection if a very high rate of rise of current and a high-peak current value are both required. Once it is established, almost all other circuit parameters are constrained.

Impulse generators using the voltage-multiplying Marx circuit furnish a good way of impedance, matching the generator to the load.

Clamping the capacitor near peak current changes the circuit into a magnetic energy source that is similar to the natural lightning circuit. Large values of charge and action are available from the slow L/R decay of the current.

There are more than enough potential test items having relatively low inductance and resistance to keep this facility busy for some time. However, if it became particularly important to test some higher impedance loads, it appears that interesting levels of simulation could be obtained. The 210-kJ generators might be reconnected in their normal 3.2-MV configuration and then both placed in parallel to provide a 3.2-MV, 83-nF source. The resulting 420 kJ arrangement could produce a single-pulse peak current near 200 kA with current rate of rise of 2×10^{11} into a total circuit load of 16 µH. This would be practical only if output-pulse-related voltage insulation and crowbar holdoff voltage were adequately high.

SUMMARY AND CONCLUSIONS

A variety of different tests with the SNLA developmental lightning simulator has demonstrated that practically all of the important characteristics of natural lightning can be simulated during full-scale system tests. Peak current, current rate-of-change, charge, action, continuing current and high-voltage values related to severe lightning can be furnished with present technology. Using multiple, separate, Marx-circuit impulse generators crowbarred near peak current provides an energy-efficient lightning simulator with the needed characteristics. Current rates of rise of 2×10^{11} A/s, peak currents of 200 kA, action integrals up to 10^7 $amp^2 \cdot s$, charge of 80 C, along with double pulses and continuing current, have been produced. The modular nature of the simulator has produced a versatile capability with a wide range of selectable output characteristics. Although it is still in development, it already has been valuable both for testing full-size airplanes and physically smaller systems.

ACKNOWLEDGEMENT

The SNLA lightning simulator facility has resulted from the contributions of many people. Numerous internal and external organizations in the U.S. Departments of the Navy and the Air Force have cooperated or have provided specific portions of program funding.

The continued efforts and direction of F. W. Neilson have coordinated and brought together broad-base support and interest. Persons responsible for much of the development of the simulator include J. C. Bushnell, J. G. Kostas, R. J. Goode, and W. P. Brigham. Many others also contributed to the successful tests with the simulator and its operation, including

R. W. Ewing, B. Stiefeld, O. Milton, W. Vandermolen, and personnel from EG&G Kirtland Operations group.

REFERENCES

1. "Special Issue on Lightning and its Interaction with Aircraft." IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-24, No. 2, May 1982.

2. M. A. Uman and E. P. Krider, "A Review of Natural Lightning: Experimental Data and Modeling." IEEE Special Issue, Transactions of Electromagnetic Compatibility, Vol. EMC-24, No. 2, May 1982.

3. J. C. Bushnell and J. G. Kostas, "The Sandia Lightning Simulator." This conference and SAND82-2274, June 1983.

4. F. W. Neilson, "An Extreme Lightning Test Facility." Unpublished internal report, Sandia Laboratories, 1977.

5. R. L. Parker, "Feasibility Studies for Crowbarring One Megavolt on the LILI Facility." Sandia Laboratories, SAND78-1700, April, 1979.

6. N. Cianos, and E. T. Pierce, "A Ground-Lightning Environment for Engineering Usage," Stanford Res. Inst. Tech. Rep. No. 1, Project 1834, Aug. 1972.

7. "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware." Rep. of SAE Committee AE4L, June 20, 1978.

8. "Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware." Military Standard MIL-STD-1757, June 17, 1980.

9. E. T. Pierce, "Natural Lightning Parameters and their Simulation in Laboratory Tests." Lightning and Static Electricity Conference, Culham Labs, England, April 1975.

10. J. Phillpott, "Simulation of Lightning Currents in Relation to Measured Parameters of Natural Lightning." Lightning and Static Electricity Conference, Culham Labs, England, April 1975.

11. R. I. Ewing, "Performance of the Sandia Lightning Simulator during F-14A and F/A-18 Aircraft Lightning Tests." This conference and SAND82-2276, June 1983.

12. R. A. Perala and C. C. Easterbrook, "An Overview of the F-14A and F/A-18 Lightning Tests." This conference, June 1983.

13. S. A. Goldstein, G. W. Barr, J. P. VanDevender, and T. H. Martin, "Considerations for the Design, Implementation, and Effective Operation of Sandia's Super-power Generators." 3rd IEEE International Pulsed Power Conference, Albuquerque, NM, June 1981.

14. T. H. Martin, J. P. VanDevender, G. W. Barr, S. A. Goldstein, R. A. White, and J. P. Seamen, "Particle Beam Fusion Accelerator-I (PBFA-1)." 1981 Particle Accelerator Conference, Washington, DC, March 1981.

15. R. A. White, "Modular Accelerator Interconnecting and Operating Systems for PBFA-1." 3rd IEEE International Pulsed Power Conference, Albuquerque, NM, June 1981.

16. W. K. Tucker, "A 3 Megavolt Sulphur Hexafluoride Trigatron." Sandia Laboratories, SC-DR-72 0506, September 1972.

17. H. W. Mathers, S. R. Sedore, and J. R. Sents, "SCEPTRE Support." IBM Corp., Contract F29601-67-C-0049 for AFWL, Kirtland AFB, NM, April 1968.

18. H. W. Mathers, "SCEPTRE (System for Circuit Evaluation and Prediction of Transient Radiation Effects)." IBM Corp., included in G. W. Zobrist, "Network Computer Analysis," Boston Technical Publishers, 1969.

19. D. W. Clifford,, K. E. Crouch, and E. H. Schulte, "Lightning Simulation and Testing." IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-24, No. 2, May 1982.

20. D. W. Clifford, E. P. Krider, and M. A. Uman, "A Case for Submicrosecond Rise-time Lightning Current Pulses for Use in Aircraft Induced Coupling Studies." IEEE International Symposium on Electromagnetic Compatibility, 79CH1383-9 EMC, San Diego, CA, October 1979.

21. J. A. Plumer and J. D. Robb, "The Direct Effects of Lightning on Aircraft." IEEE Special Issue, Transactions on Electromagnetic Compatibility, Vol. EMC-24, No. 2, May 1982.

22. B. Vonnegut, O. H. Vaughan, Jr., and M. Brook, "Photographs of Lightning from the Space Shuttle." Bulletin of the American Meteorological Society, Vol. 64, No. 2, Feb. 1983.

Fig. 2 – Double-pulse simulated lightning current waveform applied to full-size Navy jet airplane

Fig. 1 – A very severe lightning stroke idealized representation. Initial return stroke component A; intermediate current component B; continuing current component C
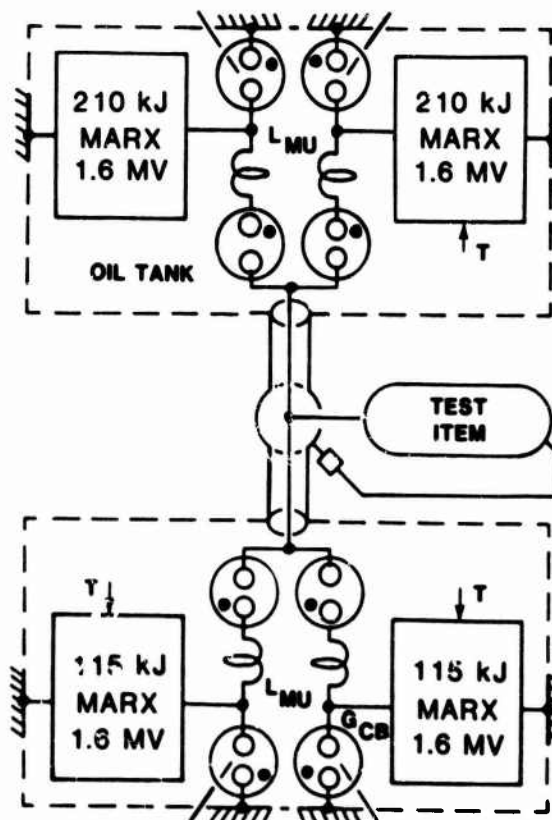
Fig. 3 – Simplified block diagram of one arrangement of lightning simulation system
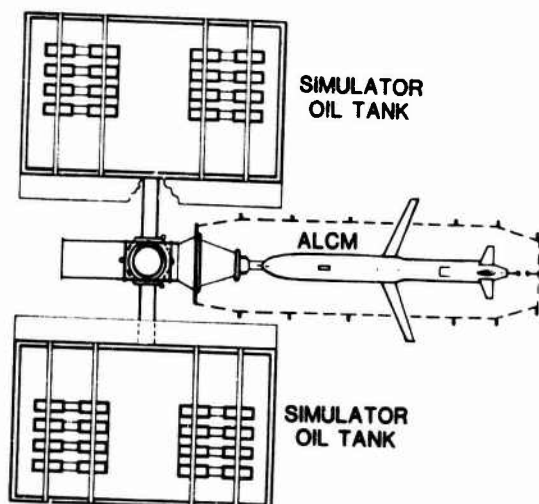
Fig. 4 - North and south oil-filled simulator tanks connected to test load and its return circuit

Fig. 5 - Navy Hornet F/A-18 aircraft enclosed with multicable return current circuit
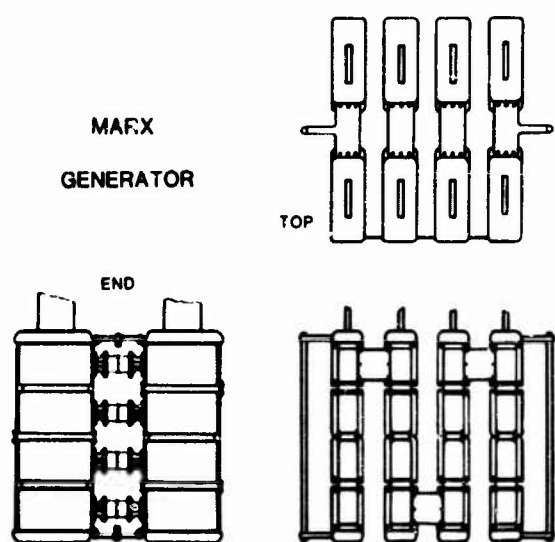
Fig. 6 - Typical SNLA pulsed-power Marx impulse generator modified for lightning simulator
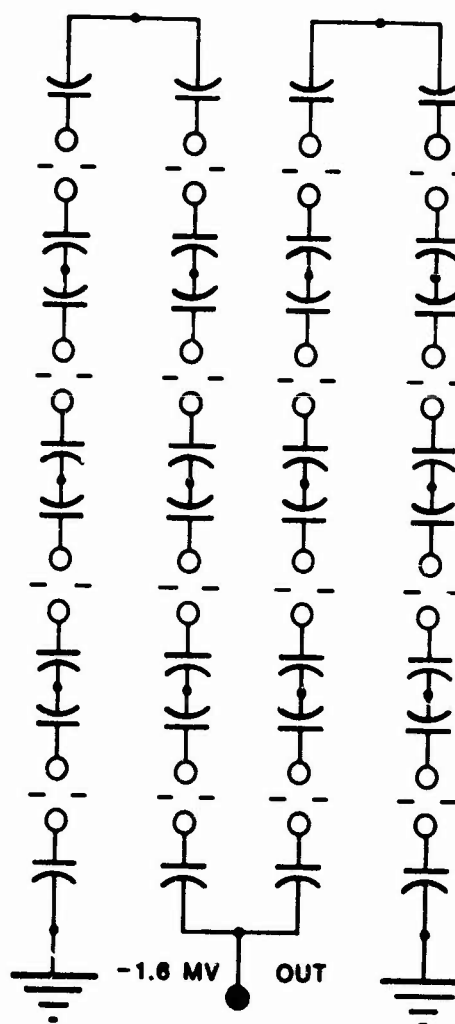
-1.6 MV   OUT

Fig. 7 - Bipolar Marx surge generator simplified charging diagram

65-13
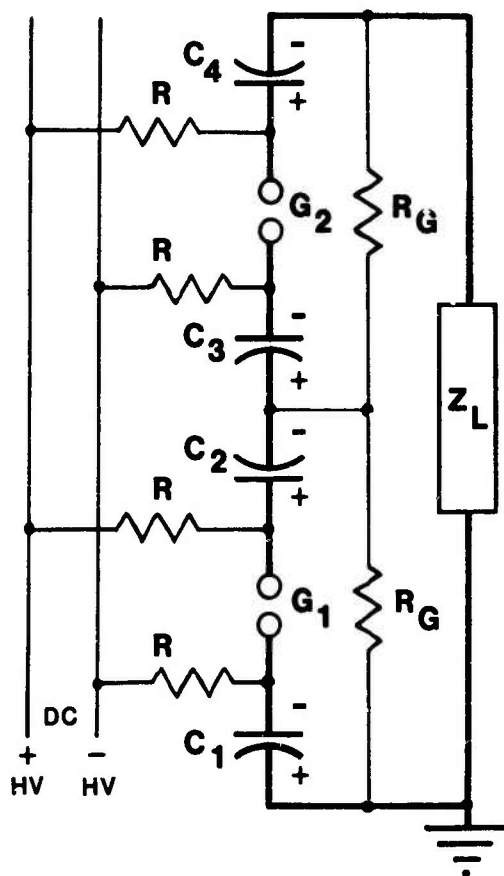
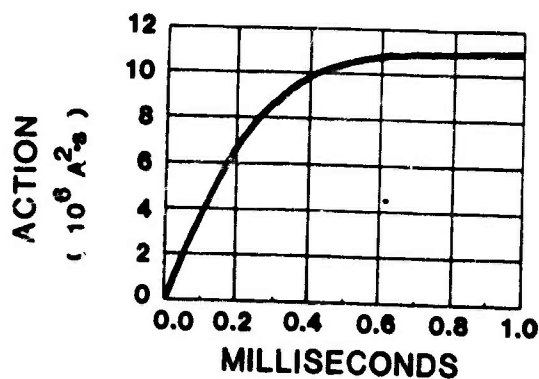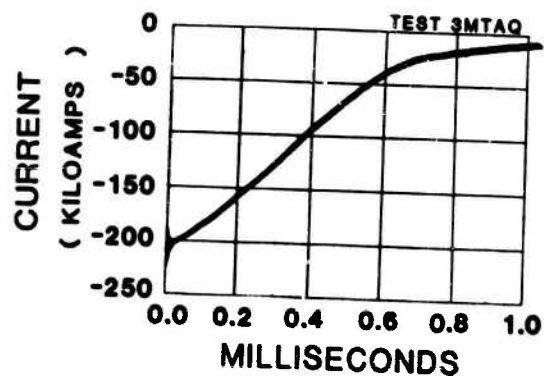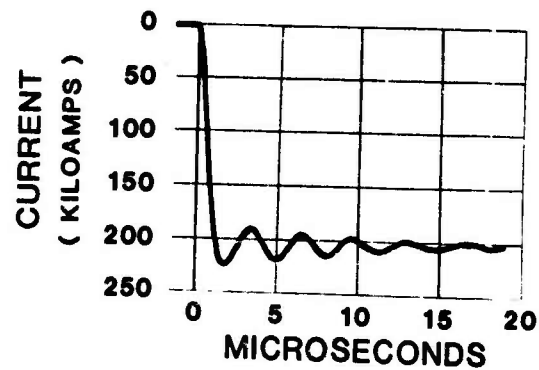Fig. 8 – Discharge path diagram of impulse
generator modified for lower 1.6-MV output

Fig. 9 – Very high 200-kA current and 1.1×10^7
$A^2 \cdot s$ delivered into low-inductance test load
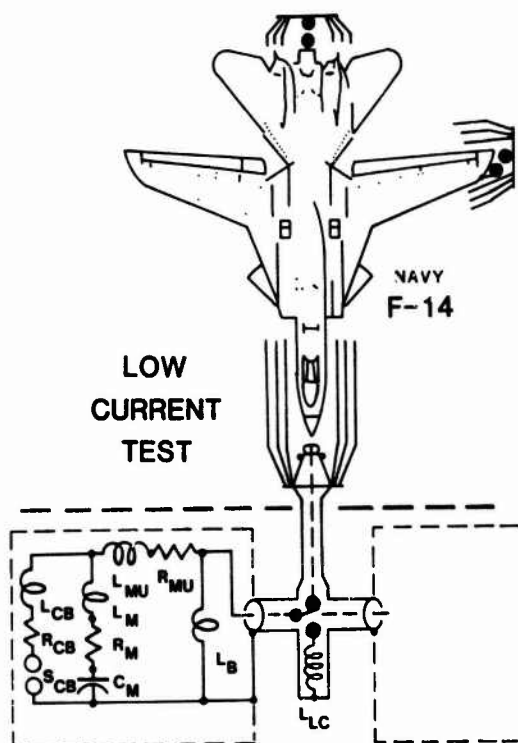
Fig. 10 - Full-size functional F-14 Navy Tomcat and crowbarred Marx simplified diagram with current bypass inductor L_B to ground
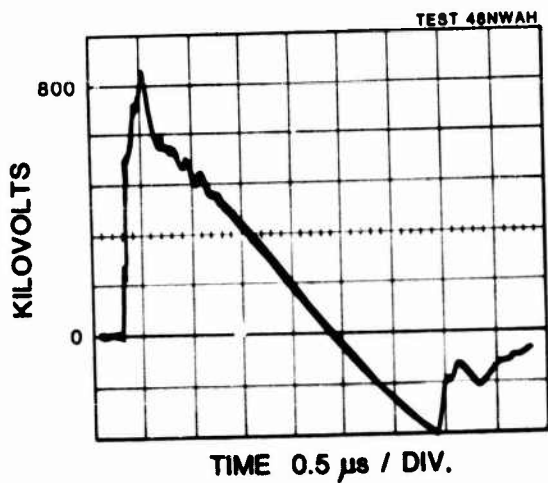
Fig. 12 - High-voltage pulse developed at nose of F/A-18 with 100-kA current pulse
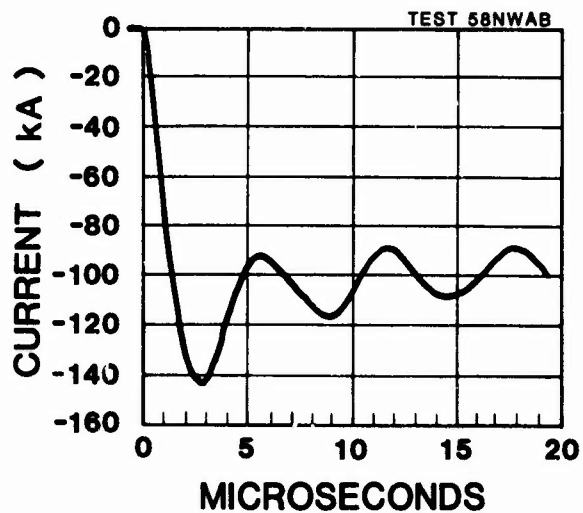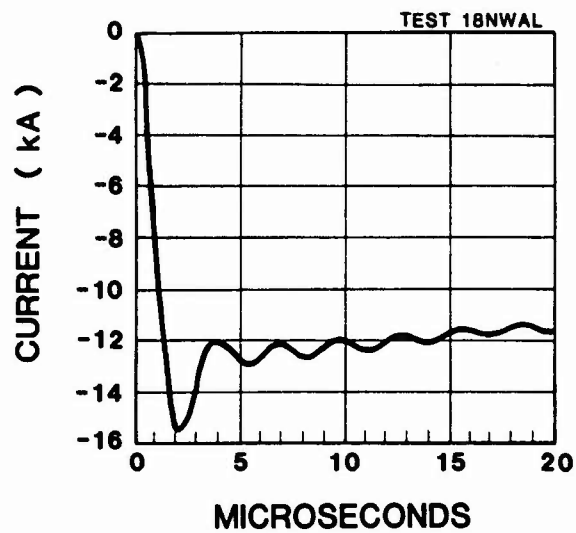
Fig. 11 - Low-current and high-current nose-to-wing pulses into F/A-18 aircraft
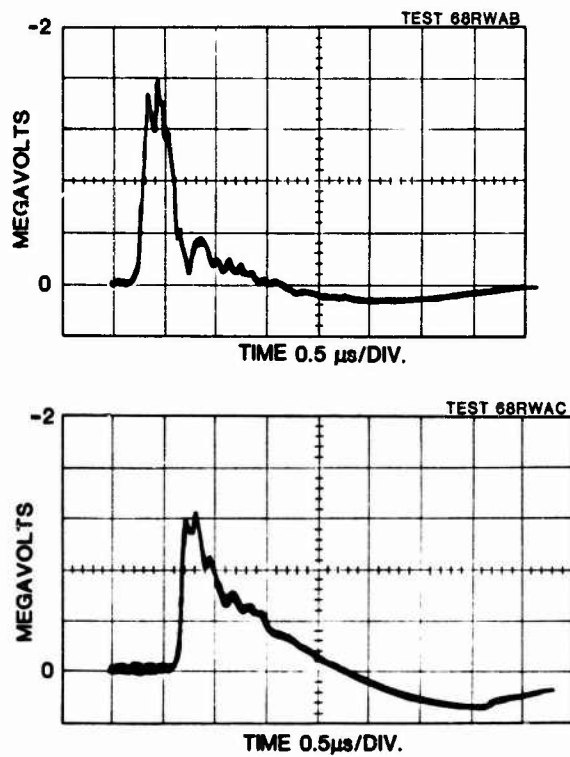
Fig. 13 - High-voltage pulses developed at full-scale aircraft
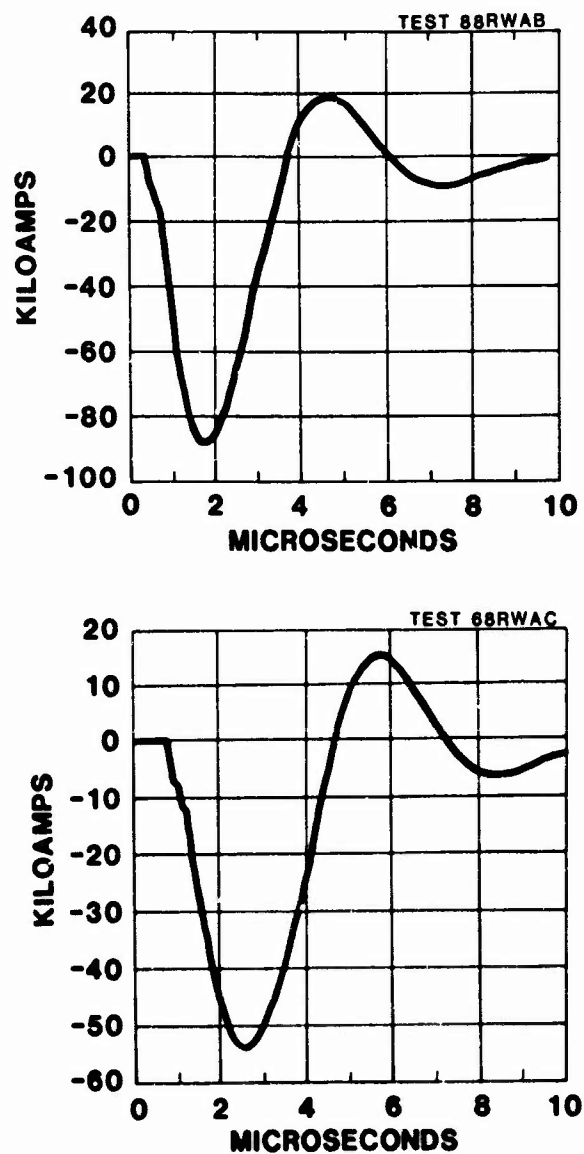
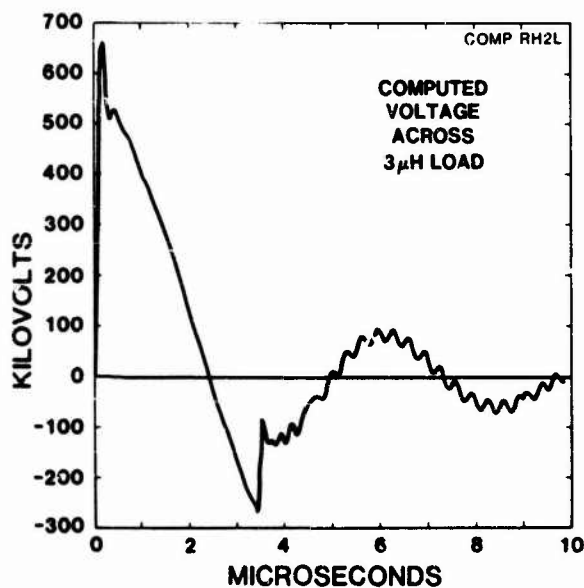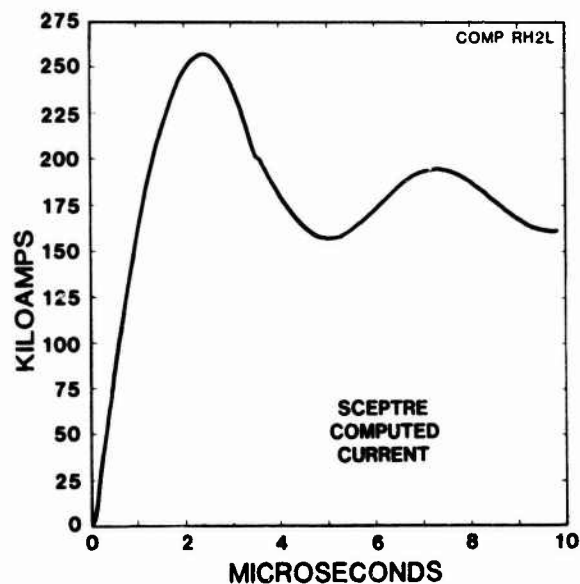Fig. 14 - Noncrowbarred current pulses corresponding to voltage pulses shown in Fig. 13

Fig. 15 – SCEPTRE-computed voltage and current for one simulator and load combination
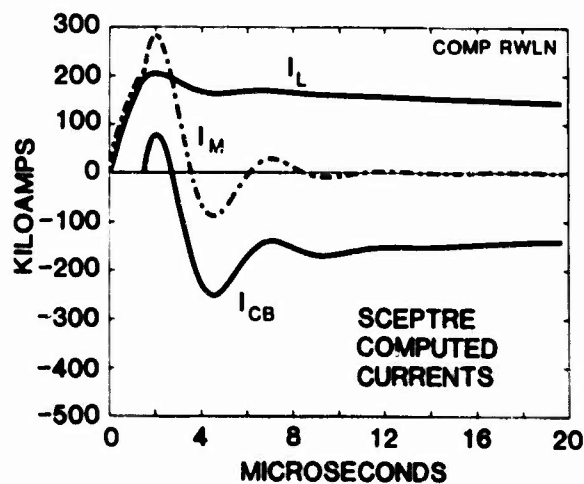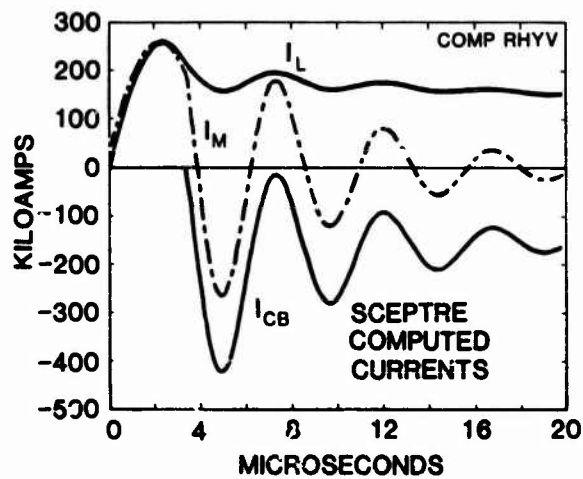

Fig. 16 – SCEPTRE-computed current waveforms for load current I_L, Marx current I_M and crowbar switch current I_{CB}. (Upper) Crowbar after peak current; (Lower) Crowbar before peak current and with 1 ohm added in Marx/crowbar loop