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Proceedings and Minutes of the National Interagency Coordination Group Meeting

National Atmospheric Electricity Hazards Protection Plan for Aircraft

December 8 - 9, 1981

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16. Abstract

The publication is a composite of the minutes and presentations given at the Third National Interagency Coordination Group meeting held at the Bergamo Center, Dayton, Ohio, December 8-9, 1981. The U.S. Air Force was the host agency with Mr. Gary DuBro participating in the capacity of chairman.

The presentations encompass both the active and anticipated programs from each agency plus formal presentations on the following subjects by guest speakers;

- Research on Electrical Properties of Severe Thunderstorms
- Sandia National Laboratories Lightning Simulation Facilities
- Lightning Strike Qualification Test of the U.S. Army
- Army Organization for Research and Development

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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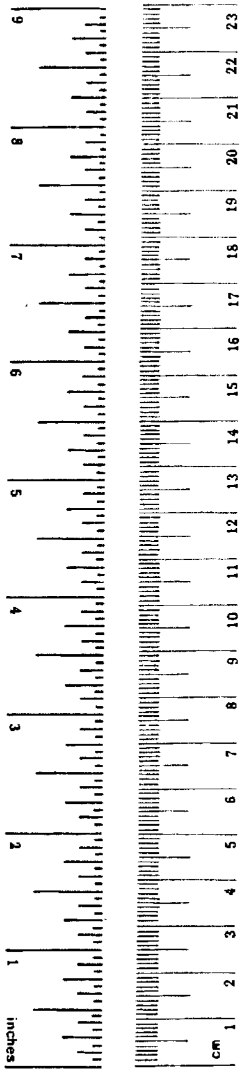
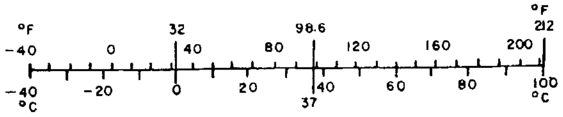
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CAVEAT

Considerable latitude was exercised in the literal transcription of the proceedings to obviate extensive delays in the publication of this document.

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EXECUTIVE SUMMARY

INTRODUCTION.

The third official meeting of the National Interagency Coordination Group (NICG) for Atmospheric Electricity Hazards Protection for Aircraft was conducted at the Bergamo Center in Dayton, Ohio, on December 8-9, 1981. The U.S. Air Force (USAF) was the host agency with Mr. Gary DuBro as chairman.

The primary purpose of the meeting was to complete required action on the National Atmospheric Electricity Protection (NAEHP) Management Support Plan, delineate the feasibility/practicality of having a dedicated national ground lightning test facility and a national airborne lightning measurement laboratory.

BUSINESS.

The meeting was formally opened by Mr. G. DuBro with a brief overview of the minutes from the previous meeting. The minutes were accepted as written.

The next item of business was a determination for the need for a dedicated national airborne lightning laboratory to supplement the F-106B aircraft. The committee established the requirement for at least one more aircraft to supplement the program. The addition of this aircraft would provide the USAF with a vehicle to continue the lightning research presently being conducted in Florida. The limited resources within the NICG agencies seriously impact the probability of requiring an additional aircraft at this time.

A detailed history, including the present status, of the Management Support Plan was reviewed. The committee agreed that the Management Support Plan was restricted to support the Advanced Development Program (ADP), and as the ADP was an ongoing program, the value of the Management Support Plan had been greatly diluted. The committee agreed to delete the Management Support Plan.

The feasibility and practicality of having a dedicated national aircraft lightning test facility was discussed in detail. The committee demonstrated a definite interest in this project but questioned the impact it would impose upon independent testing laboratories. Also, the committee members were not cognizant of existing capabilities within the United States.

Mr. L. Walko presented a review of existing atmospheric electricity hazards simulation test facilities in the free world. Mr. Walko was given an action item to update this list prior to the next scheduled NICG meeting.

Mr. DuBro was given the following two action items:

1. Coordinate the effort to determine facilities (physical plant) required to assure that simulated lightning tests can be satisfactorily accomplished on full-scale aircraft.

2. Conduct a survey to determine resources necessary for item number 1 above, including initial costs, operating costs (manpower and money) to satisfactorily operate the national ground lightning test facility.

An announcement was made that Culham Laboratory will host the 1982 International Aerospace Conference on Lightning and Static Electricity, March 23-25, 1982. Support from the committee was encouraged.

The NICG in concert with the Florida Institute of Technology will host the conference in 1983. The conference is tentatively scheduled for April 1983. Mr. Rasch was given an action item to coordinate with the Naval Air Systems Command on this item.

An overview of agency interests and areas of concern, which delineate the various agencies functions in a national research effort, was accomplished on each specific agency's programs including general details.

New business entailed the following:

- Mr. Hall recommended that the meetings be held annually. The committee agreed and Mr. Rasch was given an action item to modify the Interagency Management Plan to comply.

- Mr. Rasch was selected to participate as the NICG Secretariat for the next 2 years.

- Mr. Pitts recommended that future minutes of the NICG meetings have limited distribution. The information should be restricted to NICG members and invited guests only.

The next NICG meeting has been scheduled for January 1983. The meeting will be held at the NASA-Langley Research Center, Hampton, Va; with Mr. Pitts participating as chairman.

The members agreed that the retreat type atmosphere provided at the Bergamo Center was excellent. This minimized distraction and permitted the committee an opportunity to maximize accomplishments. This type of atmosphere is recommended for all future meetings.

Sandia Lightning Simulator

J. C. Bushnell, Sandia Laboratories Div. 1554

The Sandia Lightning Simulator has been built to produce currents as the levels of severe natural lightning. The simulator can produce up to 4 strokes per flash, plus a continuing current component. At 3 strokes per flash the output current for the first stroke rises to a peak current of 200 kiloamp in 2 microsec, and then decays with a 75 microsec time constant. Succeeding pluses have the same time characteristics and peak currents on the order of 100 kiloamperes, with arbitrary time spacing between pluses. The continuing current capability is 300 amperes for 1 second.

The simulator uses a unique crowbar design to allow good energy efficiency. The continuing current is provided by two diesel locomotive traction motors wired as generators with basic output of 1 kilovolt and 1 kiloamp. The Marx generators used to produce the high current strokes are oil insulated and of the same design as is used in the Sandia Particle Beam Fusion Accelerator.

Natural Lightning Characteristics

Natural lightning is a highly complex phenomenon, and there are many aspects of the details of natural lightning which are poorly understood. This situation exists largely because of the difficulty of studying a natural phenomenon which occurs relatively rarely and in locations which in general cannot be accurately predicted.

The individual lightning event is a flash, which is composed of a number of high current strokes, and in many, but not all cases, a continuing current component which is of much lower amplitude but much longer duration than the individual strokes. The strokes, which together constitute a lightning flash, follow the same channel through the atmosphere because the ionization produced by the first stroke provides a preferential path for breakdown for the following strokes. Swept strokes occur; e.g., on an airplane, because the lightning channel is fixed relative to the air, but moving with respect to the airplane.

Most lightning flashes occur cloud-to-cloud or intracloud, but those which occur cloud-to-ground are more apparent because they are not hidden by intervening clouds. The initiation of the first stroke in a lightning flash is through a stepped leader, which ordinarily proceeds, in the case of a cloud-to-ground flash, from the cloud in discrete steps of 50-100 meters. The return stroke is initiated when the stepped leader approaches the ground, and it is during the return stroke that the large currents typical of a lightning flash occur. A dart leader precedes the subsequent strokes in a lightning flash, and follows the residual ionization path left after the first return stroke.

Each stroke in a lightning flash rises rapidly to its peak current and then decays, in general, in a nonexponential fashion towards zero. The nature of the decay is commonly described as consisting of an initial decay portion followed by an intermediate current phase of slower decay time. The continuing current may be present between individual strokes or may begin after the last stroke.

The parameters of natural lightning are highly variable, and the correlations between them is poorly understood, and a complete description of natural lightning is not possible. The basic parameters of a lightning flash are the number of individual strokes, the time intervals between them, the rise time of the strokes, the decay time of the strokes, the peak current of the strokes, and the level and duration of the continuing current when it is present.

Because of the statistical nature of lightning, these parameters must be described statistically. The most common way is in terms of percentile values. The 99 percentile level, rather than being that exceeded numerically only 1 percent of the time, is instead taken here to mean the most severe end of the range; e.g., the 99 percentile value for the rise time is less than the 50 percentile value, rather than the upper limit. These values are taken from Cianos and Pierece, "A Ground Lightning Environment for Engineering Usage."

The principal concern in the effects of lightning is the damage which may be produced. Here the extreme lightning flash is of most concern, although the fraction of time (percentile value) which should be used is of course a matter of judgment.

Sandia Lightning Simulator Design Characteristics

The design characteristics of the Sandia lightning simulator have been chosen as much as possible to match the 99 percentile levels of natural lightning, with the exception of the number of strokes. Present technology does not allow the production of lightning flashes at the 99 percentile level for all the pertinent characteristics, and a choice must be made to give a design which is both technologically and economically feasible. It is expected that there are some significant correlations between the various parameters. In fact, the simultaneous occurrence of all the values exceeded only 1 percent of the time individually, and taken together, represent a flash whose severity in terms of damage occurs much less often than 1 percent of the time. Since such correlations are so poorly understood, a detailed analysis of this question is not possible at this time.

A combination of basic and derived parameters may be used to represent lightning flashes. Those used for the Sandia simulator are: The stroke rise time, number of strokes per flash, peak current in a single stroke, action integral (the integral of the square of the current with respect to time), and total charge transferred.

Some simple analyses show that this set of parameters is reasonable for describing the severity of lightning effects. The rise time is important because the coupling through apertures increases with decreasing rise time and correspondingly greater high frequency content. The number of strokes is important because of the synergistic effects which may occur because the first of a series of strokes produces initial effects which allow significant damage to occur on later strokes. The peak current is important because it determines the maximum magnetic forces which a structure may experience. The action integral is important because when resisting heating damage effects are expected, the action integral times the resistance gives the deposited energy. Finally, the total charge transferred is important in such phenomena as burn-through when a plasma is formed at the surface, since, in this case, the energy deposited is proportional to the total charge times the plasma voltage drop.

It is also important to simultaneously produce significant components of all of these parameters because of the synergistic effects which can occur in natural lightning, which contains all of these effects. Separate simulations at different times are not able to explore these combined effects.

The estimated voltages between cloud and ground are on the order of 100 megavolts prior to the lightning flash, and initiate the stepped leader percursor to the return stroke. The electric field gradients which exist just before initiation of the return stroke can be quite large, and are certainly substantial contributors to the aperture coupling to sytems, but are perhaps less important in terms of direct-strike lightning damage than the return stroke currents. It is for this reason that emphasis is given in the simulator design on the return stroke simulation.

The electric fields existing before the return stroke have substantial similarities to NEMP, so the EMP tests may be expected to be pertinent to this kind of vulnerability.

Basic Circuit Design

The capability to produce the levels required is made possible by a circuit concept which has not previously been used for lightning simulation, although the general concept has been studied extensively for other purposes. The key to the circuit used in the Sandia lightning simulator is the use of a crowbar switch across the Marx generator used to supply the high voltage required to produce the high current levels in an external load. The use of a crowbar switch produces an essentially nonlinear circuit in which, before closure of the crowbar switch, the circuit is a lightly damped L-C circuit, while after closure the circuit becomes an L-R circuit. The circuit concept is shown in figures 1 through 4.

With this design, the lightning current rise time is dependent upon the product of the Marx capacitance and the total circuit inductance, which is a series combination of the external load inductance (equipment under test), the intrinsic Marx inductance, the interconnection inductance, and the deliberately added inductance to provide the desired current rise time (figure 5).

The decay time of the current is then determined by the ratio of the total circuit inductance to the total circuit resistance. With a total circuit inductance on the order of 9 microhenries, a total circuit resistance on the order of 0.1 ohms is required to give a decay time on the order of the desired value of 75 microseconds. A value this low turns out to be well within achievable ranges (figure 6).

The circuit used for the Sandia lightning simulator may be contrasted with those used in most other lightning simulators, which are variations of a straightforward R-L-C circuit, in either the underdamped, critically damped, or overdamped configurations, which can produce some of the relevant characteristics.

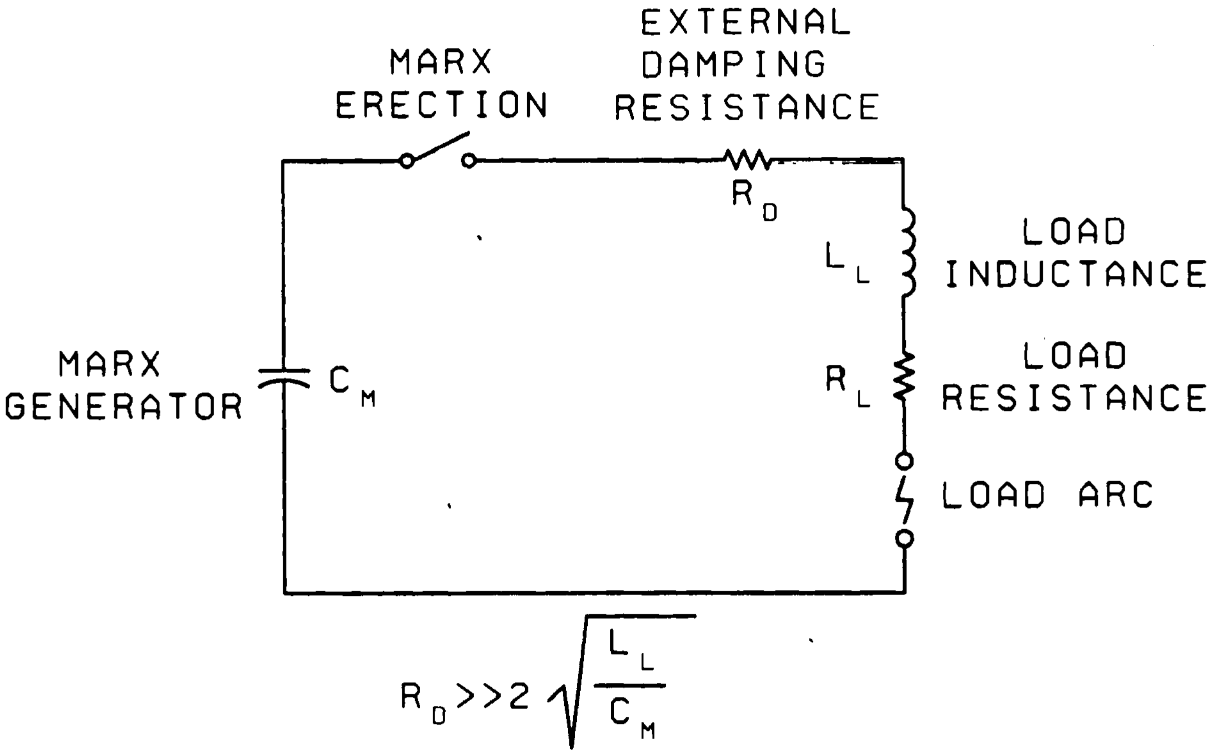
The underdamped circuit can provide the rise times and action integral desired with a practical circuit, but the current waveform is oscillatory rather than unipolar as in natural lightning, and is deficient in that respect.

The critically damped circuit gives a unipolar waveform, but the decay time-rise time ratio is much smaller than found in natural lightning.

The overdamped circuit is capable of producing the desired wave shape. To produce simultaneously the current rise time, decay time, and peak current of the Sandia simulator however requires a rather large damping resistance, and the stored energy which must be supplied is prohibitively large. Consequently, overdamped circuits are used to provide fast rise times with low current levels or slow rise time with high current levels, but not both fast rise times and high current levels together.

The nature of the circuit used in the Sandia lightning simulator obviates the requirement for a large damping resistor, and the resulting energy efficiency is approximately two orders of magnitude better than an overdamped circuit with essentially the same output charcteristics.

The crowbar circuit requires a low inductance voltage source to drive the peak current through the external load inductance, since the peak current obtainable is the initial voltage times the square root of the C/L ratio of source capacitance to total circuit inductance.



$$R_D >> 2\sqrt{\frac{L_L}{C_M}}$$

FIGURE 1. BASIC OVERDAMPED CIRCUIT

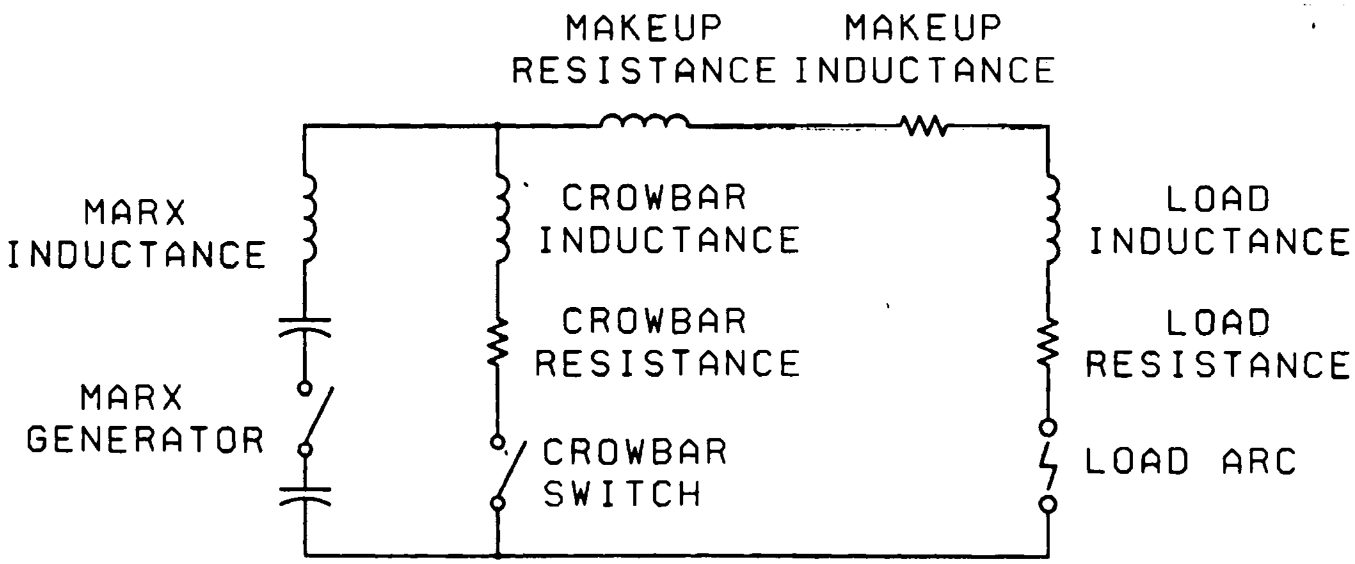
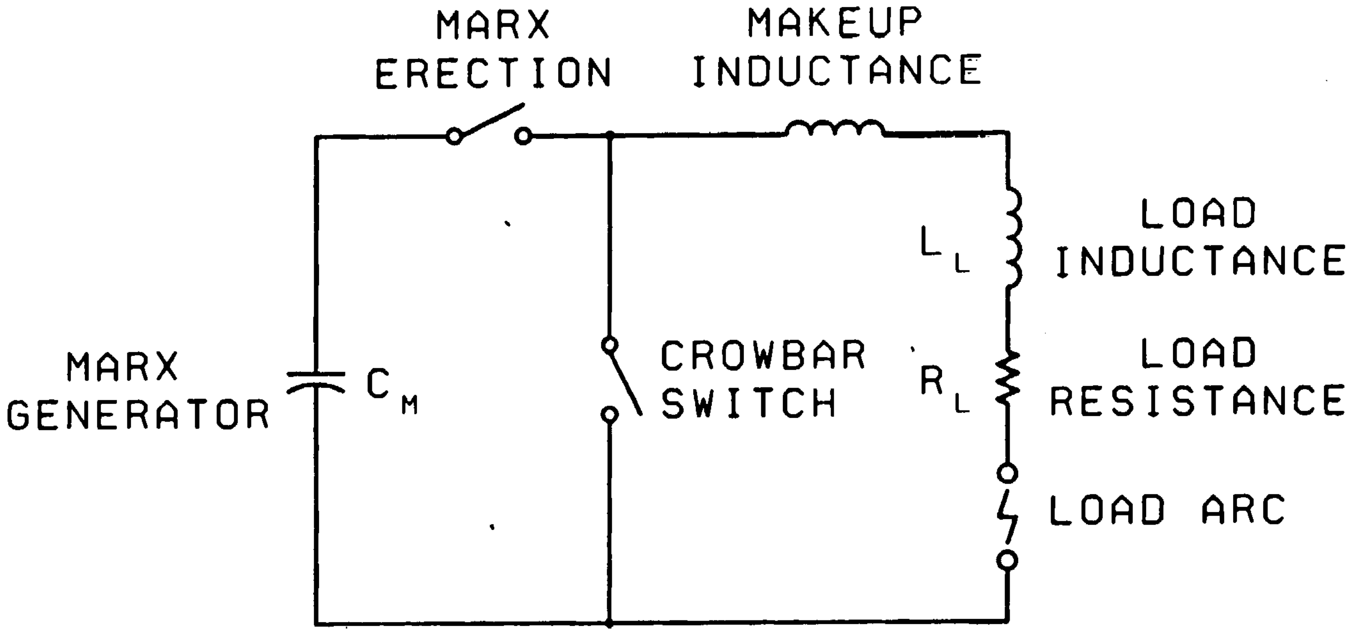


FIGURE 2. CROWBARRED CIRCUIT



$$R_L << 2\sqrt{\frac{L_L}{C_M}}$$

FIGURE 3. BASIC CROWBARRED CIRCUIT

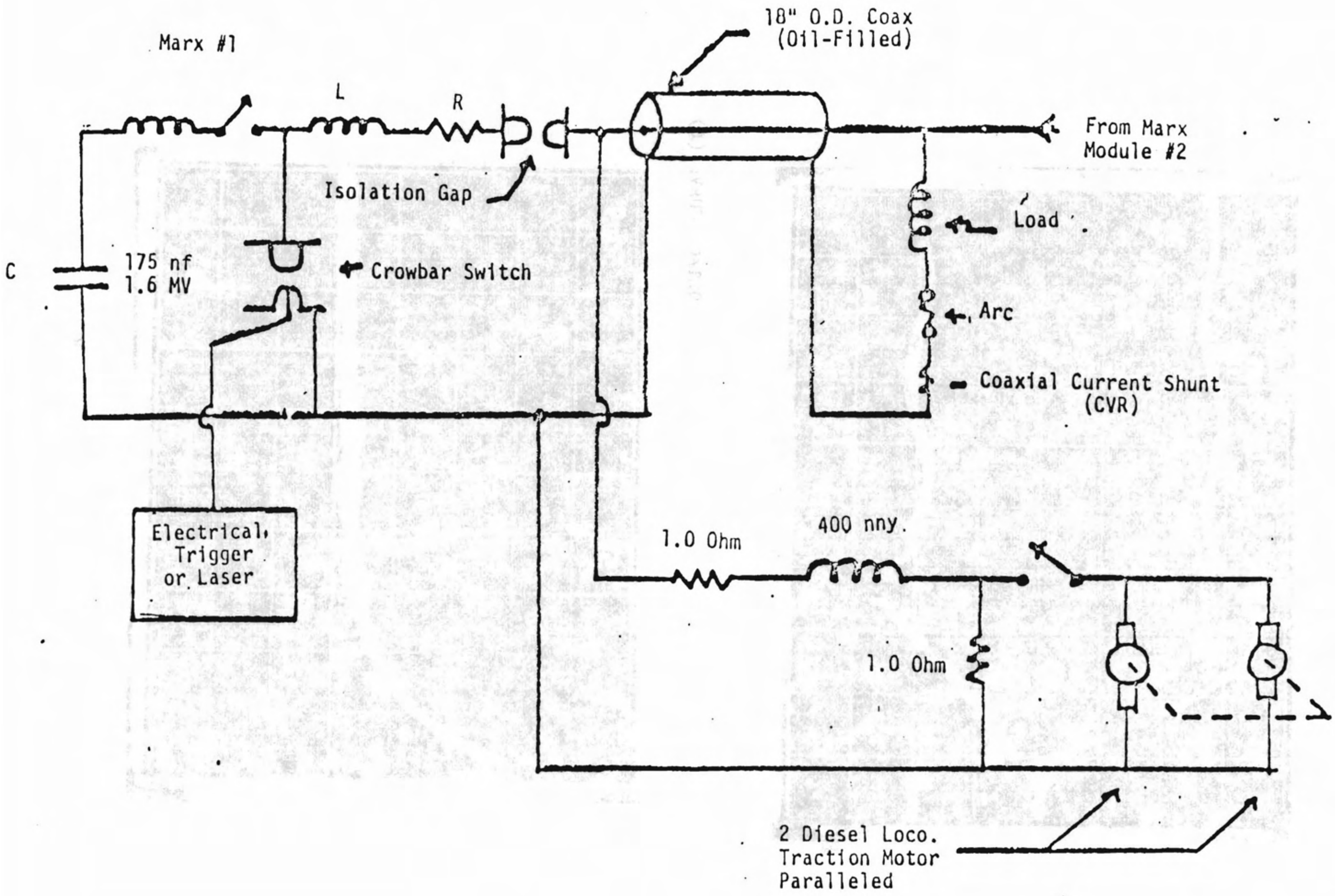


FIGURE 4. LIGHTNING SIMULATOR CIRCUIT

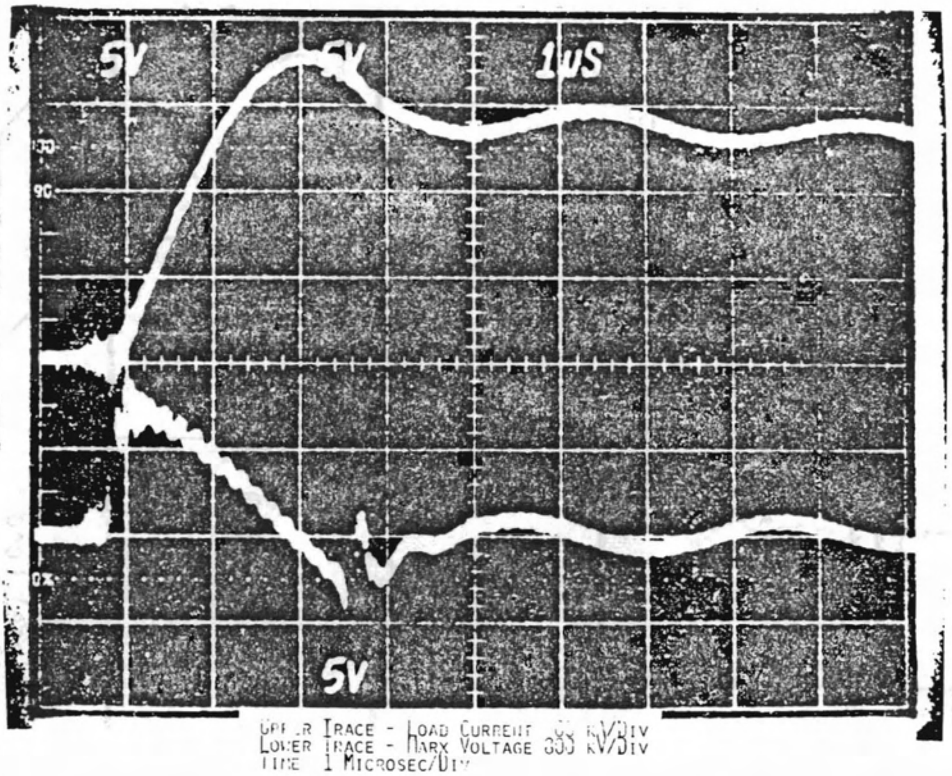


FIGURE 5. FAST CURRENT RISE TIME WITH CROWBAR (A) VOLTAGE CURVE (B)

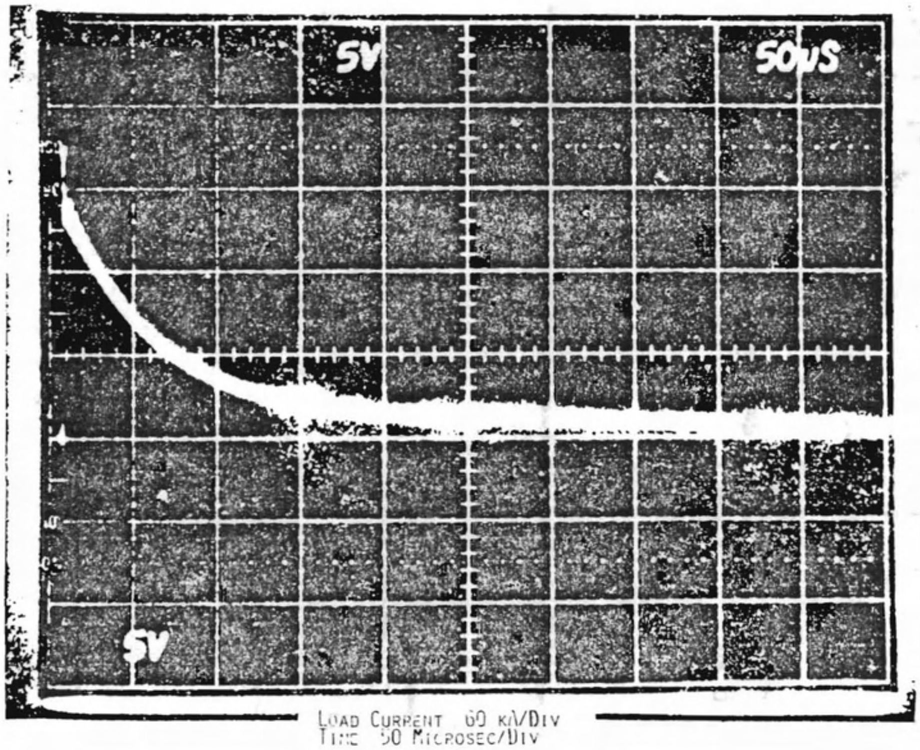


FIGURE 6. CURRENT DECAY WITH CROWBAR

A Marx generator is a high voltage generator consisting of a number of capacitors which are charged in parallel and connected in series by spark gaps. Initially, the spark gaps are open circuits, and an external power supply is used to charge the capacitors to a common voltage. When the Marx generator is fired (erected) one or more spark gaps are triggered, and the untriggered spark gaps are rapidly fired by overvoltage. The resultant configuration is a series configuration in which the capacitance is the series combination of the capacitors, and the voltage is the original charging voltage times the number of capacitors connected in series.

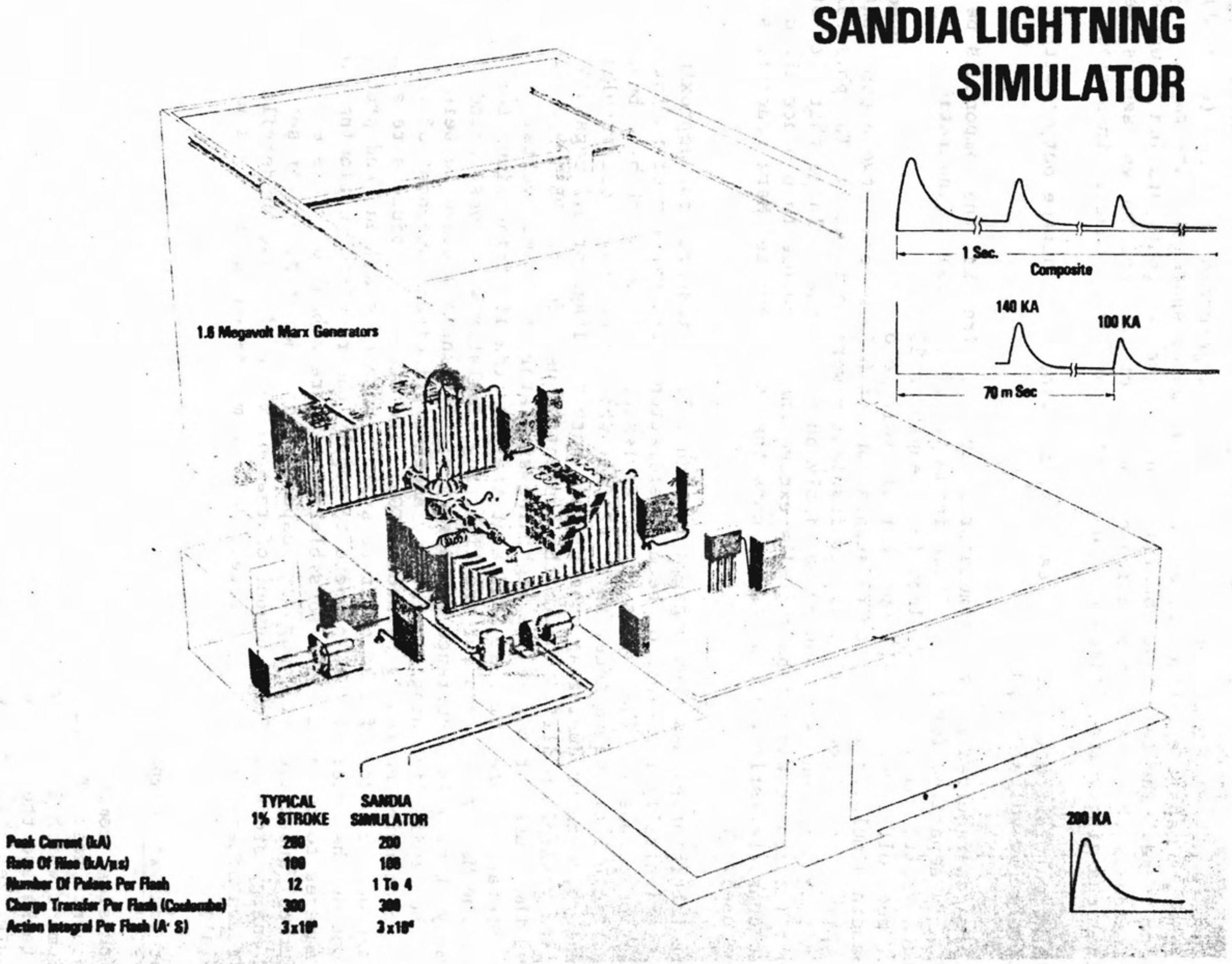
A voltage multiplication is thus realized, allowing high voltage output with relatively low voltage input.

The voltages required for the simulator circuit require that the components be physically separated for high voltage insulation. The easiest insulation to provide is air, which has a dielectric strength of 25 kV/cm. Voltage standoff of 1.6 megavolts, which is the open circuit voltage of the Marx generators used in the Sandia simulator would require separations of 0.64 meters between components with this voltage between them if air insulation were to be used. The physical size of the Marx generator would then imply an inductance so large that the total circuit inductance would substantially exceed that allowable to produce the desired output characteristics. This result means that air insulated Marx generators could not be used.

Sandia Laboratories has been engaged in high voltage research for approximately 20 years, principally for electron beam acceleration for a variety of radiation simulation purposes. The latest in the series of machines which have been built is the Particle Beam Fusion Accelerator (PBFA), which contains 36 oil insulated Marx generators, each producing an open circuit output voltage of 3.2 megavolts. A relatively simple modification to the connection used for the PBFA Marx generators allows their use for the Sandia lightning simulator at 1.6 megavolts. Since these Marx generators were built at Sandia at the time the lightning simulator was being built, the Marx generators for the lightning simulator were constructed on the assembly line. This occurrence was a very significant advantage in being able to build the Sandia lightning simulator. Another principal component of the simulator is the continuing current generator (CCG). The CCG must produce a relatively low voltage on the order of 1 kilovolt to sustain an arc to a load, and produce output current on the order of 1 kiloampere to supply the required continuing current of 300 amperes to the load. The possible sources are a bank of storage batteries, an electrical substation of 1 megawatt capacity, or a motor-generator set with inertial energy storage. For a number of reasons which will not be detailed here, the first two alternatives were rejected, and the motor-generator set is used in the simulator.

Major Facility Components

The physical components of the simulator are next described. The principal components are: The building in which the simulator is housed, the high voltage equipment which is located in oil-filled tanks, the "load-ring" interconnecting the oil tanks and the equipment under test, the continuing current generator, the computerized instrumentation system used for data acquisition and control, and the exterior test area in which tests of items too large to fit in the building are conducted. These items are next described in the order given. A drawing of the facility is shown in figure 7.



	TYPICAL 1% STROKE	SANDIA SIMULATOR
Peak Current (kA)	200	200
Rate Of Rise (kA/μs)	100	100
Number Of Pulses Per Flash	12	1 To 4
Charge Transfer Per Flash (Coulombs)	300	300
Action Integral Per Flash (A· S)	3×10^6	3×10^6

FIGURE 7. SANDIA LIGHTNING SIMULATOR FACILITY

Building. The building (Sandia Laboratories Building 888) was constructed specifically to house the lightning simulator. It consists of five rooms: The high bay containing the high voltage components and the test object, the control room housing the computer and data acquisition and display equipment, the CCG room containing the CCG and associated equipment, the pump room housing pumps, and oil filtration equipment, and a light lab and desk space for some of the personnel working in the facility.

The high bay has interior dimensions of 50 feet x 60 feet x 30 feet high. A bridge crane of 6-ton capacity and a maximum hook height of 22 feet above ground level can essentially traverse the entire high bay floor area. In the high bay are located the two oil tanks containing most of the high voltage components, the load ring where experiments are mounted; the high voltage power supplied for charging the Marx and trigger generators; gas handling equipment for pressurizing the Marx generator gaps and crowbar switches; and a 10 feet x 7 feet screen room for collecting some of the data relating to facility operation. The high bay is lined with metal screening to reduce emanation from the high voltage equipment to the outdoors when the simulator is fired (figure 8).

The control room is also lined with metal screening and in addition has an interior 10 feet x 20 feet screen room which holds the computer for data acquisition, analysis and display. There are four plastic conduits running underneath the floor, three of which connect to the high bay area with the fourth connecting to the CCG room.

The CCG room houses the CCG itself, its motoring supply and the contactor used for connection to the high voltage circuitry.

The pump room contains two independent pumping and filtration systems for the oil tanks, with connection to two external buried tanks each of 20,000 gallon capacity for oil storage when the high bay tanks must be drained for maintenance or circuit changes. Valving is included so that either pumping and filtration system may be used with either high bay oil tank. Emptying of the high bay oil tanks is by gravity, and takes about 25 minutes, while filling is done through the pumps and takes about 2 hours.

Oil Tank High Voltage Circuitry. The following is a description of the physical configuration of the various items, beginning with the most important, which is the high voltage circuitry in the oil tanks.

The two oil tanks are each 12 feet wide, 21 feet long, and 10 feet high in inside dimensions. Each tank was buit as three 12 feet x 7 feet x 10 feet sections welded together after installation. The pump and drain connections are through holes in the bottom of the tanks. The capacity of each tank is approximately 17,000 gallons.

The principal components inside the oil tanks are the Marx generators, the crowbar switches, the make-up inductances used to set the total circuit inductance, the trigger generators used for erection of the main Marxes and the crowbar switches, gas isolation switches to minimize interaction between different Marx generators and the isolation/interconnection circuit between the high voltage components and the CCG (figure 9).

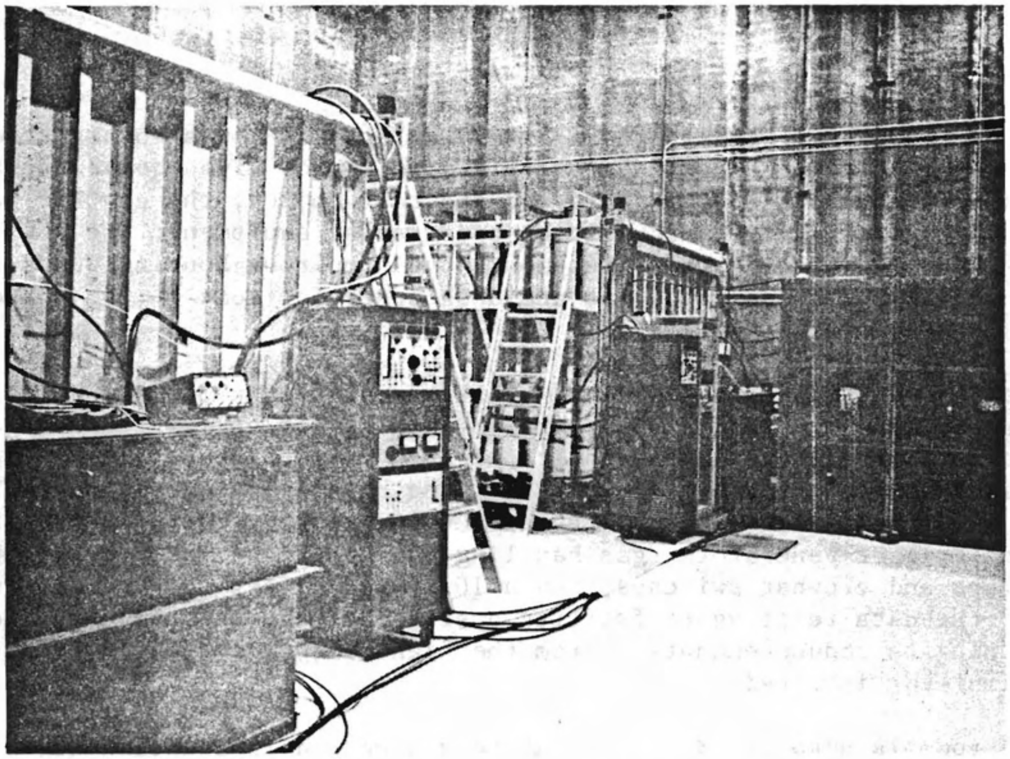


FIGURE 8. HIGH BAY AREA WITH TWO OIL TANKS AND LINED METAL SCREENING

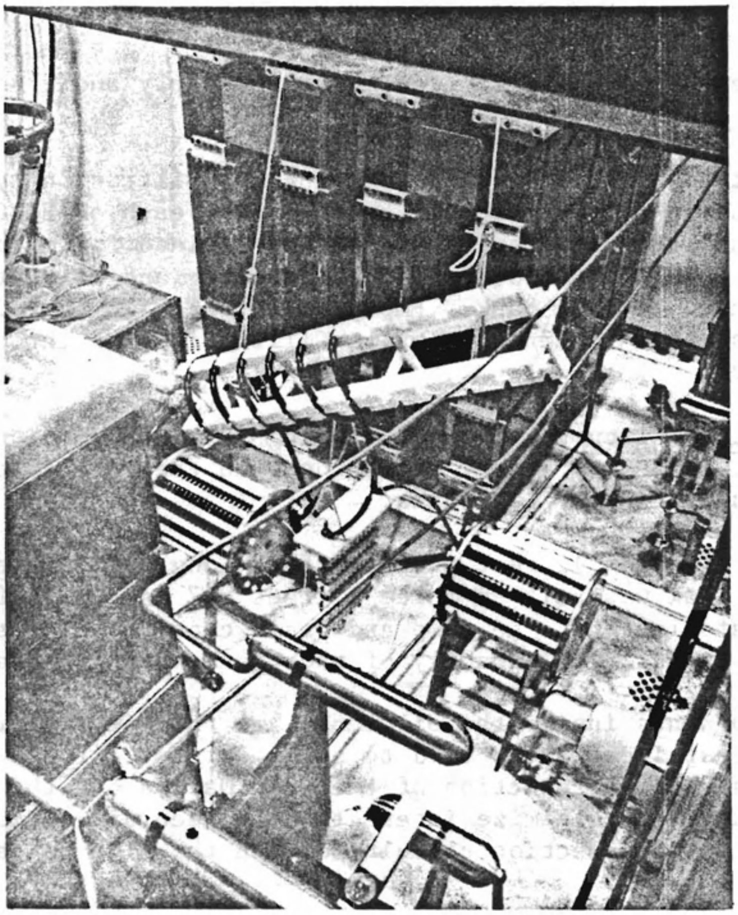


FIGURE 9. PRINCIPAL COMPONENTS INSIDE THE OIL TANK

The four Marx generators used to produce up to four outputs are located two each in the two oil tanks. Each Marx generator has 32 capacitors or 0.7 microfarad capacitance with a maximum charge voltage of 100 kilovolts for a total stored energy of 112 kilojoules per Marx, or 448 kilojoules for all four Marx generators. The 32 capacitors are arranged when erected as two parallel stacks of 16 capacitors, providing an open circuit voltage of 1.6 megavolts with an effective capacitance of 87.5 nanofarads. The Marx generators are charged with dual polarity power supplies, because in this configuration one spark gap switch is required for every two capacitors, while with single polarity power supplies, a spark gap is required for each capacitor. The internal Marx inductance for each Marx is approximately 1.5 microhenries and is substantially lower than would be possible with single polarity charging.

The spark gaps are of symmetrical construction with a mid-plane triggering electrode. With the +/- charging scheme, the DC voltage across each spark gap is 200 kilovolts, with the mid-plane triggering electrode initially at ground potential. The spark gaps are pressurized with sulfur hexafluoride at a pressure dependent upon the charge voltage, but typically on the order of 30 psi gauge pressure. The trigger generator which initiates the Marx erection is itself a small 6-stage Marx with a nominal open circuit of 400 kilovolts when connected to the main Marx gaps. The Marx trigger voltage is fed to each gap through 2 kilo-ohm resistors. The trigger Marx generators are located near the main Marx generators inside the oil tanks.

Using a single 32 capacitor Marx with initial charge voltage of 100 kilovolts and a total circuit inductance of approximately 19 microhenries, a peak output current of 100 kiloamperes may be obtained with the sine wave current wave shape rising to its peak value in 2 microseconds. In principle, a single Marx with a total circuit inductance of 9 microhenries can produce output currents of 140 kiloamperes peak with a rise time of 1.4 microseconds. In practice, because of crowbar limitations, this level is difficult to achieve routinely.

The design peak output current of 200 kiloamperes is obtained by the parallel connection of two Marx generators with a total circuit inductance of 9 microhenries. When the full output current is desired, three pulses rather than four are obtainable because two of the Marxes are required to produce the first 200 kiloampere pulse.

The series inductance of the Marx generators, the interconnection inductance and the load inductance is normally less than the desired value of 9 microhenries. In order to give a total circuit inductance of 9 microhenries, a make-up inductance is normally included in series with the output connection. This inductance is also located in the oil tank, and is a multi-turn inductor of diameter approximately 12 inches and inter-turn spacing of approximately 3 inches. The make-up inductance is constructed either of RG-218 cable with shield tied to the center conductor or of stainless steel when a resistive inductor is required.

The crowbar switches are approximately 24 inches long and 24 inches in diameter. The end electrodes are insulated from each other by lucite rings with aluminum spacers to provide capacitive grading of the voltage. The end plates are of aluminum, and the electrodes have hemispherical ends made of stainless steel and are 3.5 inches in diameter. The crowbar design is essentially the same as used for the isolation switches in PBFA.

Closure of the crowbar switches is initiated either electrically or by a pulsed laser. When electrical triggering is used, the crowbar design is a trigatron configuration in which a 1/4-inch diameter hole is drilled through one electrode, and a tungsten electrode of 0.15-inch diameter is centered in the hole flush with the end of the electrode and electrically insulated from it. To initiate crowbar switch closure, a Marx generator identical to those used to erect the main Marxes is used to supply a trigger pulse to the trigger pin. An arc is formed between the trigger pin and the electrode in which it is mounted, in turn causing breakdown of the main interelectrode gap and shorting out the Marx generator across which it is connected. The crowbar is pressurized with sulfur hexafluoride gas at a pressure on the order of 90 psi gauge.

The alternative method for triggering the crowbar switches is by use of a pulsed laser. The configuration used for laser triggering is the same hole in one electrode, but no trigger electrode. The laser is mounted outside the oil tank, and the laser output light is focused by a lens mounted inside the electrode so that the focal point is in the gap between the two electrodes. The laser beam produces ionization of the gas in the gap, initiating closure of the crowbar switch. The lasers used are Nd-doped glass, pumped by flash lamps, and Q-switched by a Pockels cell mounted between crossed Brewster angle polarizers. When the appropriate voltage pulse is applied to the Pockels cell, a rotation of the plane of polarization of the light is produced and the round trip gain of the laser cavity becomes greater than unity, giving an output pulse from the laser. The output wavelength is 1060 nanometers, and the output pulse duration is approximately 20 nanoseconds FWHM, with a maximum pulse energy of 3.5 joules.

The beam divergence of the laser is approximately 5 milliradians, appreciably larger than the diffraction limit. The laser must be mounted close to the crowbar switch to limit beam spreading and consequent loss of light transmitted through the limited aperture in the crowbar switch. In order to avoid sympathetic triggering of the laser electronics on erection of the main Marxes, the laser flash lamp power supplies and thyratron Q-switching electronics are located in the control room.

Since in multiple pulse operation of the lightning simulator, all Marxes used must be charged before erection of the first one, it is necessary to provide isolation between the Marx generators, so that the erection of one Marx does not in turn cause erection of other Marxes which are to be erected at the inter-pulse spacing of approximately 35 milliseconds, or damage due to the discharge of one Marx through unerected Marxes.

To provide this isolation, switches are placed in series with the output connection from each Marx generator. The switch design is the same as the crowbar design except that no trigger is used. The switches operate in a self-break mode. The pressure in the isolation switches is set so that switch breakdown occurs due to overvolting when the Marx to which it is connected is fired, while the voltage across the isolation switch due to firing of a different Marx is insufficient to cause its breakdown.

The final item included in the oil tanks is the isolation/interconnection circuit between the CCG and the output. This circuit provides for protection of the CCG from the high voltages produced by the Marx generators and for proper operation of the CCG itself.

Load Ring. The current outputs from the Marxes in the oil tanks must be combined and fed to the equipment under test outside the oil tanks. The load ring is used for this purpose. The two oil tanks are located with their 21-foot lengths parallel and 11 feet apart. Oil-insulated high voltage coaxial lines of 16-inch outer conductor diameter and 6 inch inner conductor diameter are connected between each oil tank and the load ring. The load ring is hexagonal of width and height, approximately 4 feet. A roughly hemispherical lucite dome, 30 inches in diameter is mounted on top of the load ring, and the output electrode, 6 inches in diameter, protrudes through the lucite dome, approximately 12 inches. The output electrode is connected to the center conductors of the coaxial lines from the oil tanks inside the load ring, which is also filled with oil. The inner conductors of the coaxial lines between the oil tanks and the load ring are supported by polyethylene cones mounted on the oil tank walls and inside the load ring (figure 10).

Three bakelite pads are located on top of the load ring outside the hemispherical dome. The equipment under test is supported by a tripod arrangement which provides both mechanical support and electrical continuity for the ground return of the lightning current in a roughly coaxial configuration to minimize inductance and to equalize currents around the circumference of test objects. Current viewing resistors (CVR's) are mounted adjacent to the three bakelite pads to complete the electrical circuit and provide for the measurement of the current waveform delivered to the load.

Continuing Current Generator. The continuing current generator (CCG) must supply a load current on the order of 300 amperes for 1 second. Of the possible alternatives for such a source, the motor-generator alternative was chosen. The CCG consists of two diesel locomotive traction motors mounted with coupled shafts. The motor armature windings were rewound to produce the desired characteristics. In operation, one of the motors is driven by a power supply to drive the combination to a maximum speed of 1800 rpm using separate field and motoring supplies. After they are up to the desired speed, the motoring supply is disconnected and the field supply is set at maximum current. In the generator mode, the outputs of the two motors used as generators are connected in parallel using blocking diodes so as to prevent one generator from driving the other due to the unavoidable small differences in output voltage.

The source of electrical energy from the CCG is the inertial stored energy of approximately 2 megajoules in the rotation of the armature, so that the generators slow down during the continuing current phase as mechanical energy is converted into electrical energy.

The armature inductance of each generator is on the order of 20 millihenries. With a 1 ohm load, the output current rise time from the CCG is on the order of 20 milliseconds. The open circuit voltage of approximately 1 kilovolt from the CCG is insufficient to initiate an arc over a distance of several inches used to separate the simulator from the load when arcing to it is desired. Because of the exponential decay of the current produced by the Marx generator/crowbar circuit, the load arc would extinguish well before the CCG output rises in the 20 millisecond time frame to maintain it. The solution to this problem is to establish an output current through the CCG armature inductance into a dummy load before the Marx generators are fired. When the first Marx generator is fired, the load arc forms, and a fraction of the shunt dummy load current transfers to the load arc in a time short compared to the intrinsic 20 millisecond time constant.

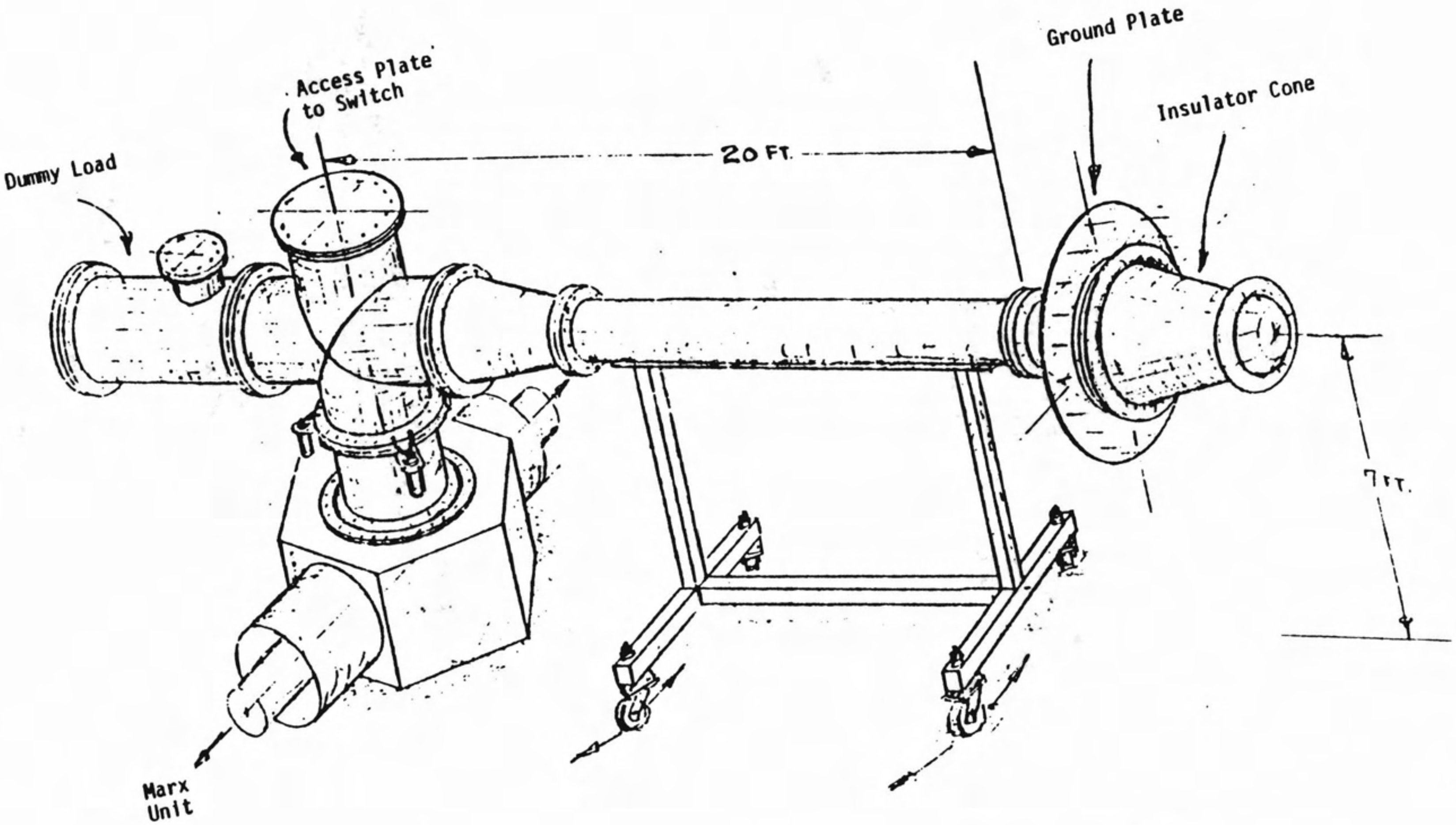


FIGURE 10. LOAD RING AND HORIZONTAL TRANSMISSION LINE

A mechanical contactor is used to make the connection between the CCG and the shunt load. This contactor as well as the CCG power supplies is located in the CCG room. Heavy duty cables are used to route the CCG output through a hole in the wall of the CCG room to a bushing on the oil tank wall through which the CCG output is fed to the isolation/interconnection circuit.

The initiation of the load arc by the high voltage from the Marx generators is an integral part of the switching of the CCG. If a hard-wired connection were made with no arc, the continuing current would begin prior to the high current, giving an unrealistic simulation. It is possible, but substantially more complicated, to include a series switch in the CCG circuit to avoid the use of a load arc, particularly since such an arc may be included away from the load if a hard-wired connection is required.

The circuit used to connect the CCG and the high voltage output is located in one of the oil tanks and is composed of the shunt load of 1 ohm referred to above, a series resistance also of 1 ohm to provide current limiting of the continuing current, and a series inductance of four 100-microhenry inductors for isolation of the CCG output from the high voltage transient occurring when the Marxes fire. Without this inductive isolation, arcover and damage to the armature windings are to be expected. The shunt and series resistors are salt-water resistors to allow large energy handling capacity. The isolation inductors are single layer solenoids wound on forms approximately 8 inches square and 12 inches long.

The CCG output capacity is roughly 1 kilovolt at 1 kiloampere for 1 second. As the CCG slows down, the continuing current decreases untilthe CCG voltage is no longer sufficient to sustain the arc, which is then extinguished. This occurs at a voltage on the order of several hundred volts and depending on the length of the load arc (figure 11).

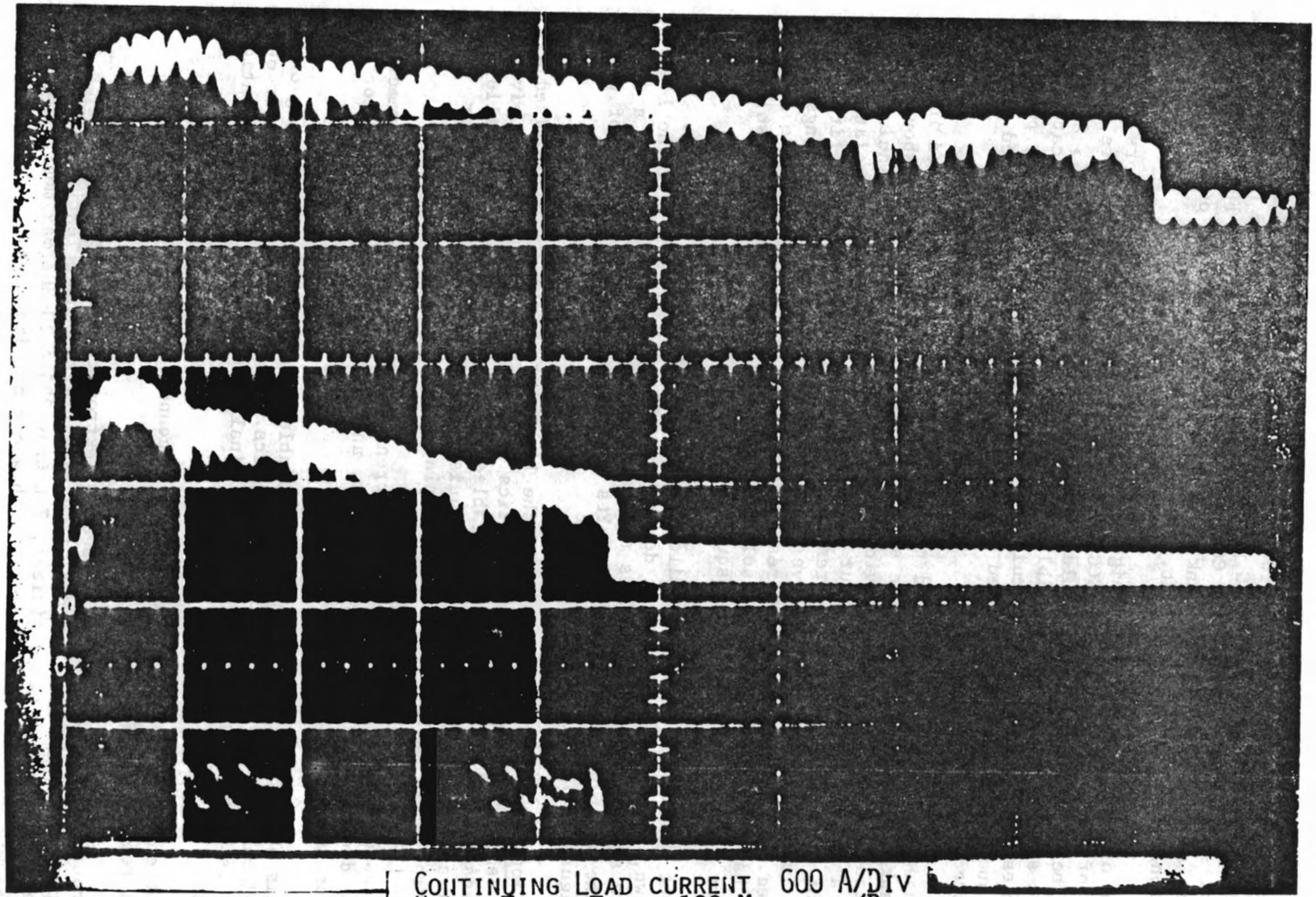
Instrumentation. The instrumentation for the lightning simulator is comprised of numerous transducers for sensing, fiber optics transmitters, clabes and receivers for data transmission, hard-wire coaxial cables for data transmission, oscilloscopes and transient digitizers for data acquisition, and a minicomputer for overall control, data analysis, and data display.

The sensors used are principally CVRs and current probes for current measurement, high voltage dividers for voltage measurement, and special purpose sensors for incorporation inside equipment to be tested.

Four channels of 25-MHz fiber optics are available at present for monitoring of experimental outputs and facility characteristics. An 8 channel 25-MHz fiber optic transmitter is under development and nearing final checkout, but is not operational at this time.

Although not entirely desirable, coaxial cable connections may be made between sensors and recording instrumentation.

The data acquisition equipment consists of 5 Tektronix 7844 85 MHz bandwidth oscilloscopes with dual beams and dual time bases, a 2-channel Tektronix 7612D 200 MHz maximum sample rate 8 bit digitizer, 7 LeCroy 2256A 20-MHz maximum sample rate 8 bit digitizers each having 4 channels with a common time base.



CONTINUING LOAD CURRENT 600 A/DIV
UPPER TRACE TIME 100 MILLISEC/DIV
LOWER TRACE TIME 200 MILLISEC/DIV

FIGURE 11. CONTINUING LOAD CURRENT

The computer incorporated in the system is a DEC PDP-11/34 minicomputer with 128K 16 bit memory, and interfaced to all the transient digitizers. The terminal is a Tektronic 4014 with full graphics capability and hard copy output. A line printer allows detailed printout of test results.

The software is written principally in Tektronix SPS BASIC and implements remote setup and control of digitizers where possible, and rapid computation and display of test outputs such as current and voltage waveforms and action integral and charge transfer as well as relatively easily written data analysis programs. A file system for easy storage and retrieval or individual test results has been written.

Exterior Test Area. A 150-foot by 300-foot area has been reserved east of the simulator building for tests which cannot be conducted indoors. A 50-foot by 90-foot concrete pad has been poured immediately outside the east roll-up door for tests.

RESEARCH ON ELECTRICAL PROPERTIES OF SEVERE THUNDERSTORMS ON THE GREAT PLAINS

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Abstract

In 1978 we began a coordinated effort to study the electrical behavior of large and severe thunderstorms that form over the Great Plains of the central United States. Methods of approach include the study of characteristics of individual phenomena and storm case studies. Our goal is to understand the interrelationships between electrical phenomena and the dynamics and precipitation. Evidence that interrelationships do exist can be seen in results to date. In one squall line storm we have studied, 44 percent of all observed lightning flashes were cloud-to-ground; the total flashing rate averaged 12 per minute and coarsely followed the changes in Doppler-derived maximum updraft speed. Most of the intracloud discharge processes in a supercell severe storm were located predominately around the region of the intense updraft of the mesocyclone near large gradients in reflectivity and horizontal velocity.

Both 10-cm and 23-cm wavelength radars have been used to detect lightning radar echoes. The lightning echoes from the 10-cm radar generally had peak signals 10-25 dB greater than the largest precipitation echo in the storm, and they were usually observed where precipitation reflectivities were less than maximum. Comparison of lightning echoes and electric field changes show that abrupt increases in radar reflectivity are often associated with return strokes and K-type field changes.

Cloud-to-ground flashes that lower positive charge to earth have been observed to emanate from the wall cloud, high on the main storm tower, and well out in the downwind anvil of severe storms. The percentage of CG's that lower positive charge is apparently small.

1. Introduction

Until recently the study of electricity from severe storms has been typified by isolated measurements of sferics, surface electric fields, or visual observations. This led the National Severe Storms Laboratory (NSSL), which is located in the Great Plains, to expand its research on severe storms to include a study of their electrical behavior.

Results from earlier studies by others include the finding of high rates of electrical activity in large storms, e.g., Jones (1951), Vonnegut and Moore (1959). Futhermore, there have been several isolated studies of electrical phenomena in tornadic storms. Jones (1951) discusses tornado tracking using sferics and observations of cyclic pulsations of luminosity high within the cloud of a tornadic storm, a phenomenon he calls the tornado pulse generator (Jones, 1965). Gunn (1956) concludes from measurements on a large tornado that passed near an 8-station field mill network that there is little evidence of unusual electrical effects near the tornado funnel and the observed electrical behavior is that expected from an ordinary thunderstorm if turbulent velocities were increased by an order of magnitude. Vonnegut and Moore (1957) interpret the smooth electric field waveforms obtained closest to the tornado by Gunn (1956) as possibly due to continuous charge flow, and they suggest that cloud-to-ground (CG) lightning may be suppressed in the vicinity of the tornado funnel. Frier (1959) reports the presence of 4 cycle per minute oscillation in the electric field that he attributes to a tornado about 100 km away. Numerous eye witness observations of unusual luminosity and electrical activity near tornadoes have been collected by Vonnegut (1968). Scouten et al. (1972), Taylor (1973) Kinzer (1974) and Brown and Hughes

(1978) have measured intense sferics from severe storms and conclude that they are not associated with the tornado but with the parent storm. Davies-Jones and Golden (1975) made daylight movies near 8 tornadoes, and they observed and filmed very little electrical activity near the tornado funnels. They found no vegetation scorching (Vonnegut, 1960) along the damage paths of 21 tornadoes. Zrnic' (1976) reports that no abnormal magnetograms were obtained for 10 tornado passages within 12 km from magnetometer sites. In addition to these observations, discussions on possible direct links between electricity and tornado genesis have been presented by Vonnegut (1960), Wilkins (9164), Colgate (1967, 1968), and Watkins et al. (1978).

In the central United States, large and often severe storms typically occur during the spring and summer. These storms can be roughly catgorized into two groups. In the first group are those triggered by synoptic scale events such as fronts and disturbances in the jet stream. These storms are most frequent during the spring. In the second group are those triggered by smaller mesocale processes. These generally occur in the summer and move more slowly than the storms in the first group. Springtime storms are emphasized here. They are typified by large hail (>3 cm in diameter is not unusual); strong straight-line winds (often $\geq$ 30 m/s); high cloud tops (often 15 km and above); intense updrafts; mesocyclones (e.g., Lemon and Doswell, 1979); and they sometimes produce tornadoes. Storms can occur as individual cells along a squall line or can be isolated. Their structure can vary from the single to the multicell type. Sometimes an isolated storm develops into a supercell (Browning, 1977), which is a particularly long-lived severe storm. The varied severe storm situations make coordinated study of their electrical behavior challenging. Our goal is to develop an understanding of relationships between electrical phenomena and the dynamics and precipitation of storms. We are examining these both as case studies of storms and for studies of specially selected events that occur during these storms.

The first season of coordinated electrical observations at NSSL was 1978. At first, use of the Doppler radars was dominated by other experimental priorities, and only a few partial data sets suitable for our purposes were obtained. During the 1980 season, however, radar data specifically for use in electrical studies were acquired. Initial results from the 1978 and 1979 seasons and a few comments based on cursory examination of a small amount of data from 1980 are presented here.

2. Instrumentation

Radar information on storms is obtained with both conventional and Doppler radars. NSSL operates two 10-cm wavelength Doppler radars and one 10-cm conventional radar (WSR-57). One Doppler (NRO) is located at NSSL and the other (CIM) is 42 km to the northwest. This arrangement forms a primary dual-Doppler data acquisition area that is approximately figure 8 in shape, about 200 km in length and 100 km in width, with the long axis aligned from southwest to northwest (Brown et al., 1975), which is generally the direction of movement of springtime storms. Both precipitation reflectivity and single Doppler information, i.e., the radial component of velocity toward or away from the radar, can be obtained to ranges greater than 300 km. Dual Doppler data are usually obtained by coordinating scans up through a selected storm or region of a storm. Each tilt sequence takes about 4 to 5 minutes.This scanning technique and dual Doppler data synthesis provides much information on the structure and dynamics of large storms (Ray et al., 1975). Other meteorological data are obtained from atmospheric soundings and NSSL's surface network that measures wind, pressure, temperature, and humidity. The NRO

Doppler and a colocated 23-cm wavelength conventional radar are utilized to acquire radar echoes from lightning. The NRO Doppler has also been used to study electric-field levitation of precipitation.

Measurements of electrical phenomena are made with both fixed and mobile facilities. The fixed facilities include Taylor's (1978) lightning discharge mapping system that allows three dimensional location of VHF radiation sources (20-80 MHz) from lightning. Each station can record impulse rates of up to 1.6×10^4 per second and out to a range of about 60 km. Typical three dimensional location accuracy varies between about ± 250 m at 30 km to ± 1 km at 60 km. Electric field changes, ΔE, are measured with sensors (slow and fast antennas) of the type described by Krehbiel et al. (1979), which have microsecond rise times and exponential decay time constants of 10μs for the slow antenna and 100 μs for the fast antenna. Other parameters we measure include the atmospheric electric field at the ground, optical transients from lightning, strike points for CG flashes, and corona current. Movie and television video tape recordings of clouds and lightning are also made.

A van has been equipped as a mobile laboratory to measure most of the electrical phenomena mentioned above. Mobile intercept of severe storms and tornadoes has been accomplished for several years by NSSL for photographic studies and verification of Doppler radar signatures (Davies-Jones and Kessler, 1974; Davies-Jones, 1981), but application of the technique to electrical measurements is new (Arnold and Rust, 1979). Use of a mobile laboratory creates logistical problems, but placing instrumentation in a relatively fixed position within the severe storm, in particular beneath the precipitation-free cloud base (figure 1), provides the possibility of making quantitative electrical measurements in this region. The region is characterized by a strong, inflowing low-level wind that turns upward into the updraft. A mesocyclone, with a typical rotation diameter of 5-10 km, often develops in this region, and Doppler radar usually displays a velocity distribution resembling a Rankine combined vortex (Donaldson, 1970). The mesocyclone is sometimes visible beneath cloud base as a lowered rotation called a wall cloud. If strong tornadoes occur, they usually form under the wall cloud. Details of mesocyclones and related storm development have been given by several investigators, e.g., Lemon and Doswell (1979). Using the results of the previous work on the correlation between visual severe-storm cloud features and Doppler-derived storm windfields, we can, through documentation of the visual features of these storms, infer gross storm dynamics with which to correlate electrical activity even when storms occur outside the Doppler data acquisition area. Mobility also substantially increases the number of severe storms that can be studied.

3. Observations

a. Squall line, 6 June 1979

We examine one group of cells (sustained, identifiable reflectivity cores) within a squall line that developed during midafternoon of 6 June 1979. This group of cells constitute the 'storm' of interest. Our analysis thus far covers this storm as it approached the laboratory from the west during 1640-1708 Central Standard Time (CST). In figure 2 the 60° sector (dashed lines) to the west encloses most of the storm; the storm is identified by the cross-hatched area within the 45 dBZ contour. The 60° sector is that from which impulses were received with the VHF mapping system. This storm is categorized as severe because it produced large hail (prior to 1640 CST) and straight-line winds in excess of 25 m/s.

There was neither a mesocyclone nor a tornado.

We located 342 flashes within this storm between 1640-1708 CST. Of these flashes, 149 were CG giving an IC:CG ratio of 1.3:1. We mapped the CG strike locations onto radar reflectivity contours at a height of 5 km. The median value of reflectivity at 5 km above the strike points was 40 dBZ. About 75 percent of all flashes struck beneath reflectivities of $\geq$ 20 dBZ. The strike point does, however, not indicate the location of the intracloud position of these flashes because of significant horizontal propagation (e.g., Teer and Few, 1974; Taylor, 1978; and Krehbiel et al., 1079).

We examined the electric field change records for waveforms indicative of continuing current (CC) (Kitagawa et al., 1962) and found them in only 9 percent of the CG's. This is a lower limit since, if we were unable to discern clearly a waveform indicative of a CG with CC, we did not include it in the count. The actual occurrence of CC appears to have been substantially less than the 46 percent of CG's containing CC found for storms in New Mexico by Kitagawa et al., (1962). Flashing rates in the observed storm, while not extreme, were high, with averages of 5 per minute for CG's and 12 per minute for all flashes.

From the dual Doppler radar data, we derived estimates of all three wind velocity components. Shown in figure 3 are the Doppler analysis at one height and the reconstructed VHF source locations for one flash that is typical in this storm. The source locations tended to occur in regions of weak updraft (<10 m/s), often adjacent to regions of downdraft, and mostly in the northwest half of the strom. After storm motion was subtracted from the horizontal wind, hortizontal streamlines at the level of the lightning generally flowed from the reflectivity cores and strong updrafts toward the lightning. Few VHF sources were within cores of high reflectivity (>45-50 dBZ).

We also examined various radar-determined parameters to correlate with lightning. Maximum reflectivity and maximum inferred updraft speed are shown in the lower portion of figure 4, with the number of lightning flashes plotted in the upper portion of the figure. The plots are partitioned into 4-minute time intervals that coincide approximately with the dual Doppler data acquisition periods. The lightning activity is generally characterized by a slight decrease in CG flashes and an increase in intracloud (IC) activity during the last interval analyzed. In the 16-20 minute interval is an interesting correlation of increaese in updraft, relectivity, and flashing rates. Note also the maximum updraft speed and the total flashing rate change in the same direction. A determination of whether this is characteristic of large storms awaits additional analysis.

b. Severe storm, 20 June 1978

From a severe thunderstorm on 20 June 1978, only single Doppler data up to midstorm levels (7 km) are available. This storm contained hail, produced a mesocyclone with three reported funnel clouds (but no observed tornado), and was characterized as a supercell. Discharge processes within the cloud were located predominately around the mesocyclone and near the large gradients in reflectivity and horizontal velocity. Figure 5 is a plan view of the storm's reflectivity structure at a height of 4 km. Superposed on the reflectivity are all the VHF impulses that could be located from those observed between

1906-1911 CST and a star showing the center of the mesocyclone. The impulses are from seven flashes (4 were CG's) and have a mean height of 6.5 km.

c. Radar observations of lightning

Observations of radar echoes have been reported by several investigators, e.g., Ligda (1950, 1956); Miles (1952, 1953); Hewitt (1953, 1957); Goncher et al. (1977); and Szymanski et al. (1980). Our purpose in using radar to study lightning is twofold: (1) study the physical processes of lightning and (2) locate lightning activity within severe storms throughout extended periods of the lifetime of a storm. Shown schematically in figure 6 is the concept of acquiring lightning echo data with the Doppler radar at NSSL. Figure 7 shows an example of a lightning radar echo with the simultaneous ΔE waveform from the slow antenna. The radar video signal shown is from a selected range interval, ΔR, at a range of about 86 km and altitude of 4 km. The simultaneous slow antenna ΔE waveform show a field change lasting about 1.4μs that apparently was caused by an IC flash that developed into a CG flash with at least 8 return strokes. The range of the CG strike point for this flash was independently placed by the CG location system at 123 km from the radar site. The radial length of the flash within the radar antenna beam was about 90 km.

We have previously reported a preliminary analysis of 19 lightning radar echoes observed during a summertime severe storm (Szymanski and Rust, 1979). Those lightning radar echoes were detected at ranges from 30-180 km and at altitudes of up to 10 km. They generaly had peak signals 10-25 dB greater than the largest precipitation echo in the storm. Lightning echoes usually were observed where precipitation reflectivities were less than maximum, in agreement with lightning locations observed by Proctor (1974) and MacGorman (1978) using other techniques and the VHF mapping technique described earlier. The locations of flashes reported by Szymanski and Rust may be biased, however, since very intense precipitation echoes at 10 cm wavelength can obscure the echoes from lightning channels. To reduce substantially the radar return from precipitation, present experiments at NSSL arealso utilizing a longer wavelength (23 cm) L-band radar with circular polarization. Other aspects of our present study include continued lightning echo measurements with the Doppler radar in storms overhead to correlate lightning occurrence with changes in precipitation reflectivity and velocity and with the L-band radar for long range location of lightning within severe storms.

As seen in figure 7, there can be abrupt increases in the amplitude of the lightning radar echo. Lightning echoes from this and other range intervals show shifts in the time of the reflectivity peaks relative to the return strokes. Many of the abrupt changes in reflectivity due to lightning are coincident with return stroke field changes, but some are not. In the lightning echoes that we have observed, there often appear to be reflectivity changes associated with phenomena that can be identified from E records, e.g., return strokes, K-type chnages, and events during continuing currents.

d. Positive CG's in severe storms

Although several investigators have detected positive CG flashes (+CG) in mountainous terrain and to tall structures, e.g., Berger (1977), +CG's to level terrain were thought to be rare. On the other hand, Takeuti et al. (1978) have observed a predominance of +CG's in the highly sheared winter storms in the Hokuriku coastal region of Japan. Others have observed occasional +CG's during the dissipation stage of storms.

We have observed +CG's during both the severe and final stages of severe storms. Prior to 1980, +CG's with documentation in addition to E records number less than 100, but we have obtained numerous other waveforms suggestive of +CG's. During a 7-minute interval of the 6 June 1979 storm (section a above), six +CG's were documented. During the active stage of a severe storm on 20 May 1980, several flashes emanating from well out in the downwind anvil were positive, while those from the downwind anvil, but close to the main tower, were of both polarities (figure 8). From a limited number of visually confirmed CG's, we think that CG lightning emanating from high on the main storm tower under the upwind (back-sheard) anvil and from the mesocyclone region of severe storms can be positive (Arnold and Rust, 1979). The percentage of +CG's during a severe storm is apparently small. It is intriguing that positive CG's can occur prior to as well as in the dissipating stage of the storm and thus may be directly related to a particular phase of severe storm development.

4. Concluding Remarks

Our attempt to study electrical activity in its relationship to other parameters within severe storms began in 1978. We believe that both individual, selected events and storm cases should be examined to relate electrical processes to the evolution of large storms of the central United States. Based on first results of our study and on findings of other investigators, we present in figure 9 a depiction of apparent differences in characteristics for thunderstorms with extremely different scales, ranging from the very small (airmass, nonsevere) to the supercell severe storm. Undoubtedly, the figure is a simplification, and there is a wide variety of combinations of storm sizes and characteristics between those shown. It appears that there are differences in electrical phenomena beyond a mere scaling of the activity in a small storm to that in a large severe storm, e.g., the occurrence of +CG's in the mature stage. Other parameters may also be different and are being investigated. While we are continually sensitive to the prospect of possible unique electrical characteristics of severe storms, we feel that our goal of correlating electrical features with the dynamics and precipitation is the most important present program function.

5. Acknowledgments

G. Moore provided forcasting and guided the mobile laboratory for storm intercept. S. Goodman provided VHF mapping and Doppler information for the 20 June storm. We thank D. Burgess for his suggestions. J. Weaver spent many hours engaged in nowcasting for storm intercept. Electrical measurements were made with the help of K. Cameron, L. Cunningham, S. Horsburgh, M. MacNiven, and C. Watson. M. Maier provided the CG strike location data. There are many others at NSSL, too numerous to mention, whose continual help keeps the storm electricity program functioning. We thank M. Brook of New Mexico Tech for the loan of slow and fast antennas to make our initial measurements.

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In addition to the aforementioned illustrations, a series of very interesting and informative photographs and sketches of the existing research installation at the National Service Storm Laboratory at Norman Oklahoma is included in figures 10 through 32.

The color reproductions of atmospheric research cover the entire spectrum from the geometrical complexity of the structure of lightning to laboratory preliminary breakdowns of the characterized strobes. This includes both cloud-to-ground and intra-cloud lightning mapping.

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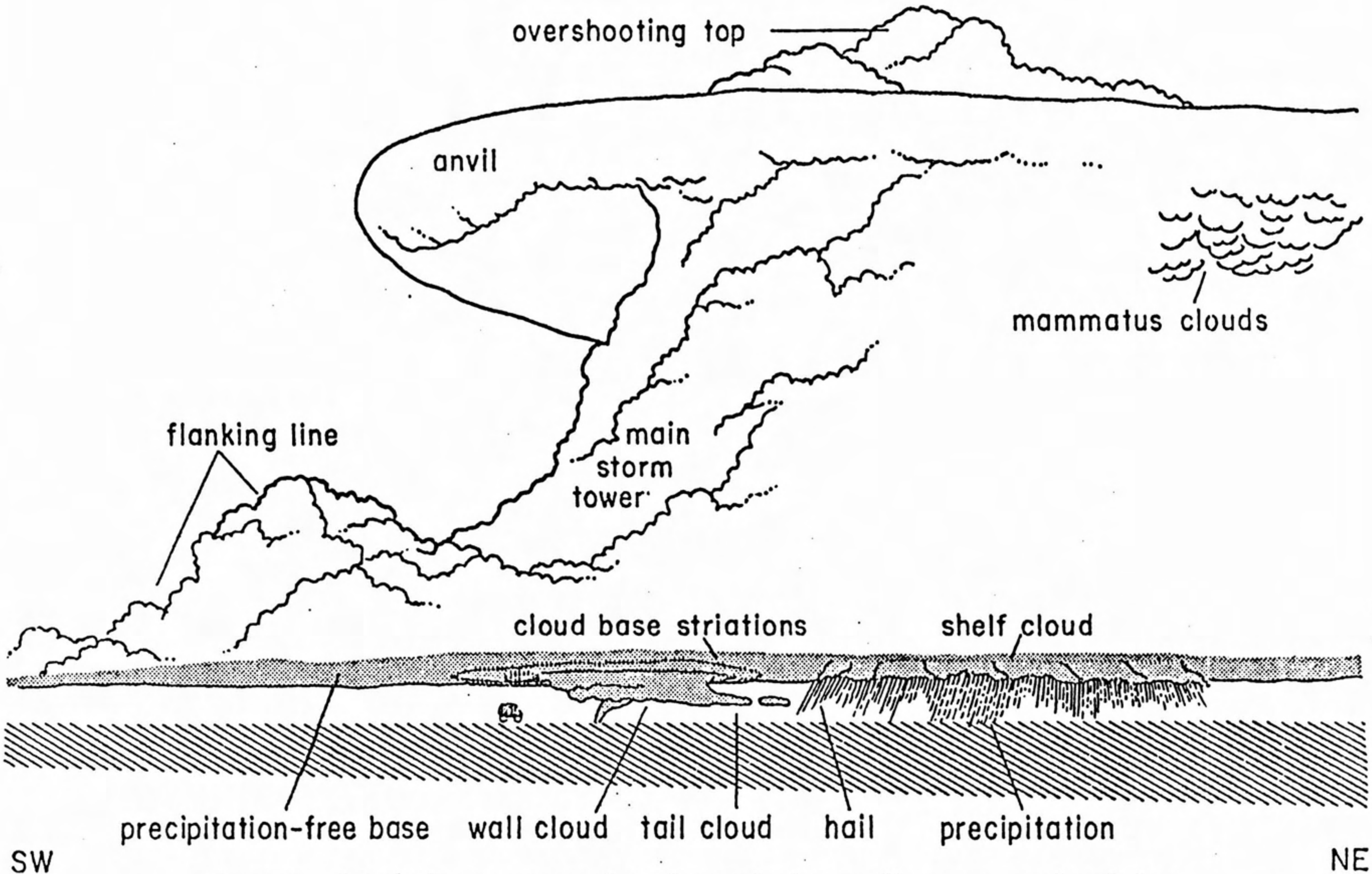


Figure 1. Schematic representation of a typical tornadic storm as viewed from the southwest. The sketch is not to scale; the horizontal dimension is compressed (after orginial diagram by C. Doswell and B. Dirham). The favored position of the mobile laboratory is shown by the symbol beneath and left of the wall cloud.

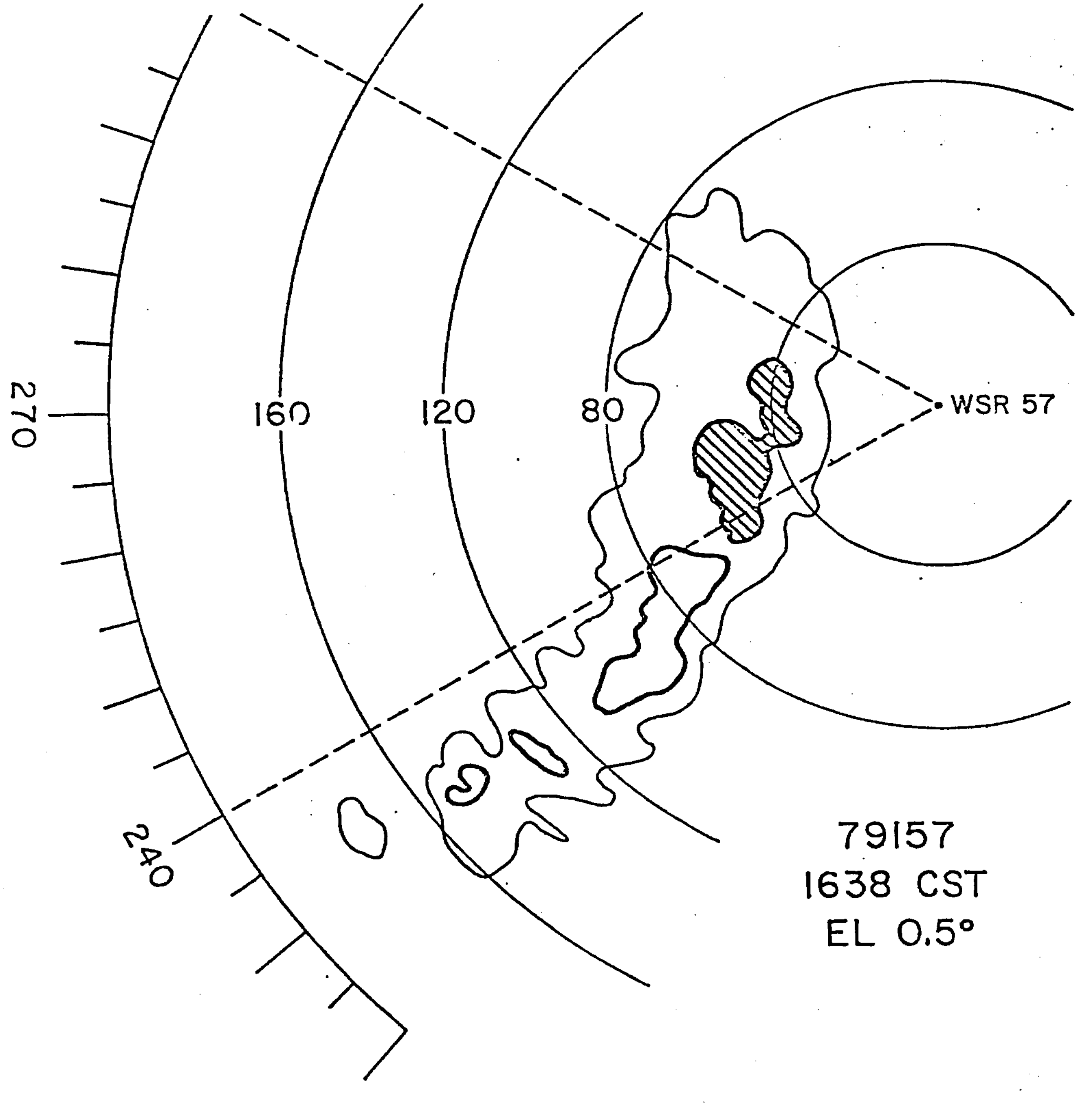


Figure 2. Outline of the squall line and storm of interest (crosshatched) June 6, 1979 (79157) at 1638 CST. Inner, heavy, countours ≥ 45 dBZ reflectivity. Dashed lines denote the 60° sector of the VHF mapping system; range rings are labelled in km.

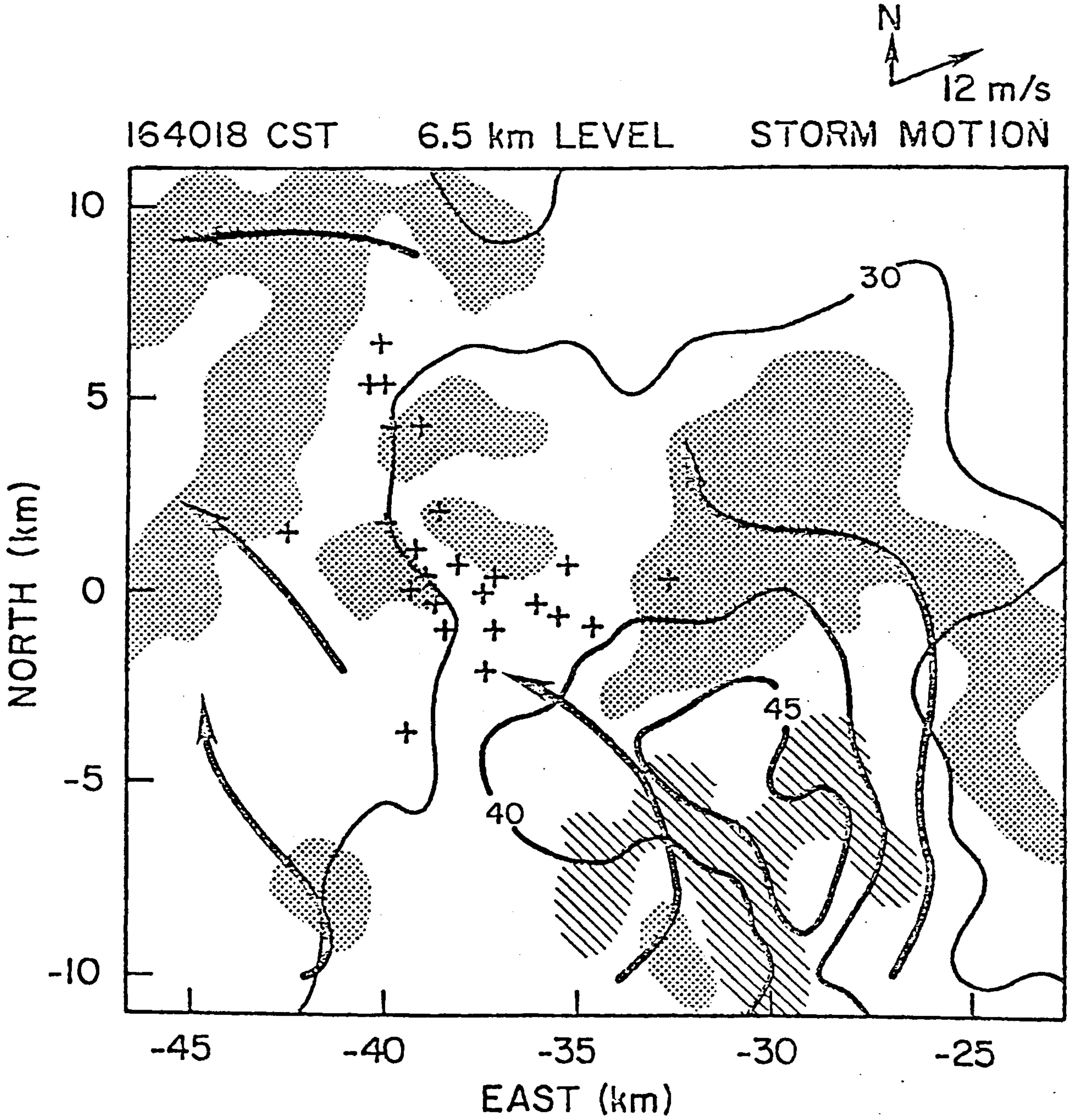


Figure 3. VHF source locations for a flash at 1640:18 CST superimposed on radar data for an Oaklahoma storm on June 6, 1979. Each calculated VHF source location in this flash is plotted as +. Radar data are shown at a height of 6.5 km from a series of radar scans between 1644-1648 CST. Contour lines indicate radar reflectivity in dBZ. Arrows indicate streamlines in the horzontal wind after storm motion is subtracted. Dotted shading indicates areas of downdraft (mostly ≤ 5 m/s). Striped shading indicates areas of updraft ≥10 m/s.

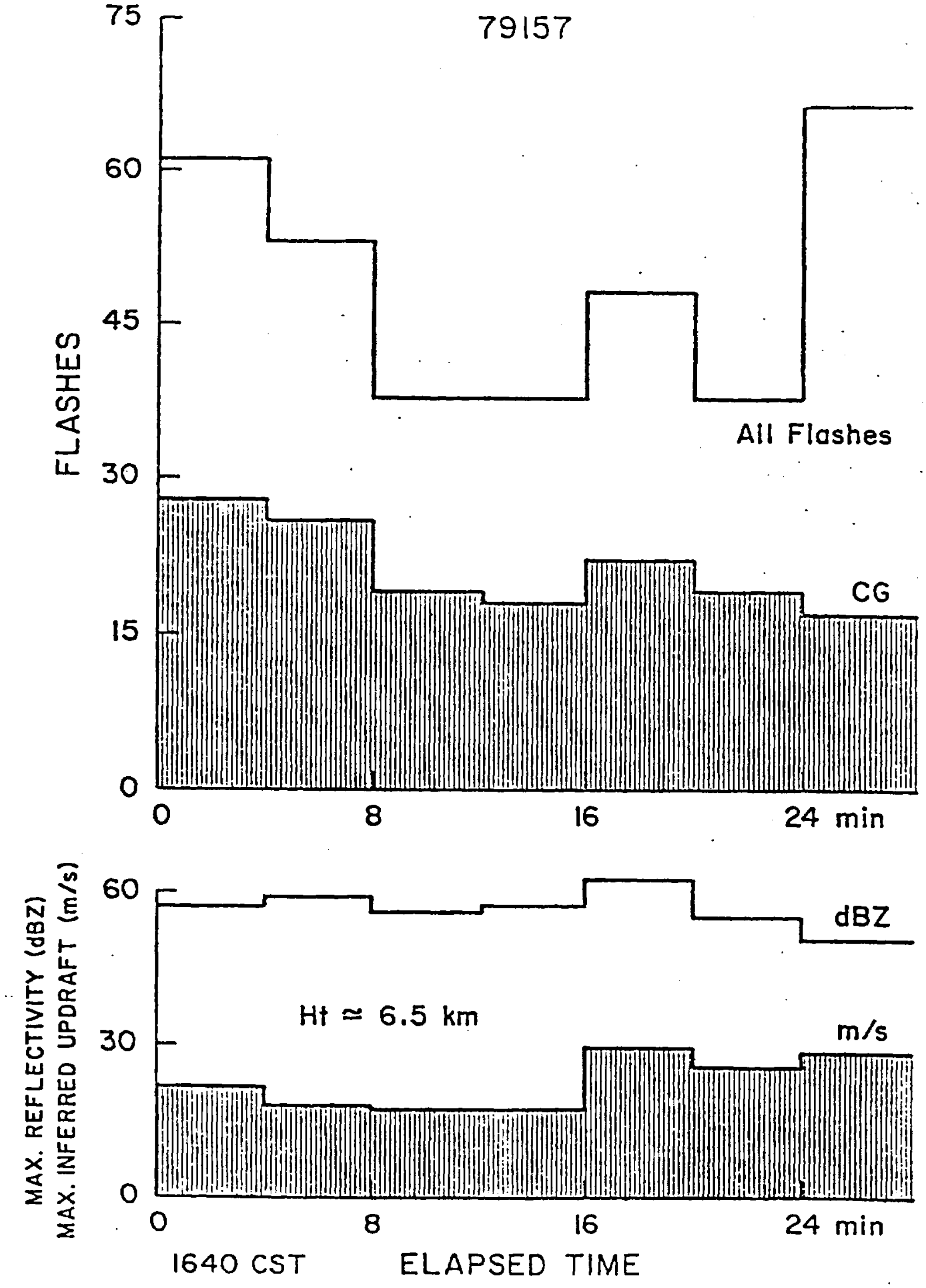


Figure 4. Number of flashes, maximum radar reflectivity, and maximum Doppler-derived updraft speeds during a 28 minute period of a storm on June 6, 1979. Radar data are from a height of 6.5 km. Time 0 is at 1640 CST.

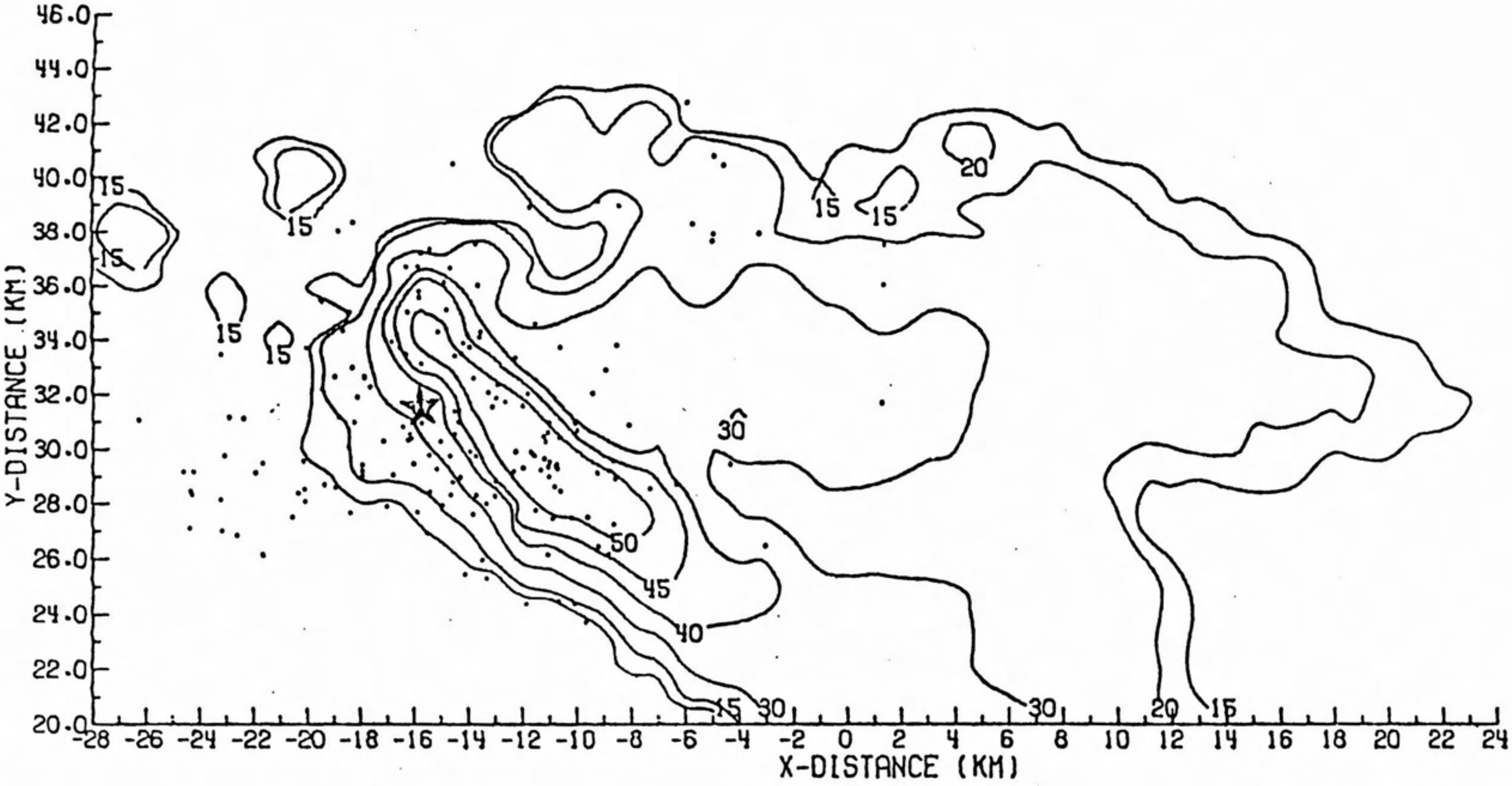


Figure 5. Reflectivity at a height of 4 km, June 20, 1978 at 1902 CST. The star marks the mesocyclone center, and the dots are the plan location of all VHF impulses from all heights that could be mapped between 19106-1911 CST.

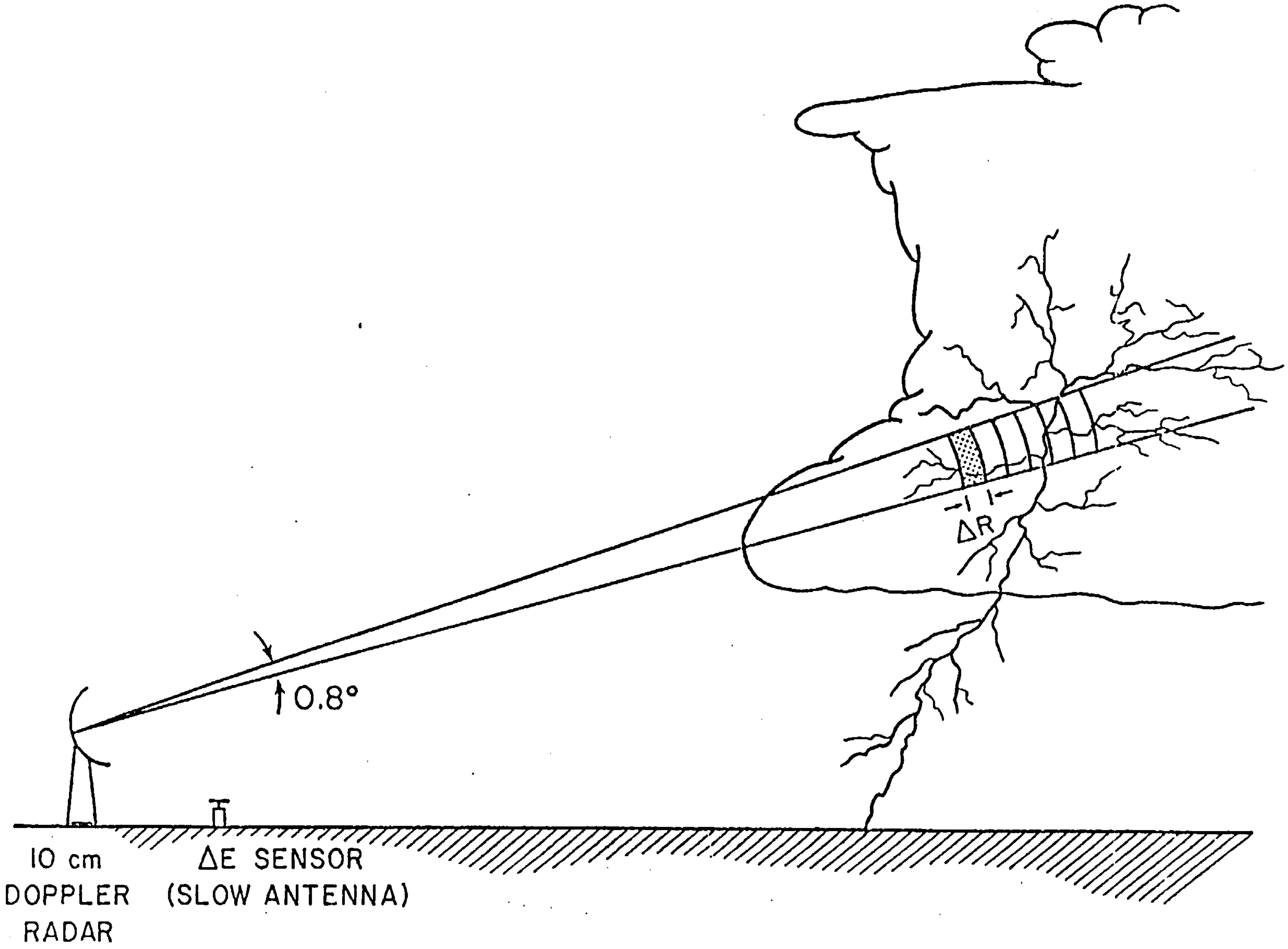


Figure 6. Sketch of data acquisition scheme for lightning radar echoes and associated electric field changes (Δ E). The radar antenna typically is held at a fixed position while acquiring the data. The shaded region represents a volume of space in which time variations of reflectivity may be studied in detail. Typically this volume can be moved in range in 150 m increments.

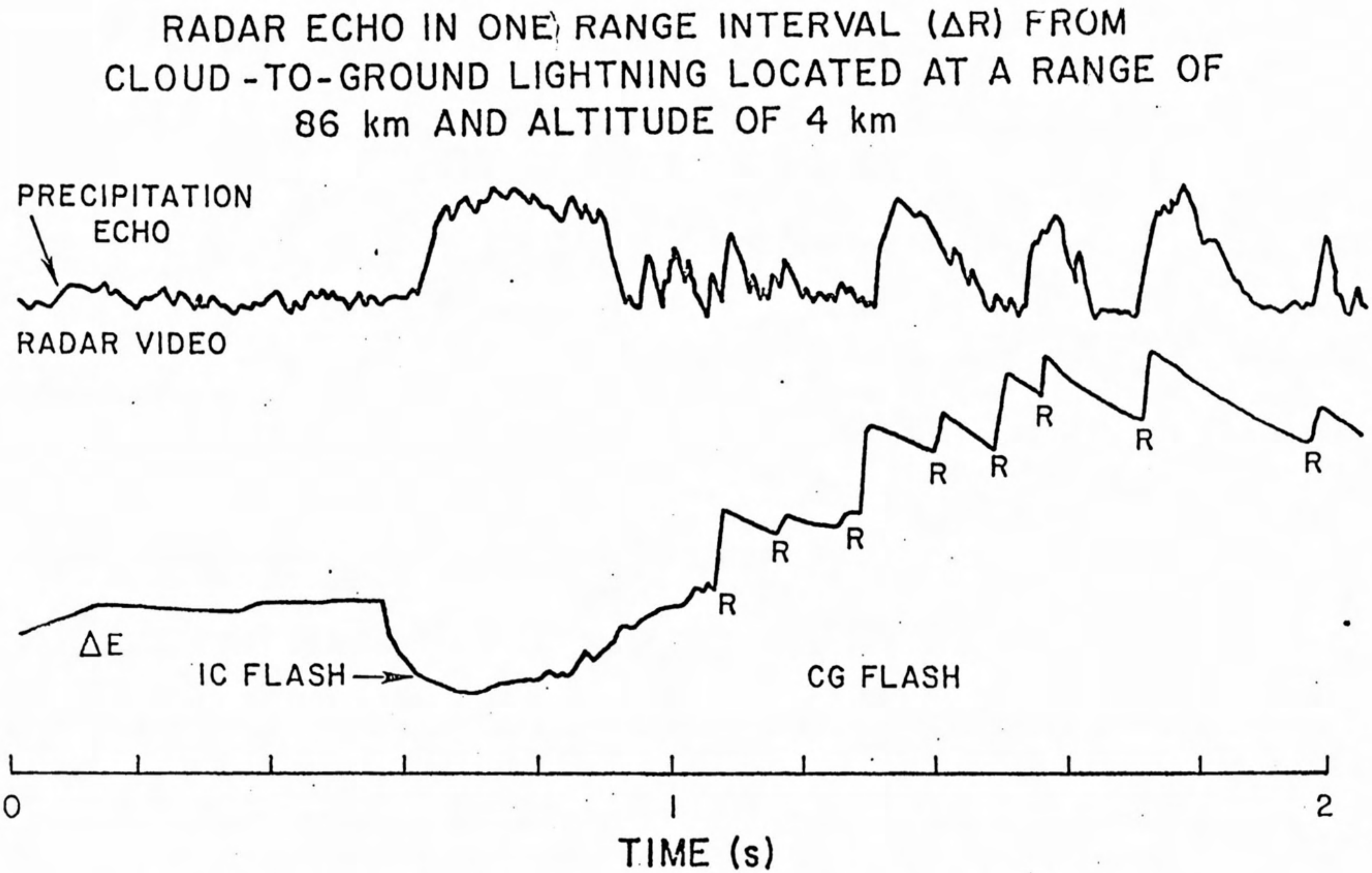


Figure 7. Above: Time history of a lightning radar echo from a range interval ΔR at 86 km and 4 km altitude, May 3, 1979 (79123) at 0002:52 CST. Below: Slow antenna waveform recorded simultaneously with radar data. The relatively slow field change at the beginning of the flash (at 0.3 s) suggests an intracloud flash. The more abrupt changes, denoted R, are typical of cloud-to-ground return strokes as negative charge is effectively brought to earth. This flash was independently identified as a CG with at least 8 strokes by a lightning strike location system.

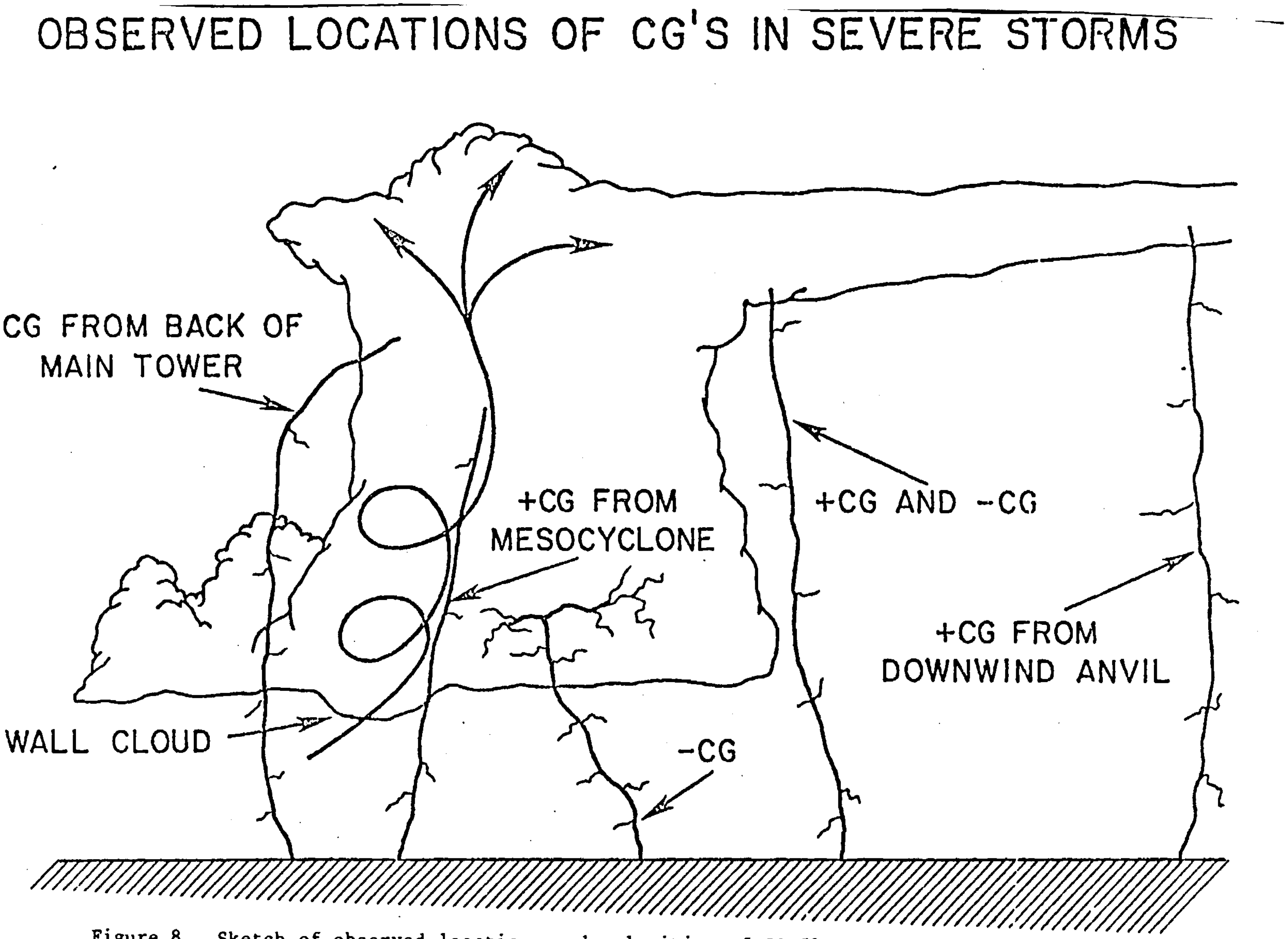
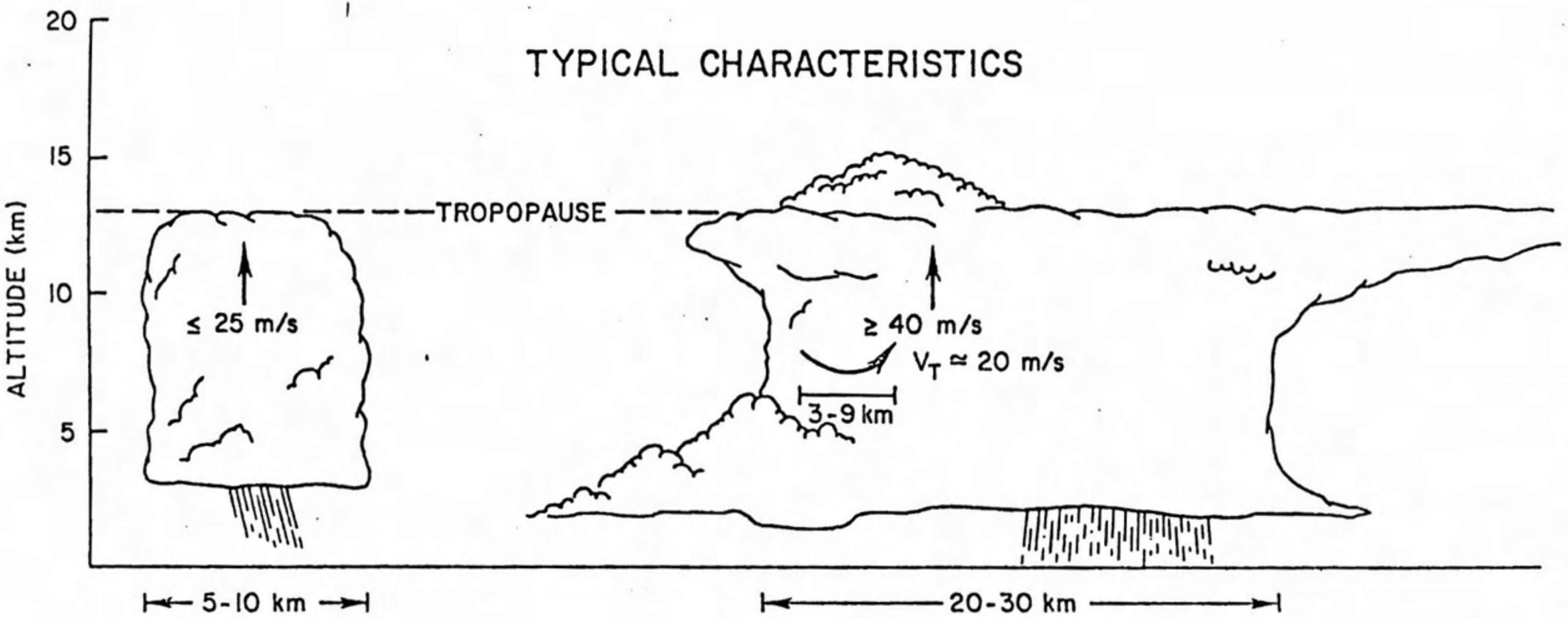


Figure 8. Sketch of observed locations and polarities of CG flashes from severe thunderstorms. The spiral denotes the region of intense updraft and rotation. Only negative CG's have been observed in the precipitation core. The +CG's seem to constitute only a very small percentage of the total flashes to ground.



AIRMASS, NONSEVERE

- *forms in weak shear*
- *continually changing*
- *lifetime ≤ 1 hour*
- *lightning*
  - *average CG rate 1-5/minute*
  - *average rate all flashes 2-10/minute*
  - *can have +CG during dissipation stage*

SEVERE

- *forms in strong shear*
- *quasi-steady state*
- *lifetime ≥ 4 hours*
- *lightning*
  - *average CG rate 5-12/minute*
  - *average rate all flashes 10-40/minute*
  - *can have +CG during severe and dissipation stages*

Figure 9. Oversimplified depiction of apparent differences between very small (airmass, nonsevere) storms and supercell, severe storms. Other differences are likely.

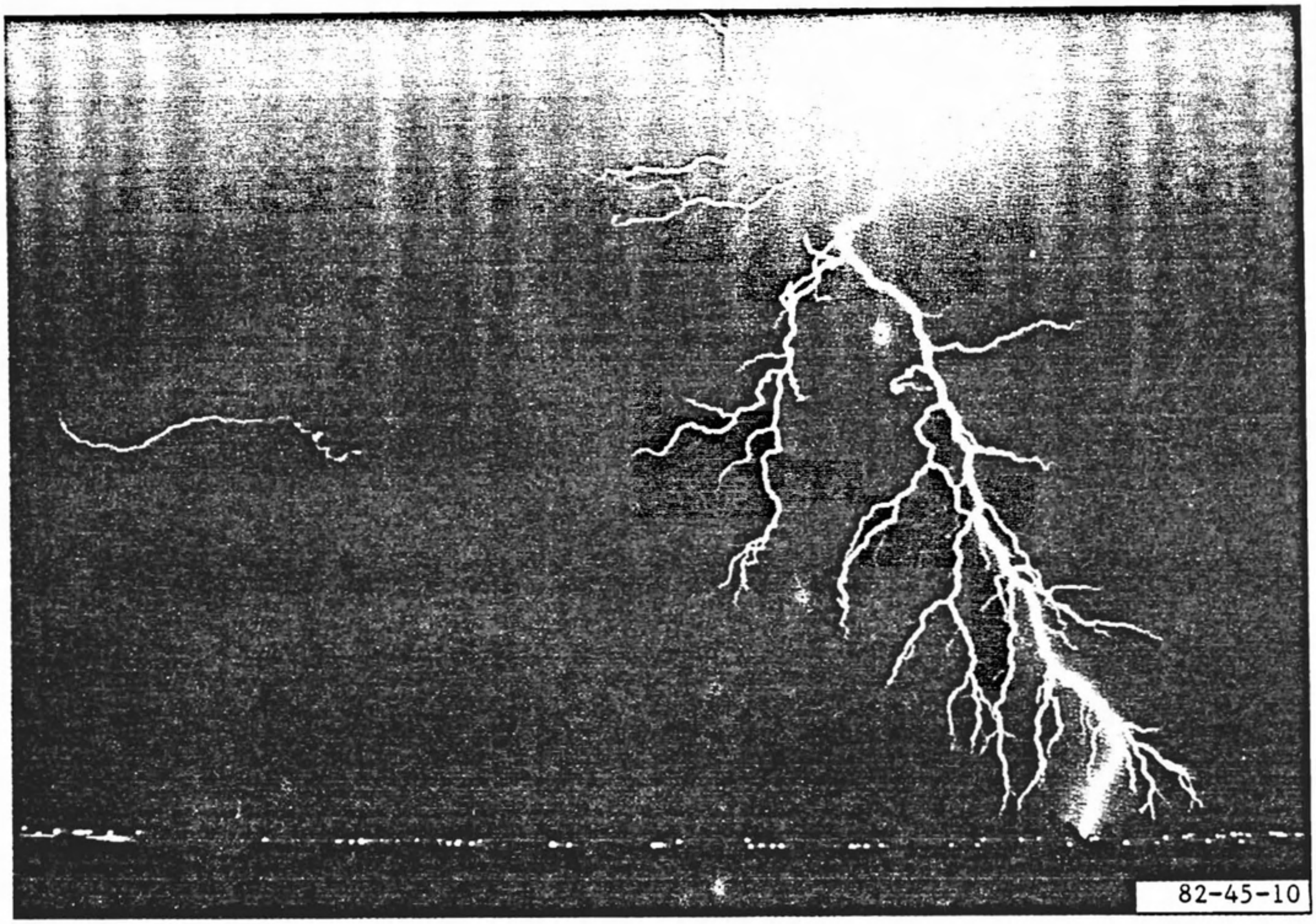
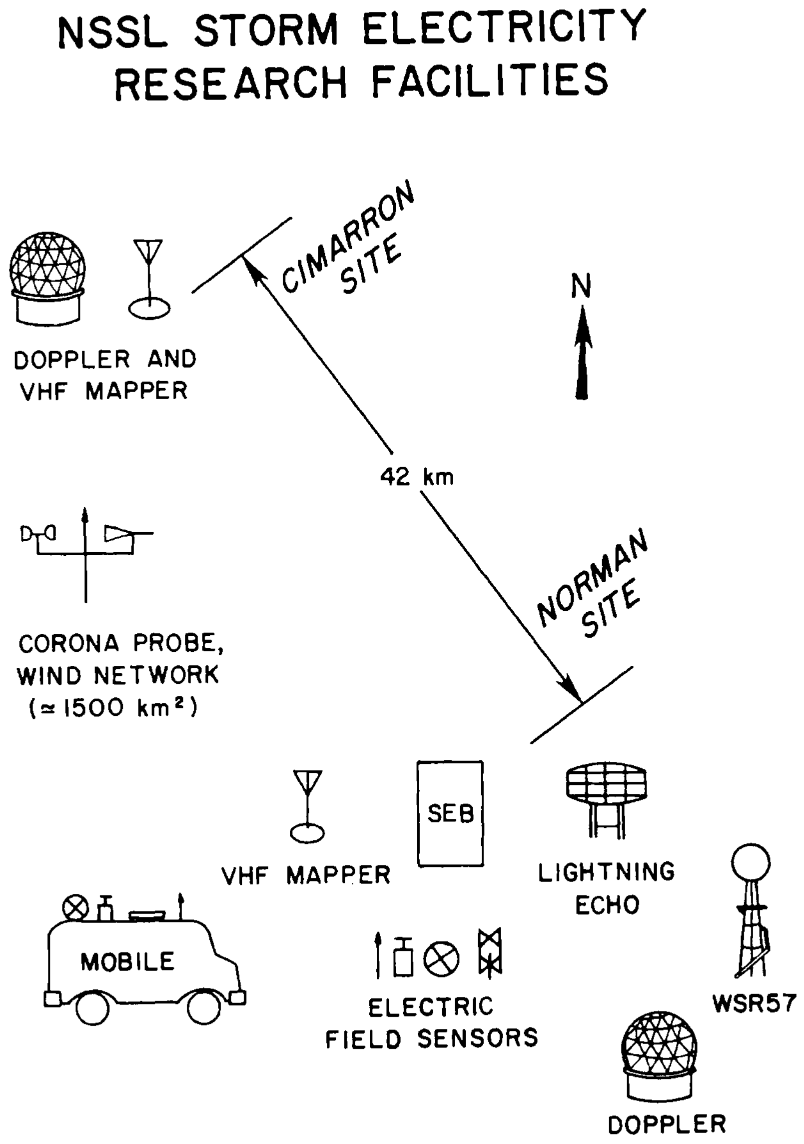


FIGURE 10

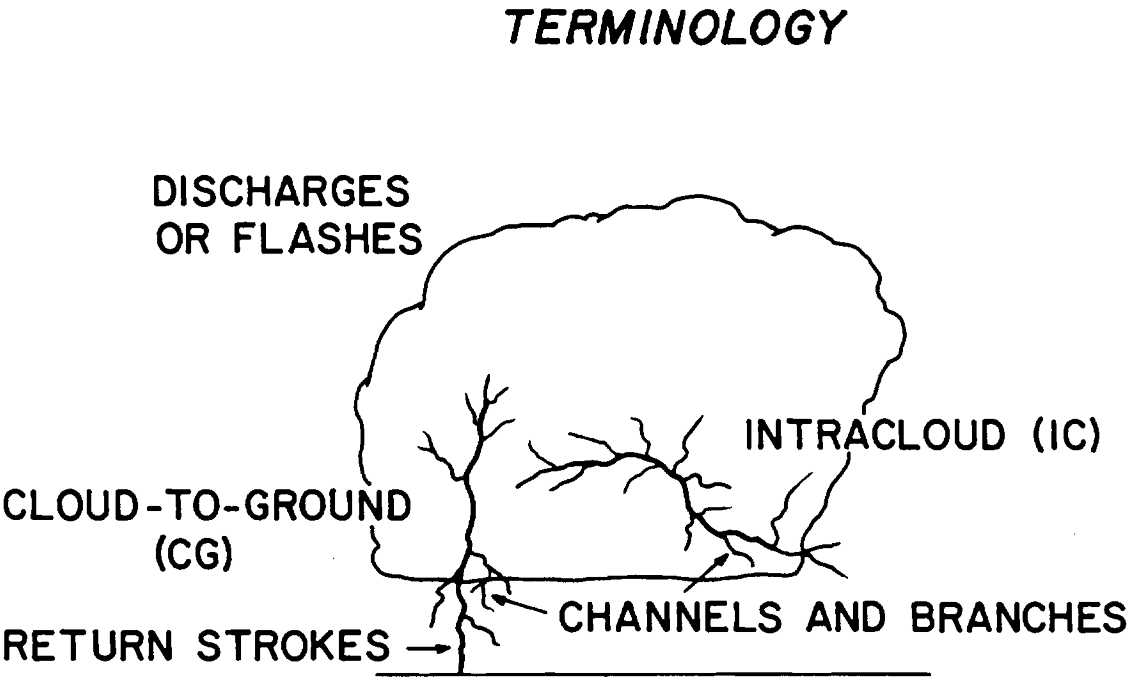
An example of the geometrical complexity of the structure of lightning.



82-45-11

FIGURE 11

Schematic of major components of research instrumentation at the National Severe Storms Laboratory including dual Doppler radars, dual VHF system for space-time mapping of lightning, radar for observing lightning, storm electricity building (SEB) housing sensors for measurement of several parameters of lightning and atmospheric electricity, a mobile laboratory for intercepting and tracking with storms, and meteorological observation systems.



82-45-12

FIGURE 12

The terminology of lightning.

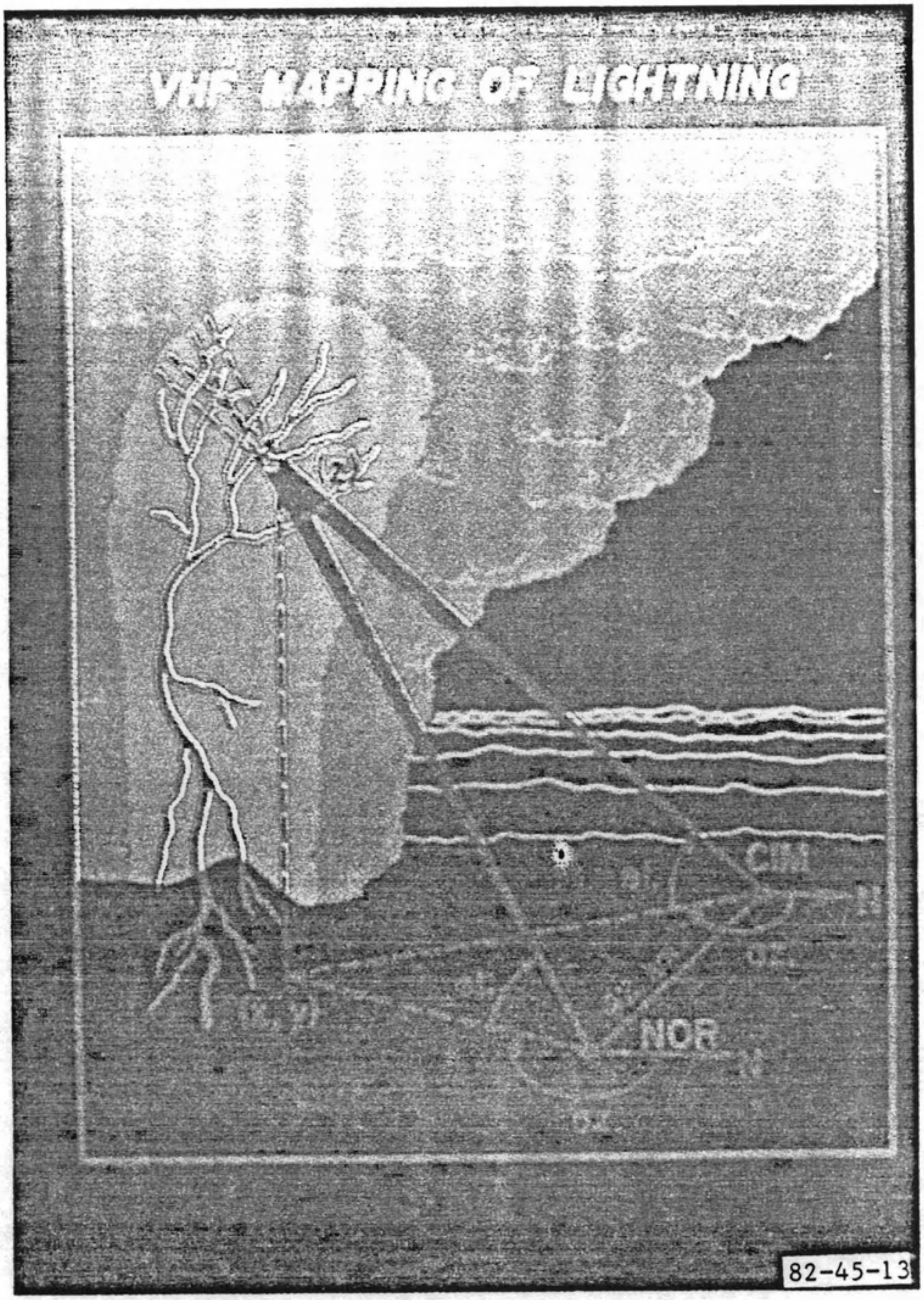
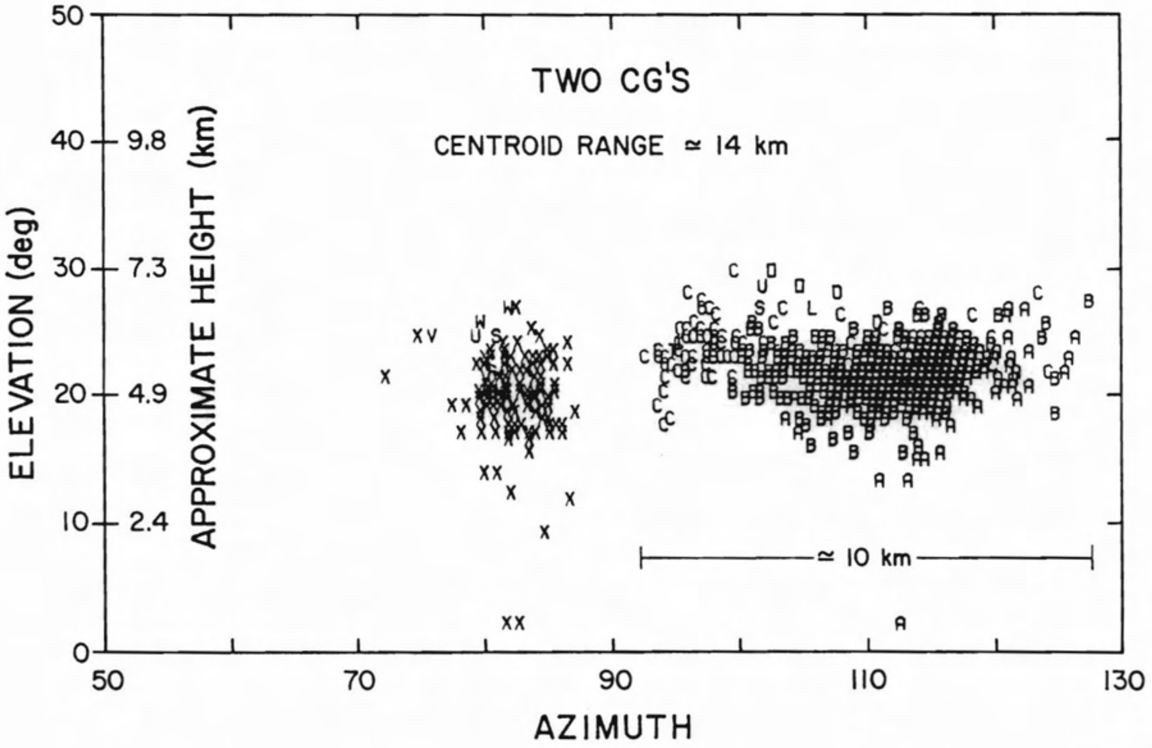


FIGURE 13

Location of lightning impulses using the dual VHF system with sites at NSSL in Norman, OK (NOR) and at Cimarron, OK (CIM).



82-45-14

FIGURE 14

Two single stroke CG's, one represented by letters A, B, and C, the other by letter X. (A few other letters are also scattered through these regions.) Each letter indicates azimuth and elevation angle during successive 75 ms time periods.

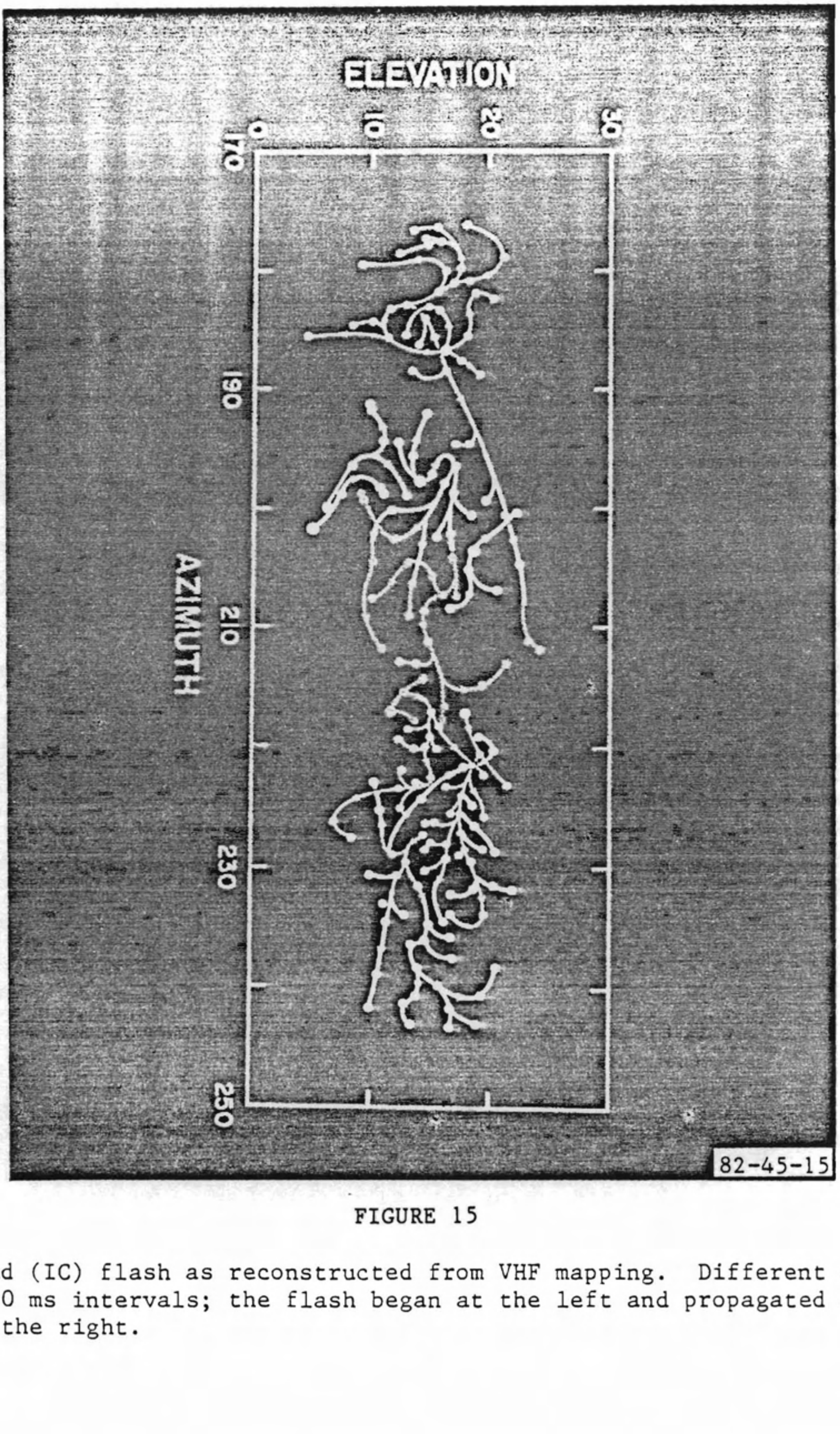
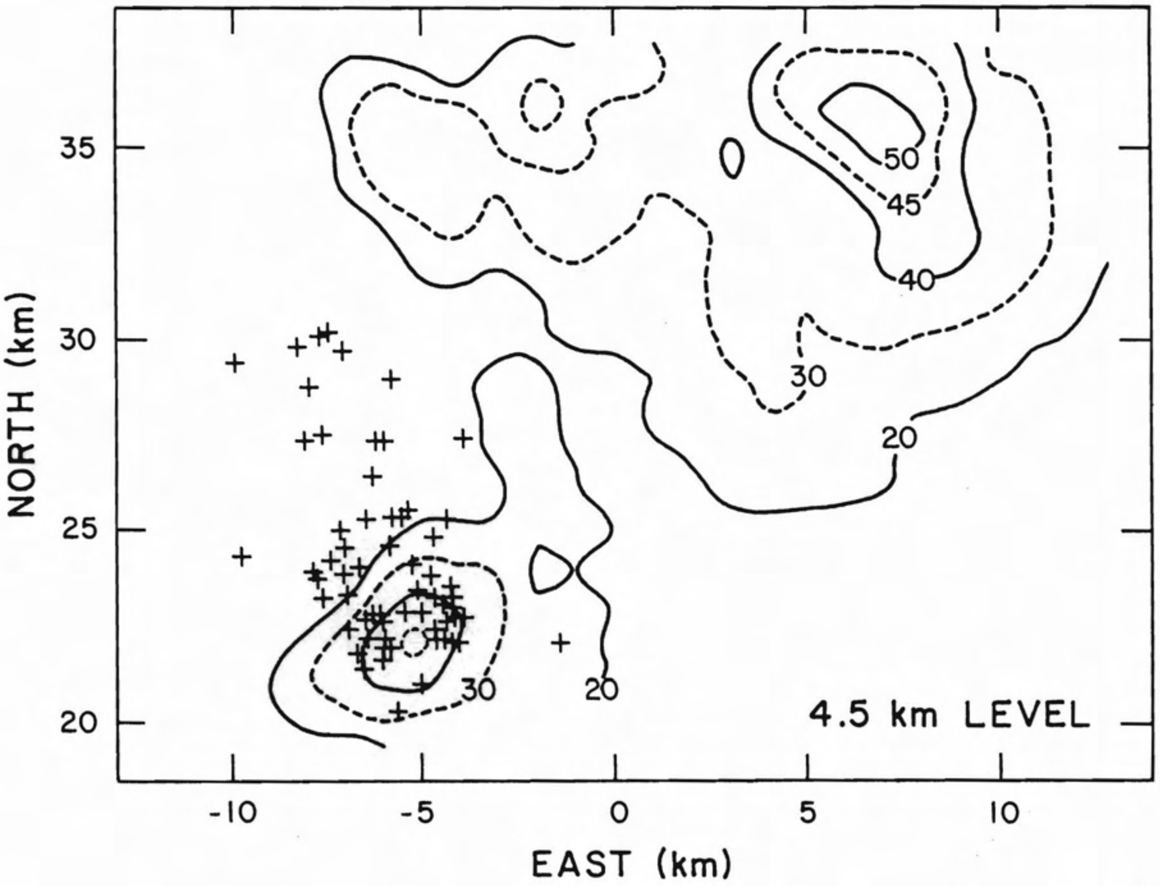


FIGURE 15

Intracloud (IC) flash as reconstructed from VHF mapping. Different colors are for 50 ms intervals; the flash began at the left and propagated about 30 km to the right.



82-45-16

FIGURE 16

VHF source locations superimposed on radar reflectivity contours for a flash at 1515:36 CST, 1 June 1978. Reflectivity data are at a height of 4.5 km. Contours are in dBZ. Each + is the plan location of a VHF source occurring 4-5 km above ground.

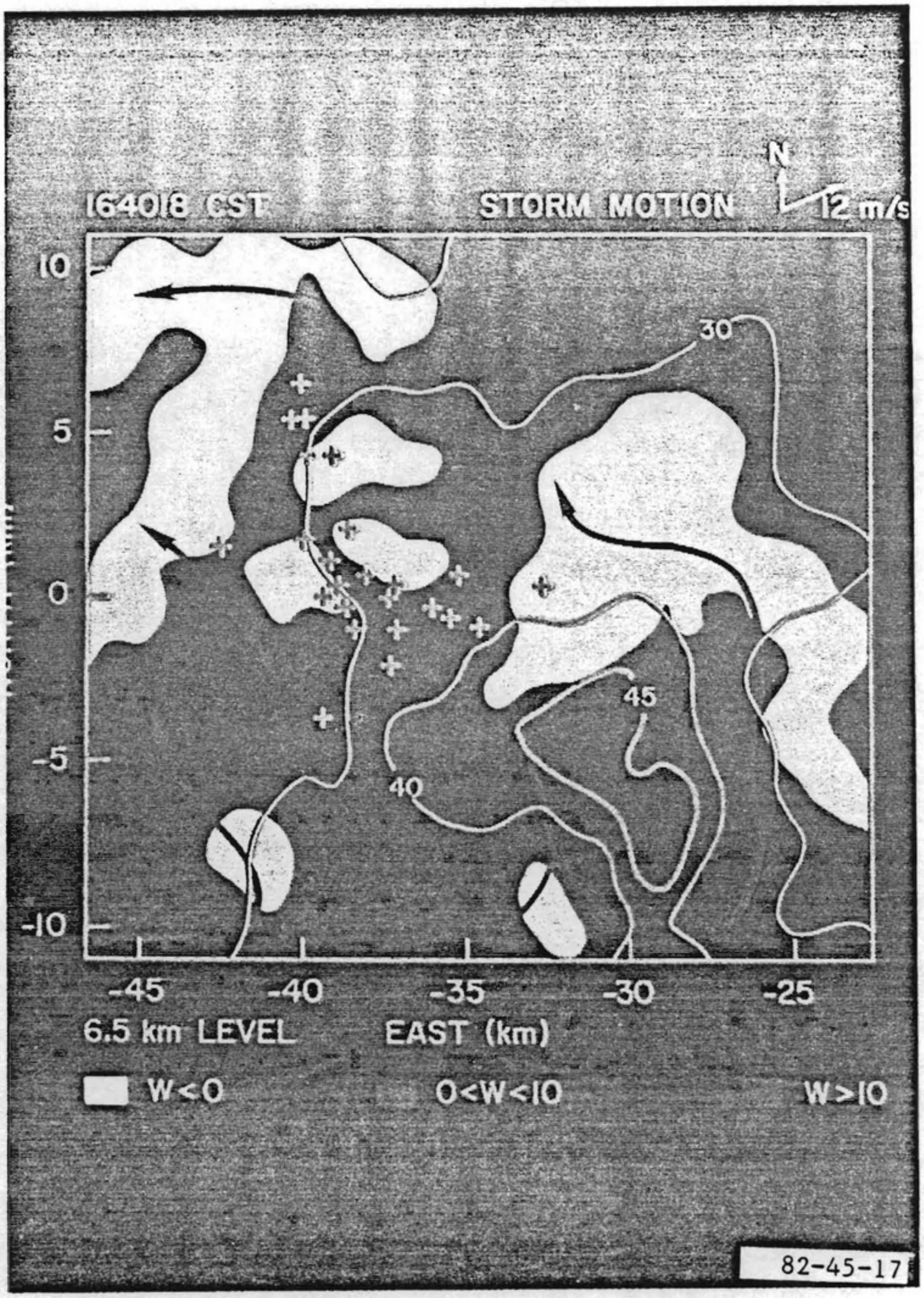


FIGURE 17

VHF source locations (+) within ±500 m of the 6.5 km level for one flash, which is typical of others in this storm. Vertical motions in the storm (W in m/s) are derived from analysis of dual Doppler radar data. Reflectivity contours are in dBZ and the arrows indicate streamlines in the horizontal wind. Note the lightning is downwind of the main updraft and precipitation cores.

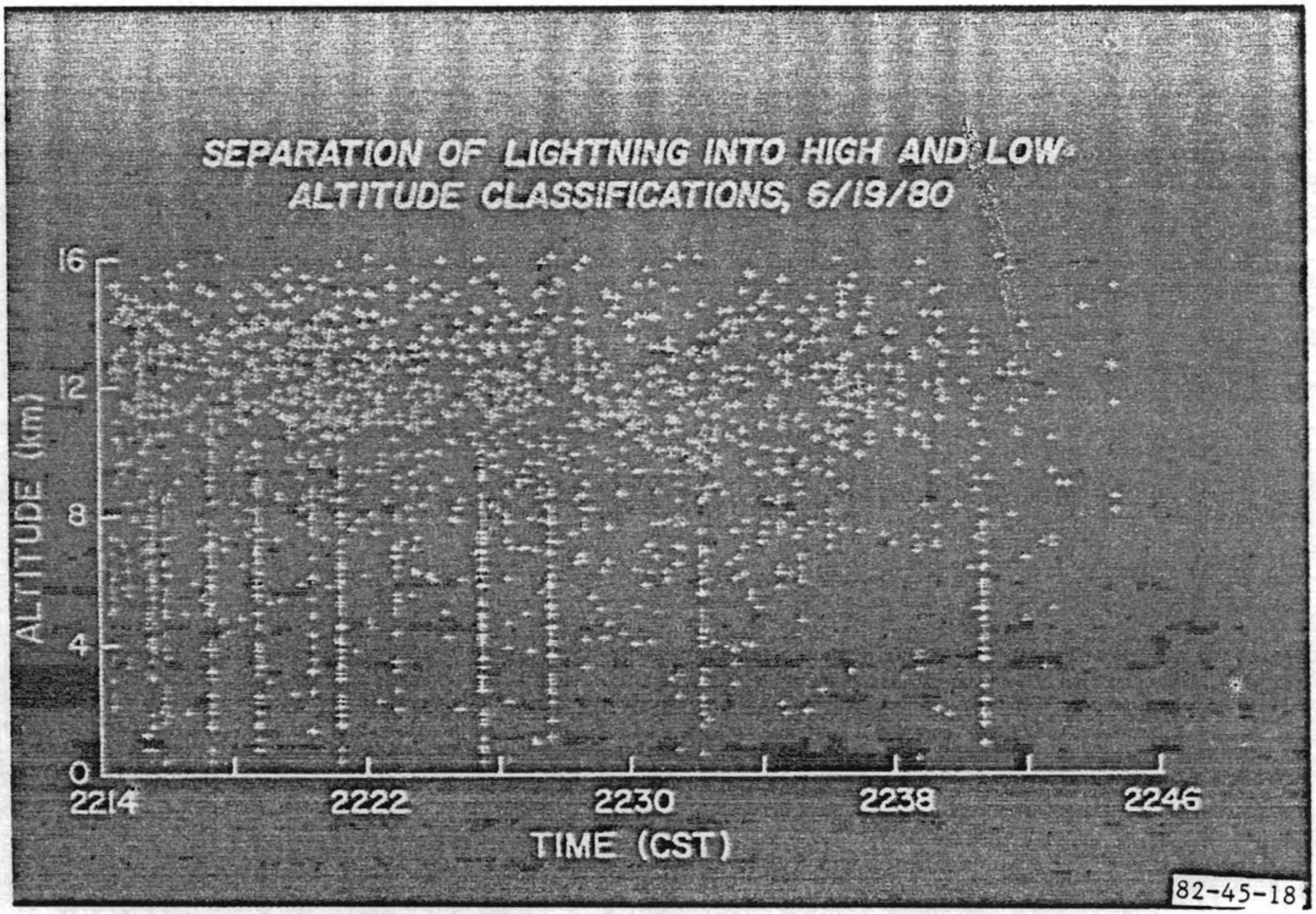
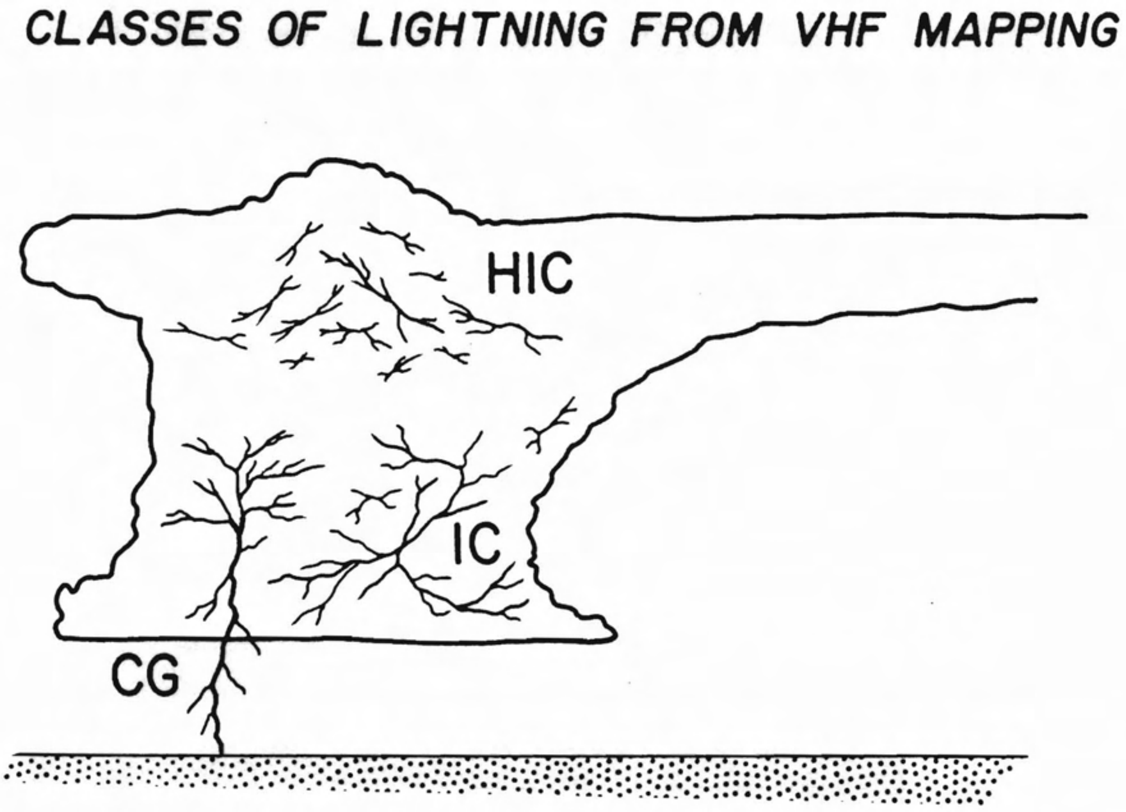


FIGURE 18

VHF impulse source altitudes for flashes during part of one storm. This color coded presentation depicts our recent observation that flashes originating high in a storm do not, in general, propagate into the lower region and vice versa. The yellow +'s are for flashes originating high in the storm, the green for those in lower regions.



82-45-19

FIGURE 19

Depiction of classes of lightning that has been expanded to include high intracloud flashes (HIC). The HIC seem to occur at higher flash rates and be independent of flashes lower in the storm.

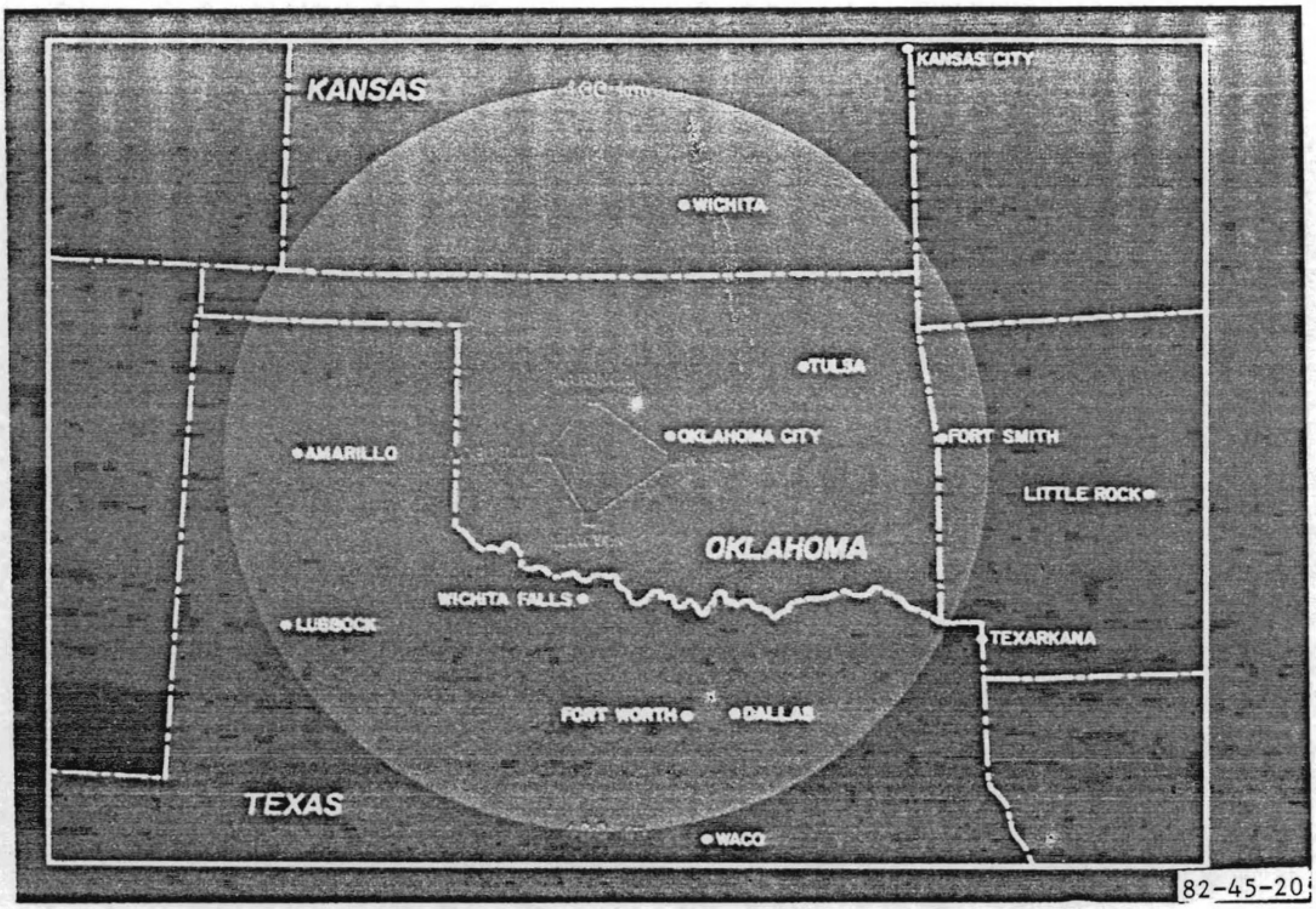
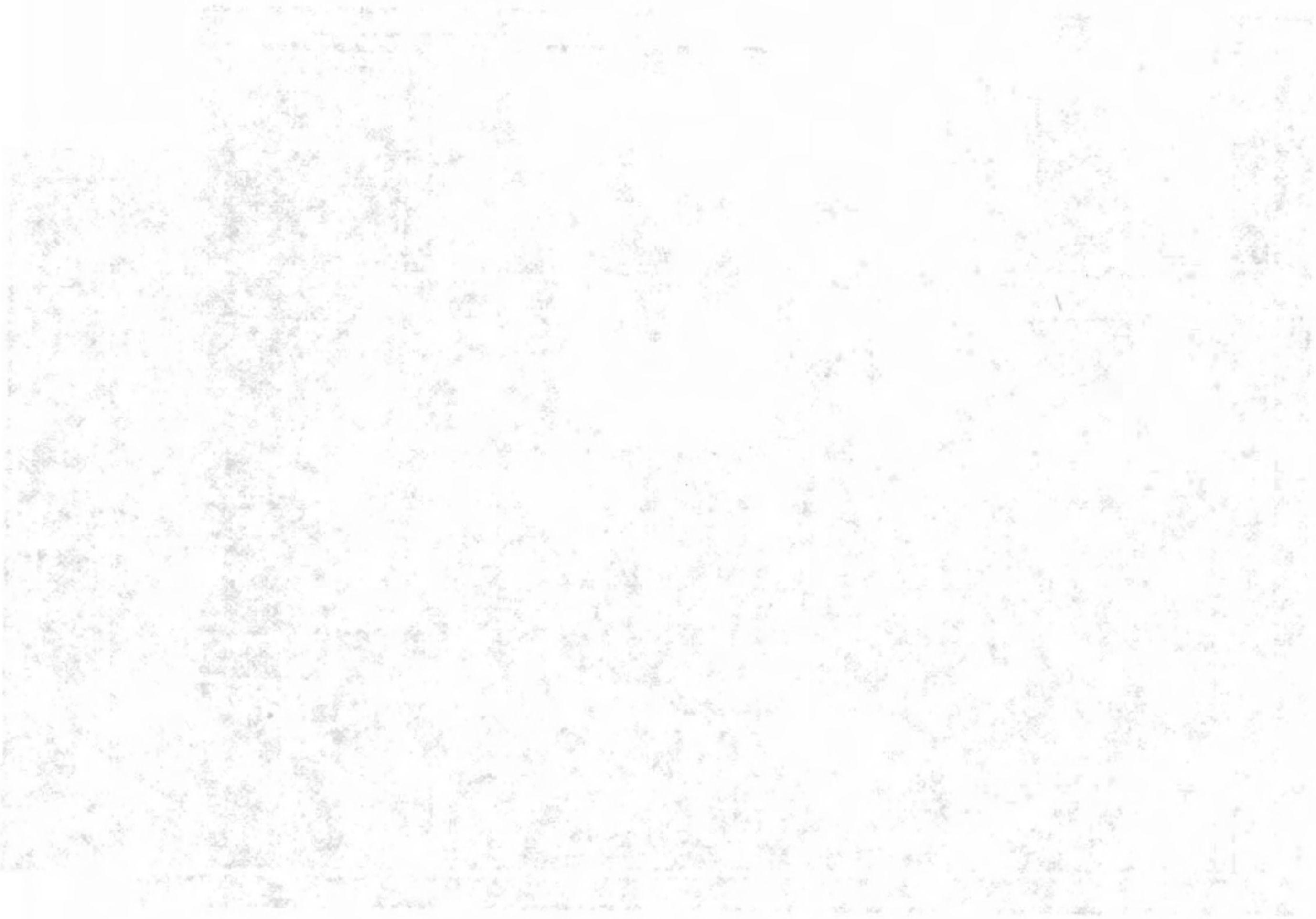


FIGURE 20

Cloud-to-ground (CG) lightning strike location network. The four-site locations and baselines are in red; the yellow circle denotes the nominal detection range of about 400 km. The system (commercially available from Lightning Location and Protection, Inc.) has been modified to detect flashes lowering positive change to ground (+CG flash) in addition to the more common negative flashes (-CG). The capability of the -CG flash detection is well documented; the +CG flash detection modification is still undergoing tests.



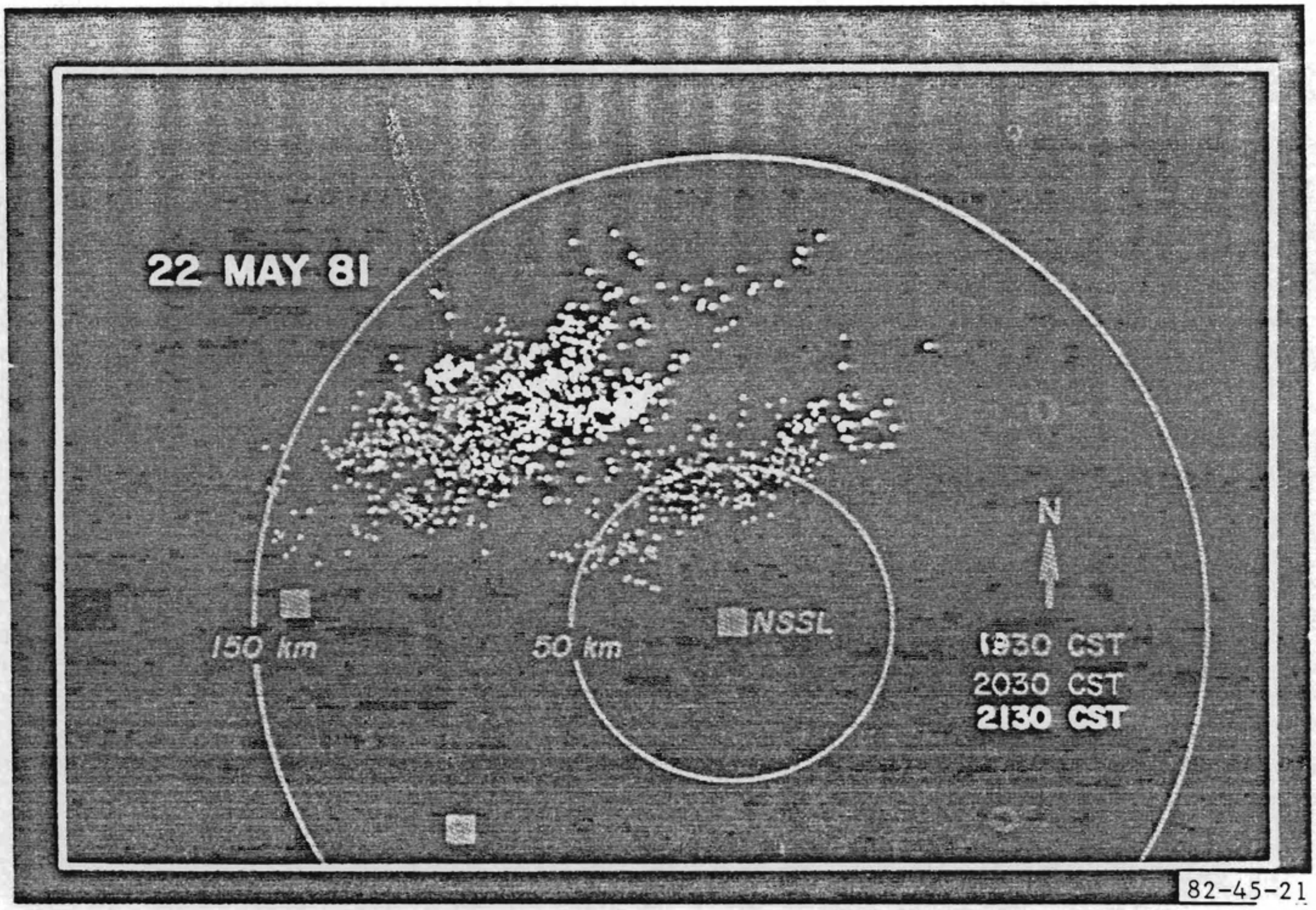


FIGURE 21

Example of storm tracking using CG flash strike points for two storms moving northeastward through the network. Different colors are for alternate 30-minute intervals.

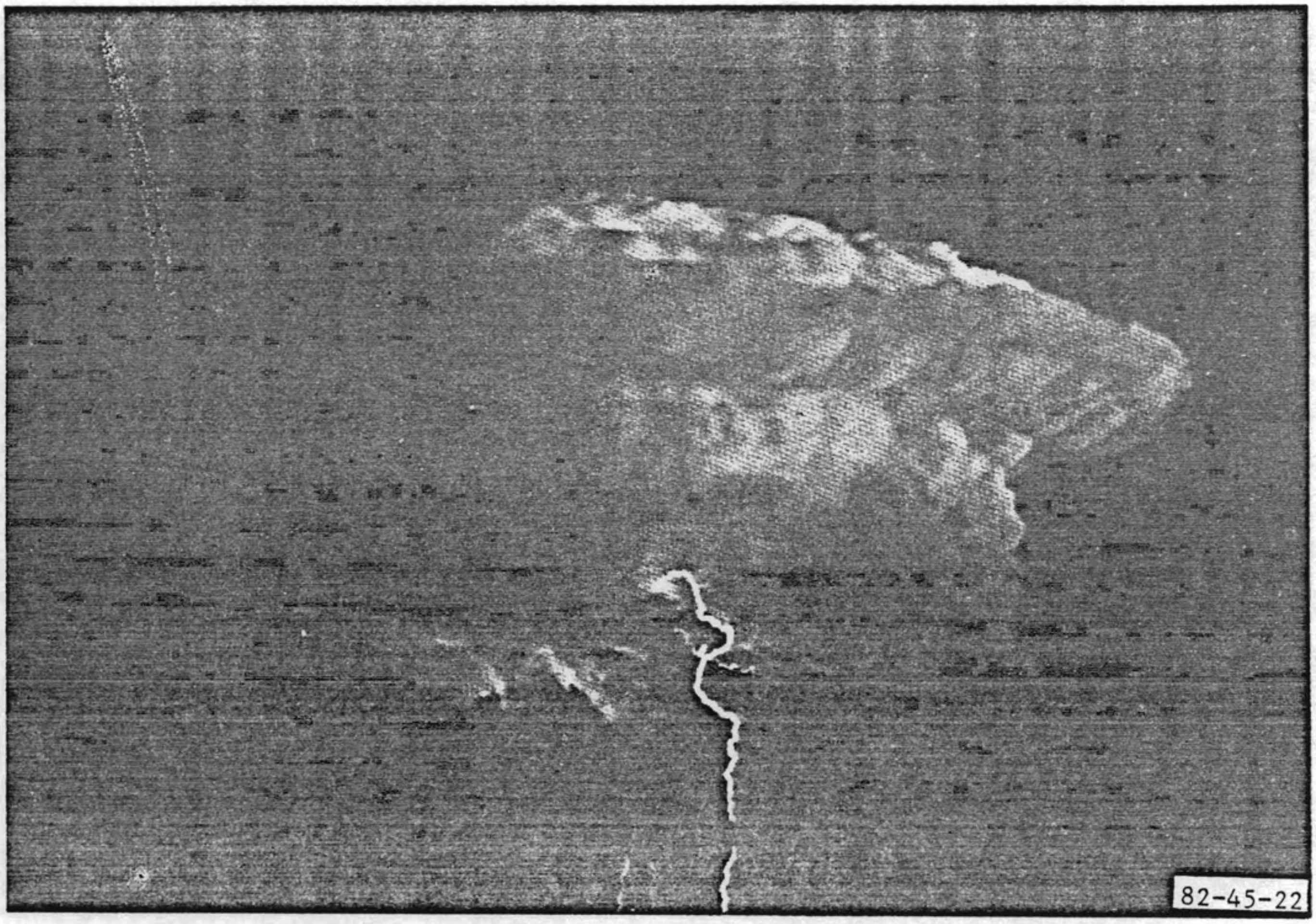
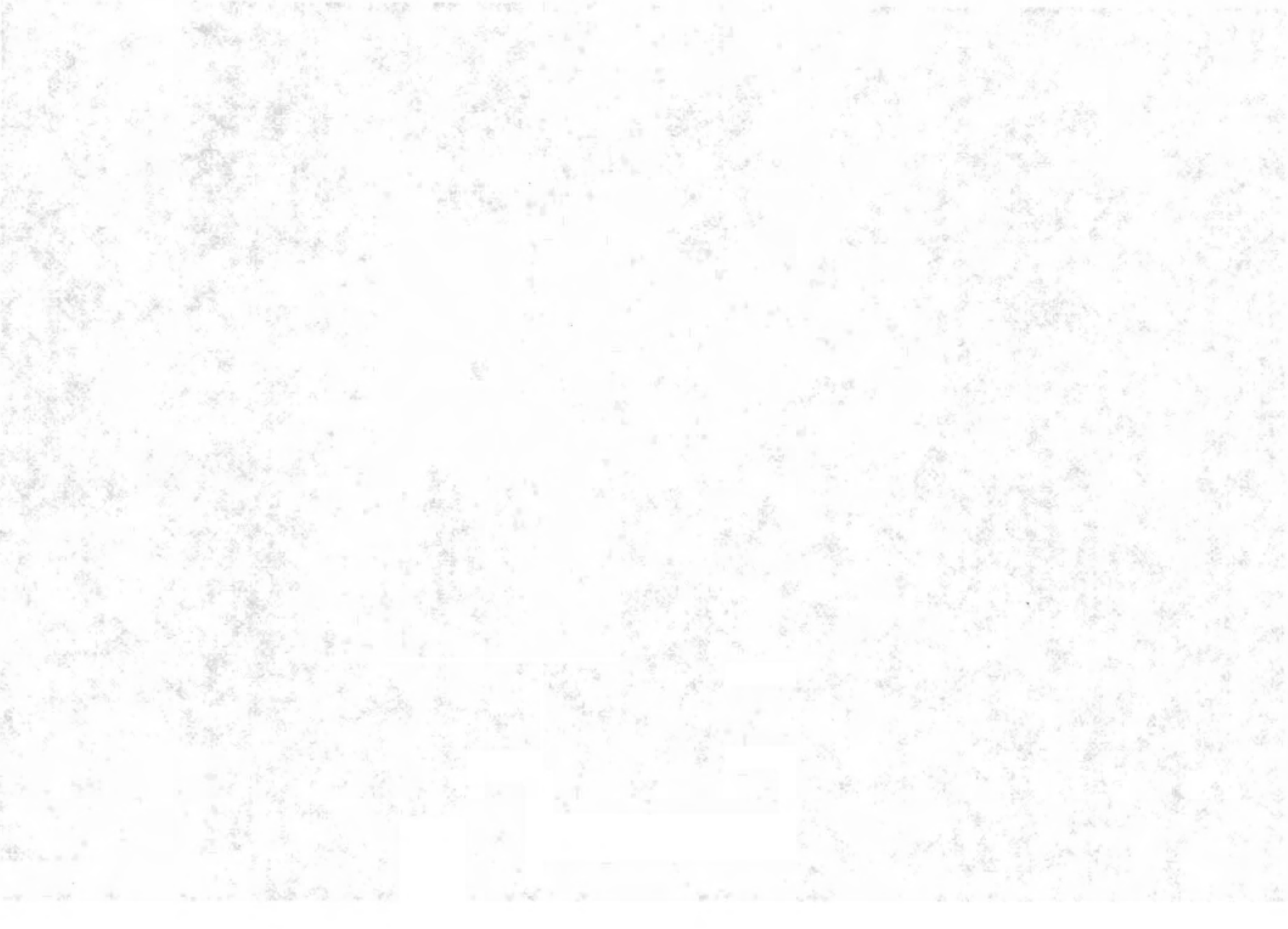


FIGURE 22

Observation of lightning emanating from high in a large storm. Two of the more common CG flashes in the precipitation are seen at the bottom.



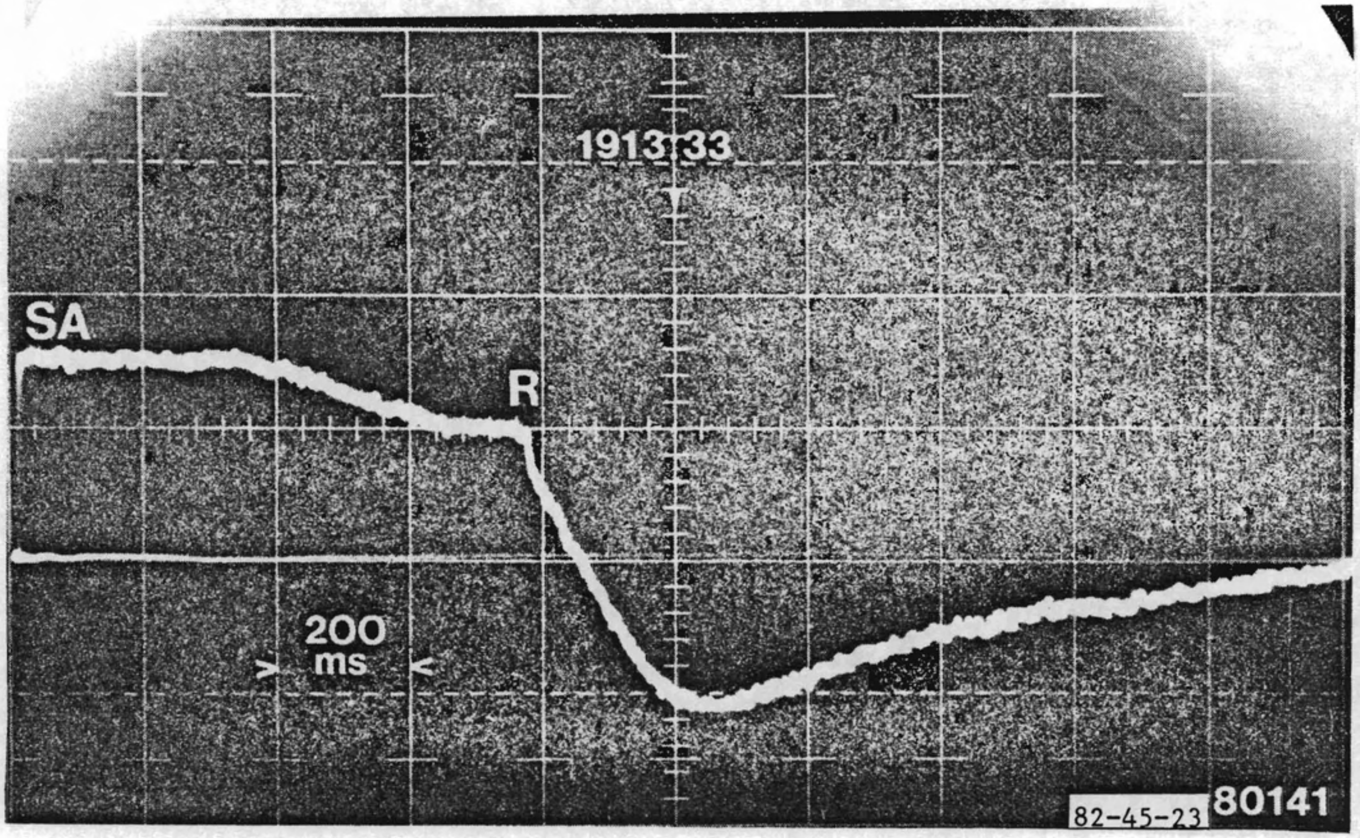


FIGURE 23

Electric field change, ΔE, for a +CG flash. Typically these flashes are characterized by significant preliminary breakdown, a single return stroke (R), and a large field change indicative of continuing current flow.

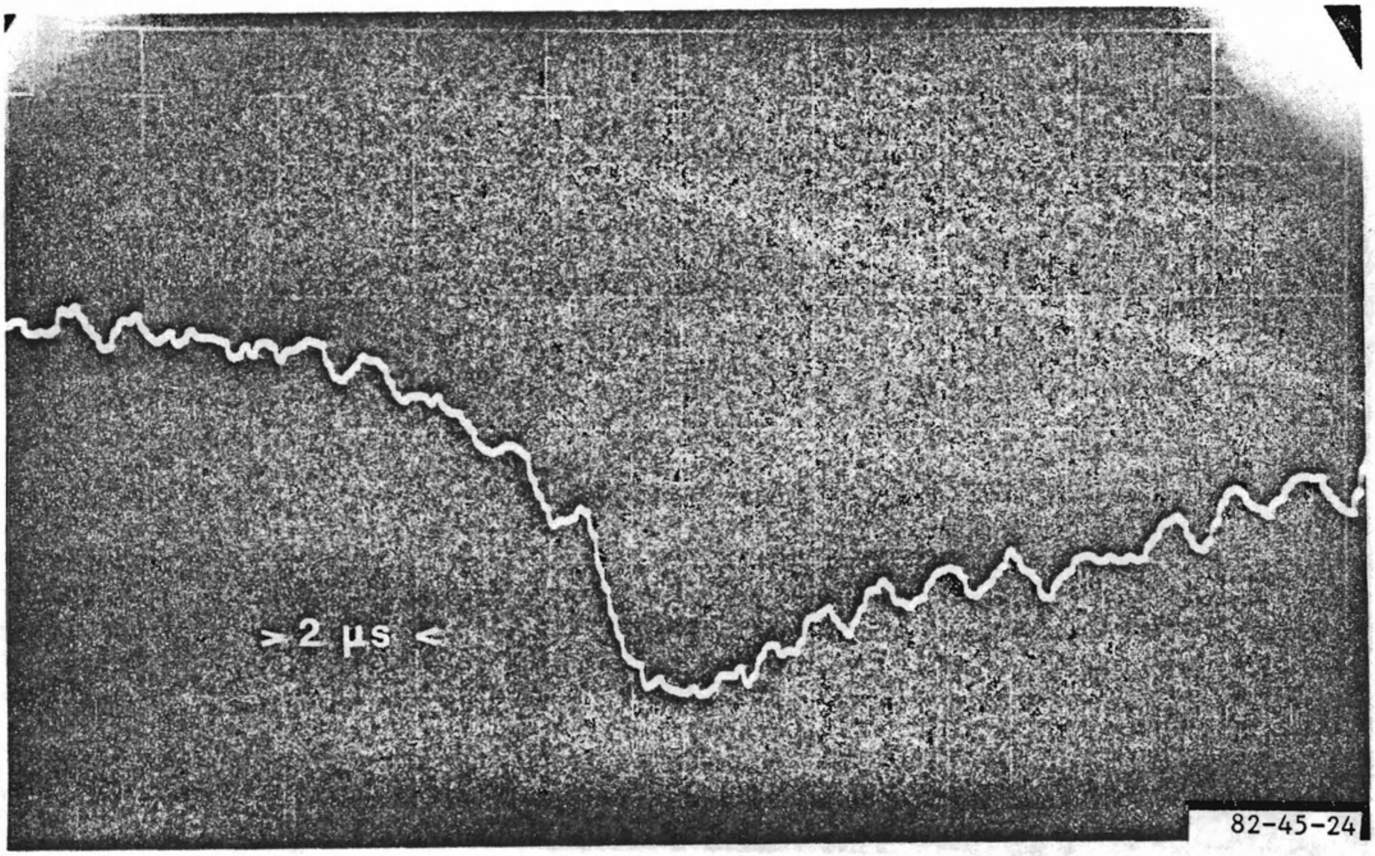
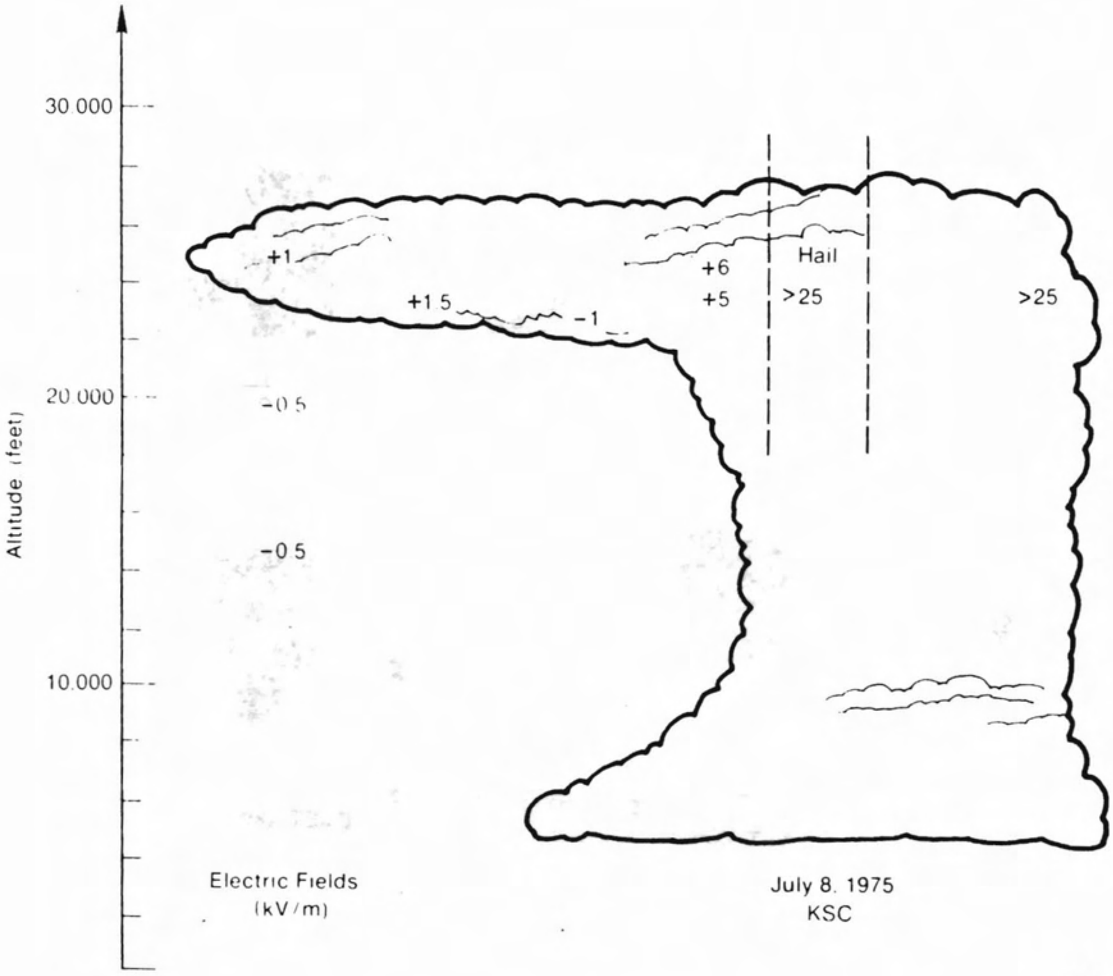


FIGURE 24

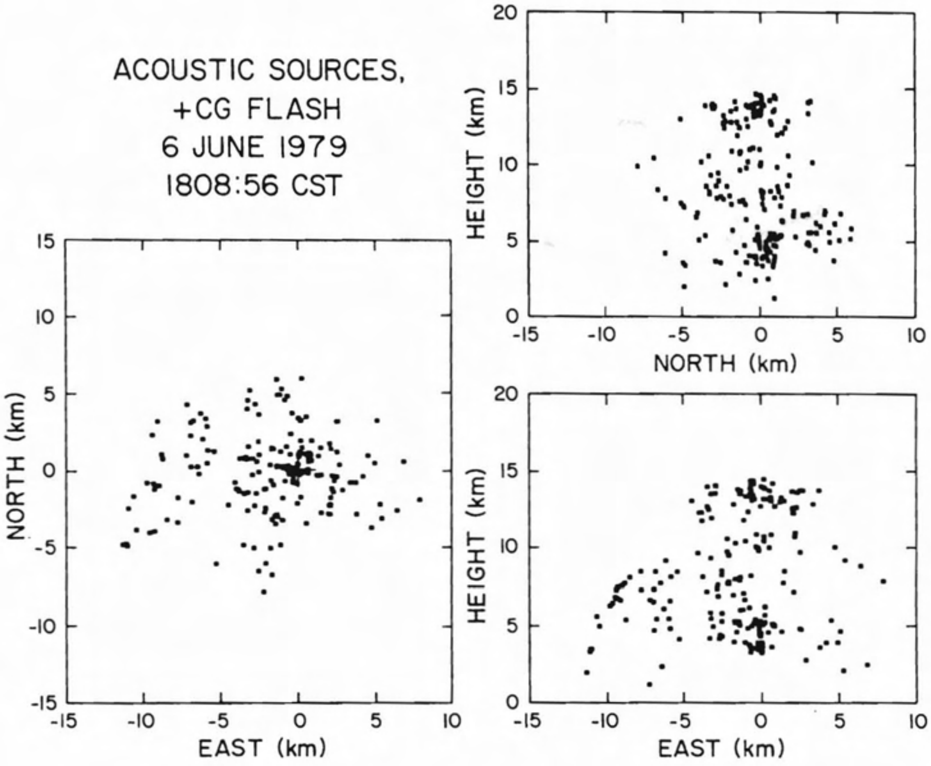
Expanded ΔE for a return stroke for a +CG flash striking about 10-15 km from NSSL. The slow ramp is followed by a fast one with a submicrosecond rise time. The fast ramp shown here is at the bandwidth limit of our recorder and may be further slowed by propagation effects. +CG return strokes thus appear to have fast rise times.



82-45-25

FIGURE 25

Electric fields, E, in Florida thunderstorm. E in main storm turret exceeds 25 kV/m (limit of instruments), while those in anvil are very low.



82-45-26

FIGURE 26

Reconstructed thunder sources for a +CG flash. NSSL is at the origin, and the freezing level is about 4 km. Note there are significant channels through a large depth of the storm, including at anvil heights.

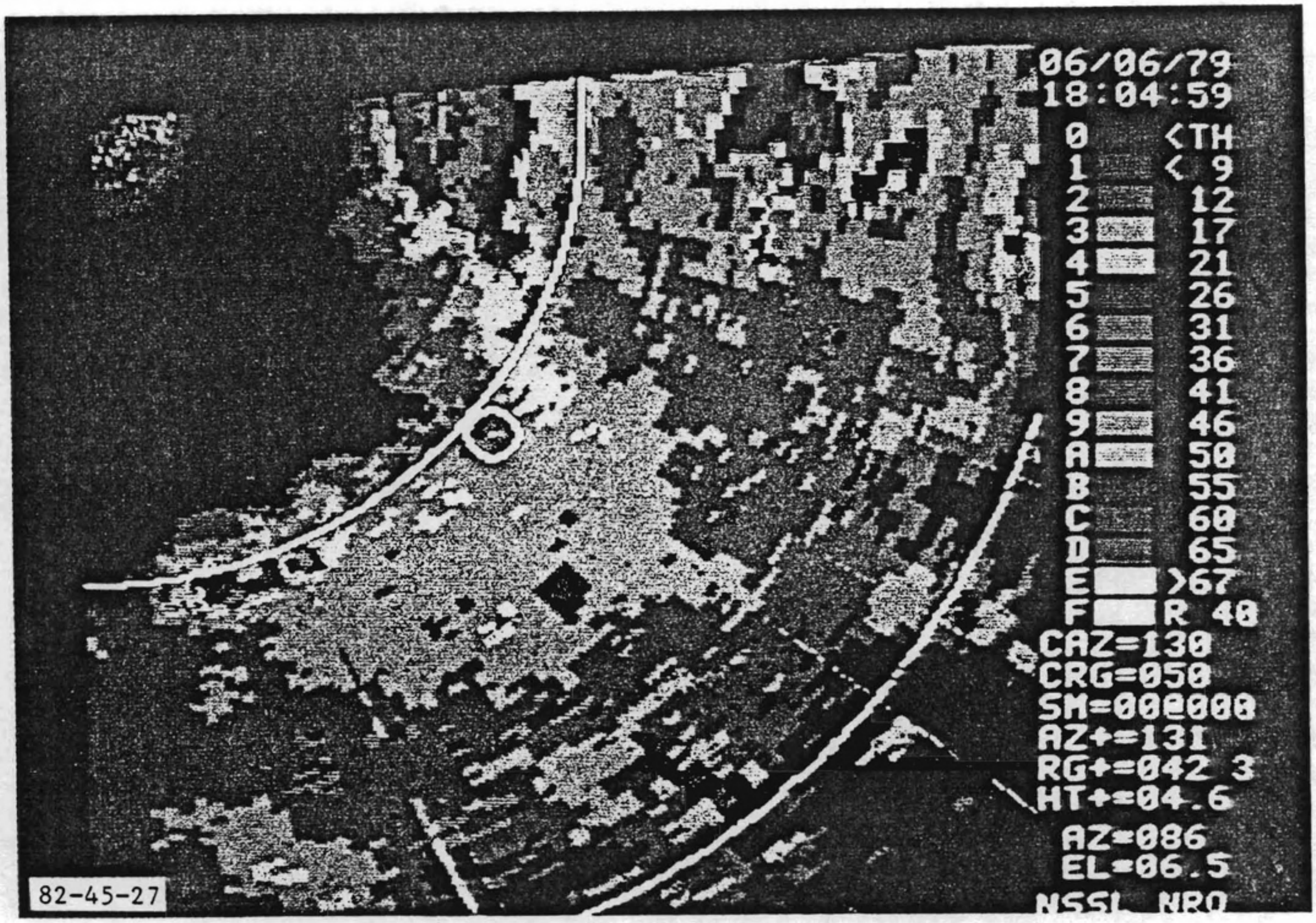


FIGURE 27

Plan Position Indicator (PPI) through back of squall line. A +CG flash occurred in the area of the cursor in reflectivities of 17 dBZ at a height of 4.6 km. The higher portions of this +CG flash were in even lower reflectivities.

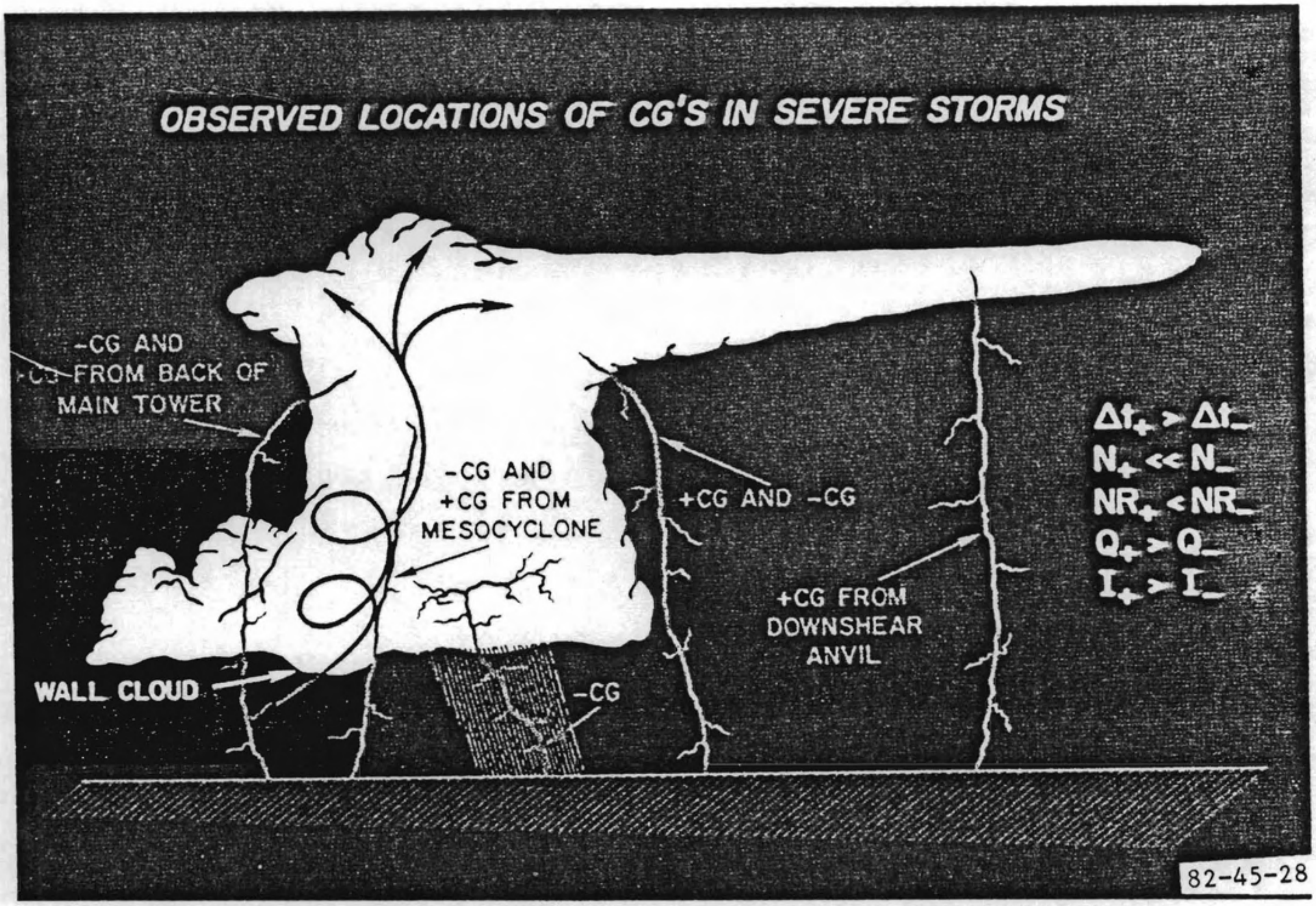
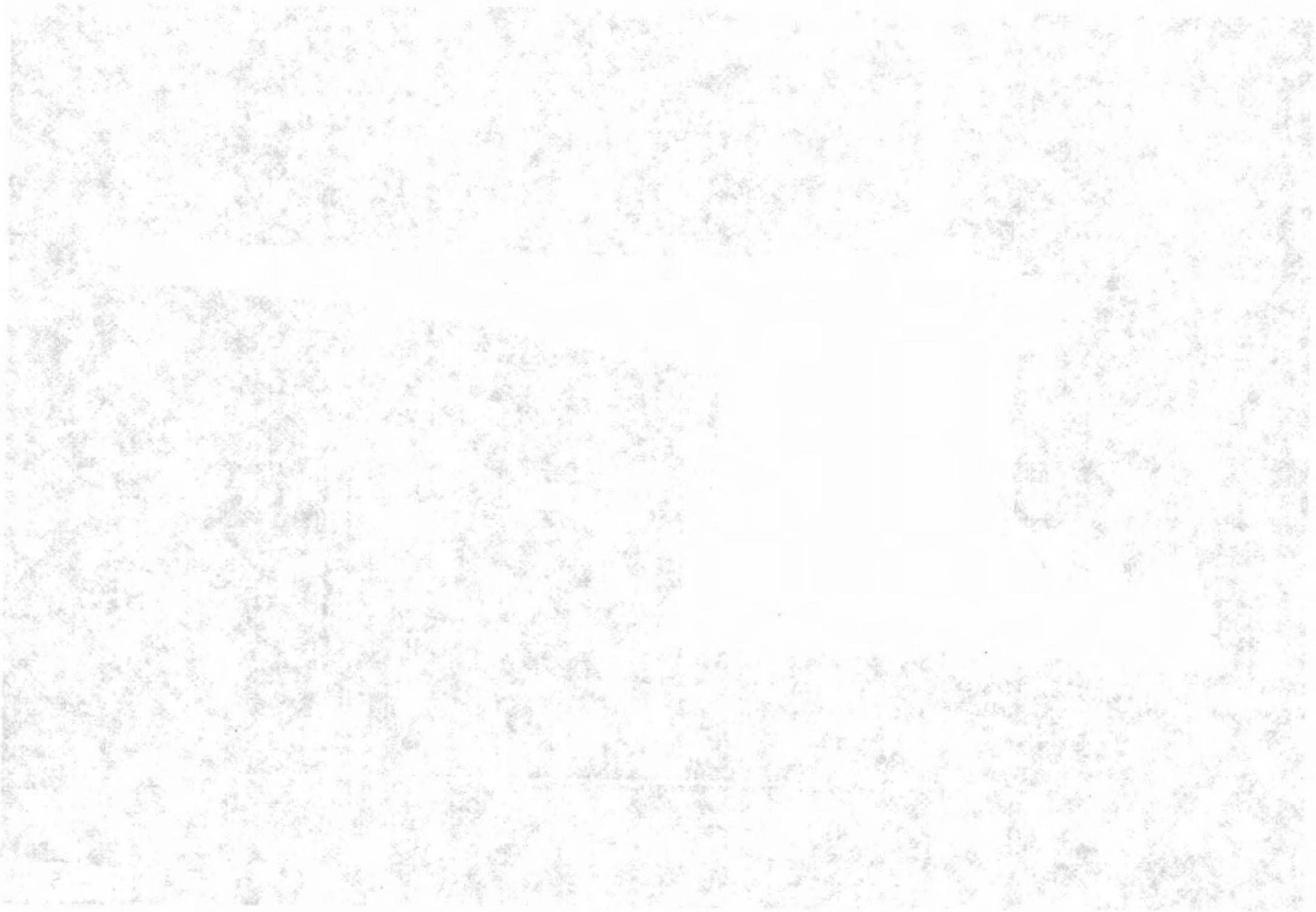


FIGURE 28

Sketch of observed locations and polarities of CG flashes from severe thunderstorms. The spiral denotes the region of intense updraft and rotation. Typical characteristics of +CG flashes relative to -CG's are: the total duration (Δt_+) is longer; the total number of flashes (N_+) is much less; the number of return strokes per flash (NR_+) is less, generally only 1, and the total charge transfer (Q_+) and peak current (I_+) also are often greater.



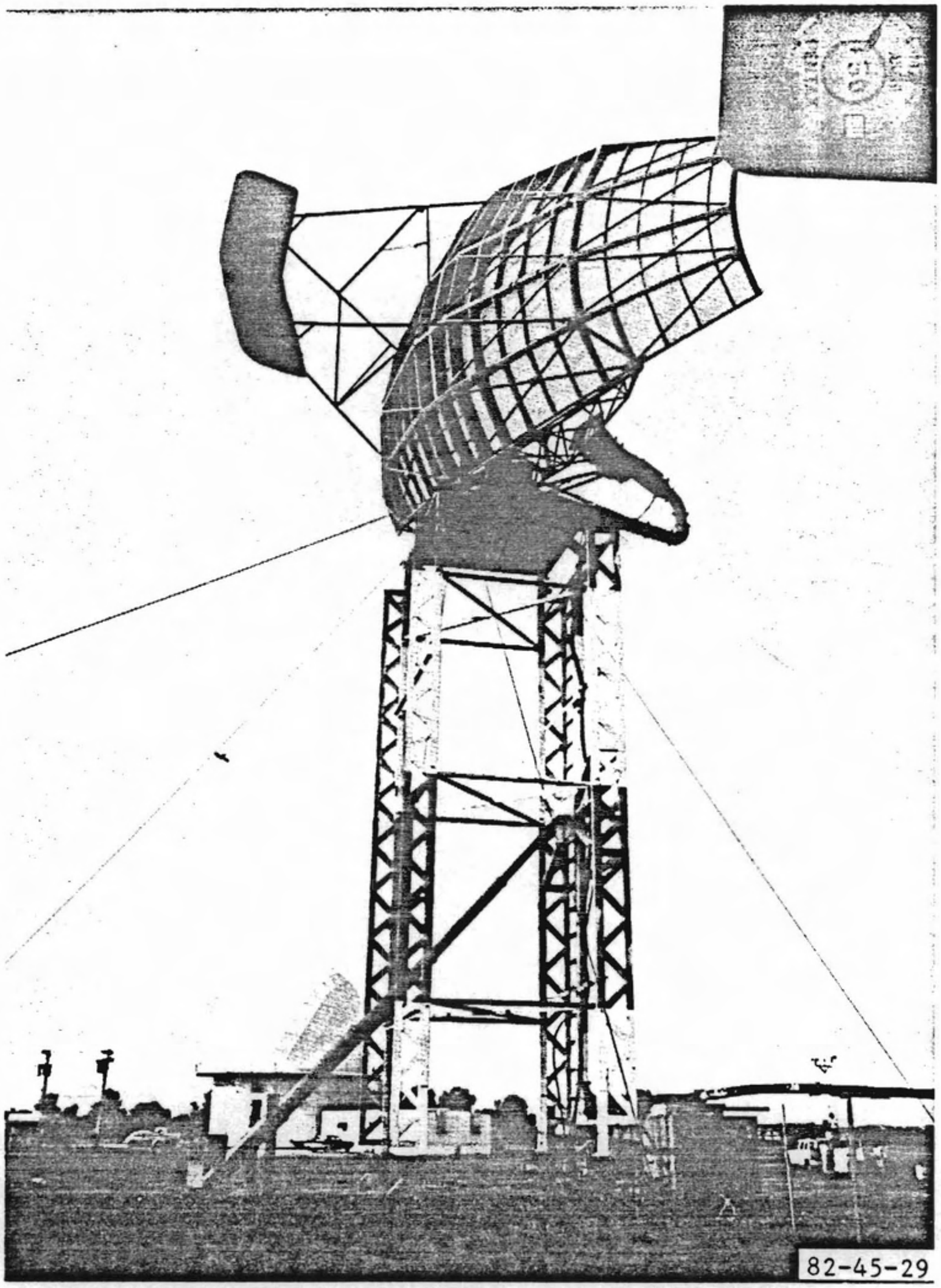


FIGURE 29

23 cm wavelength (L-band) aircraft tracking radar modified for lightning echo observations. (Doppler radar at NSSL is in background). The radar has both linear and circular polarization capabilities.

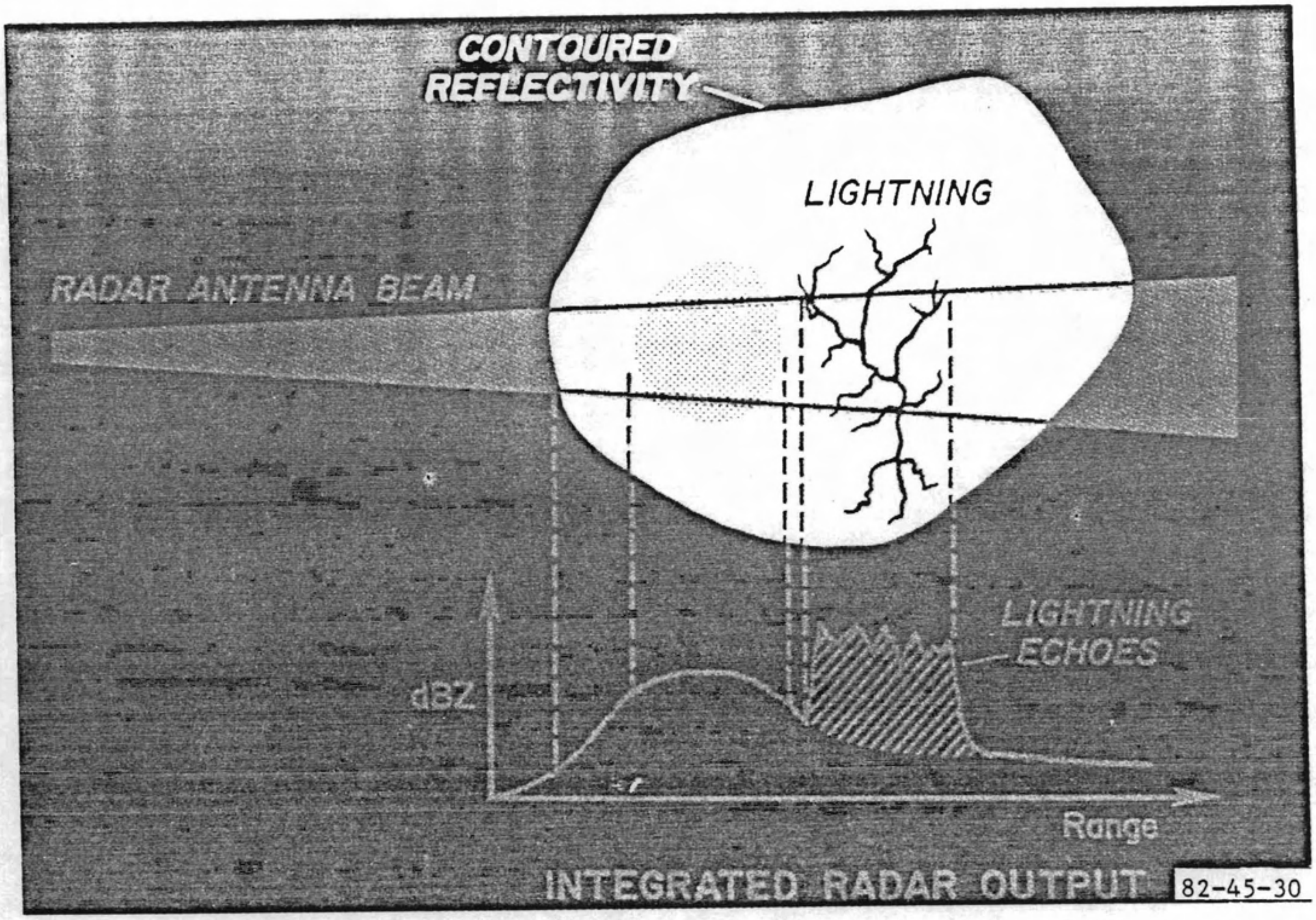
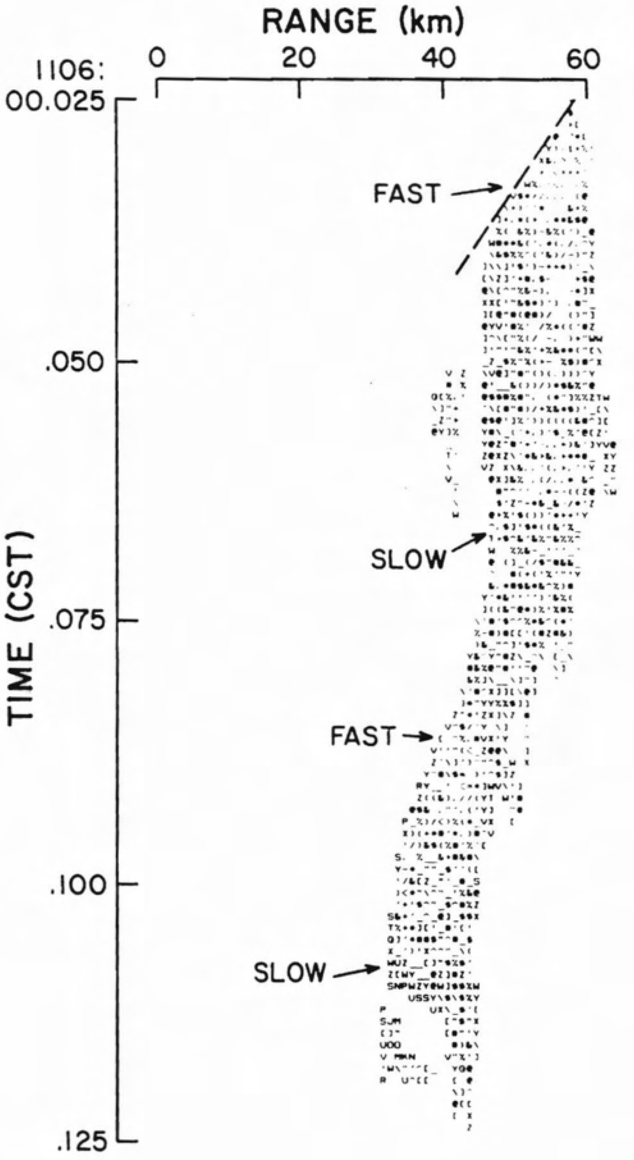


FIGURE 30

Concept of radar observations of lightning within a storm. The shaded blue area corresponds to the precipitation core, which is also seen in the integrated radar output. The presence of lightning in the beam results in transient power increases that are easily discernible.



82-45-31

FIGURE 31

L-band radar echo from lightning obtained by automatic processing of storm data. The flash lasted ≈1 s and seemed to propagate, as is typical, in fast and slow modes. The symbols are codes for quantitative determination of echo power.

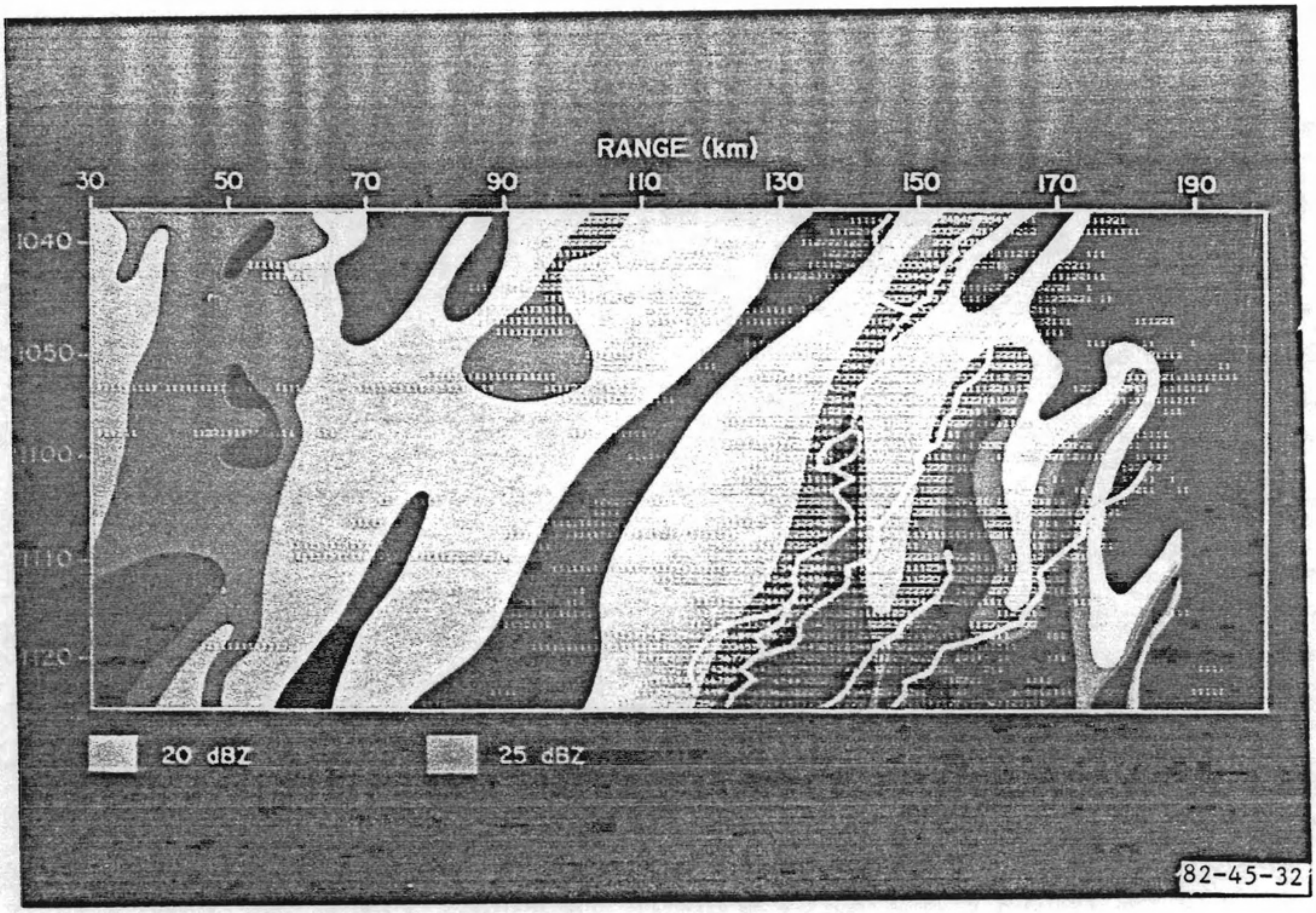


FIGURE 32

Contoured precipitation reflectivity (colors) and lightning density (numbers) for a 44-min period during a squall line. A total of 1044 flashes were observed in 2-4 cells. The white lines trace the location of maximum lightning activity associated with the cells.

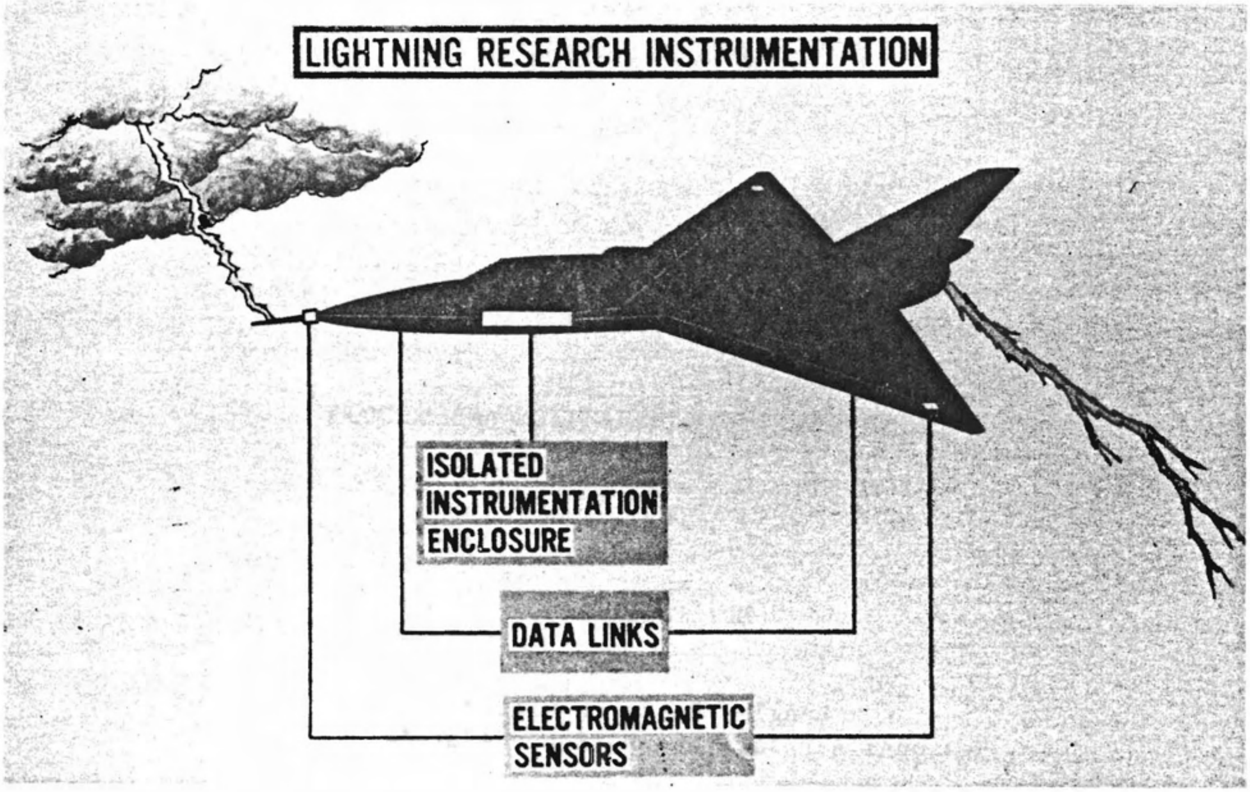
FLIGHT EXPERIMENT DEFINITION AND SUMMARY

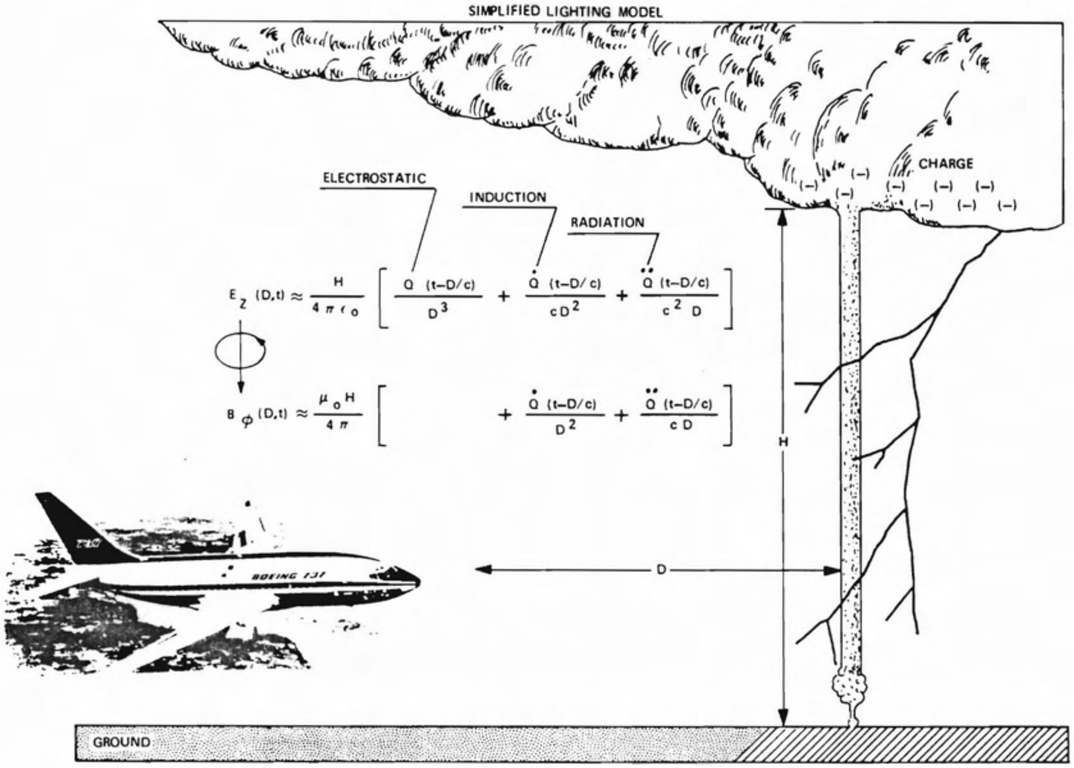
by

Mr. Felix Pitts

Langley Research Center
National Aeronautics and Space Administration

Description of NASA F-106B in-flight direct strike measurement program. Electromagnetic measurements, instrumentation concept, and results summary.





$$E_Z(D,t) \approx \frac{H}{4\pi\epsilon_0}\left[\frac{Q\ (t-D/c)}{D^3} + \frac{\dot{Q}\ (t-D/c)}{cD^2} + \frac{\ddot{Q}\ (t-D/c)}{c^2\ D}\right]$$

$$B_\phi(D,t) \approx \frac{\mu_0 H}{4\pi}\left[\qquad + \frac{\dot{Q}\ (t-D/c)}{D^2} + \frac{\ddot{Q}\ (t-D/c)}{c\ D}\right]$$

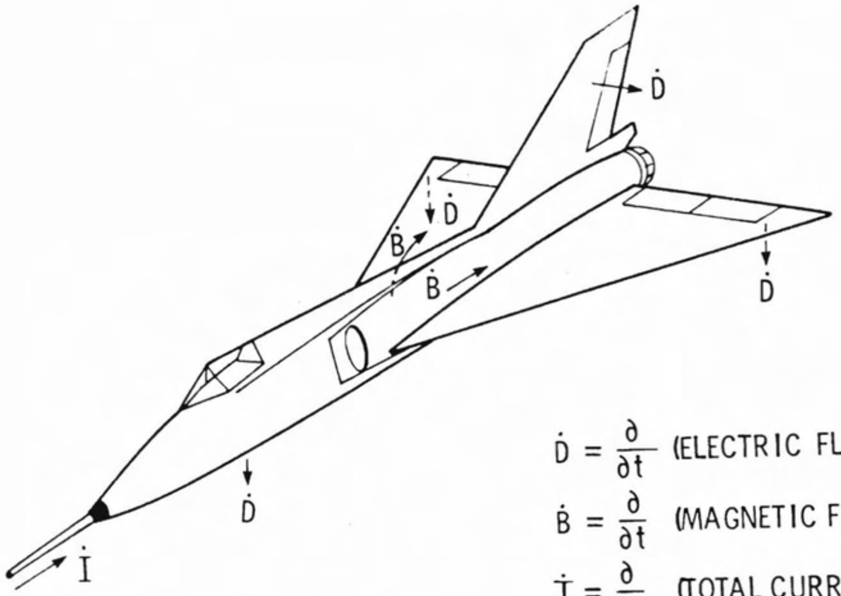
MEASUREMENTS SUMMARY

MEASUREMENT	SYMBOL	AMPLITUDE RANGE	SENSOR TYPE
RATE OF CHANGE OF ELECTRIC FLUX DENSITY	$\dot{D}$	50 A/M^2	FLUSH PLATE DIPOLE
RATE OF CHANGE OF MAGNETIC FLUX DENSITY	$\dot{B}$	2×10^4 TESLA/SEC	MULTIGAP LOOP
RATE OF CHANGE OF CURRENT	$\dot{I}$	10^{11} A/SEC	INDUCTIVE CURRENT PROBE

MEASUREMENTS SUMMARY

MEASUREMENT	SYMBOL	DIMENSION	SENSOR TYPE
• RATE OF CHANGE OF ELECTRIC FLUX DENSITY	$\dot{D}$	A/M^2	FLUSH PLATE DIPOLE
• RATE OF CHANGE OF MAGNETIC FLUX DENSITY	$\dot{B}$	TESLA/SEC	MULTIGAP LOOP
• RATE OF CHANGE OF CURRENT	$\dot{I}$	A/SEC	INDUCTIVE CURRENT-PROBE
• ELECTRIC FIELD	E	V/M	FIELD MILL
• CURRENT	I	A	CURRENT TRANSFORMER

MEASUREMENT LOCATIONS - 1980

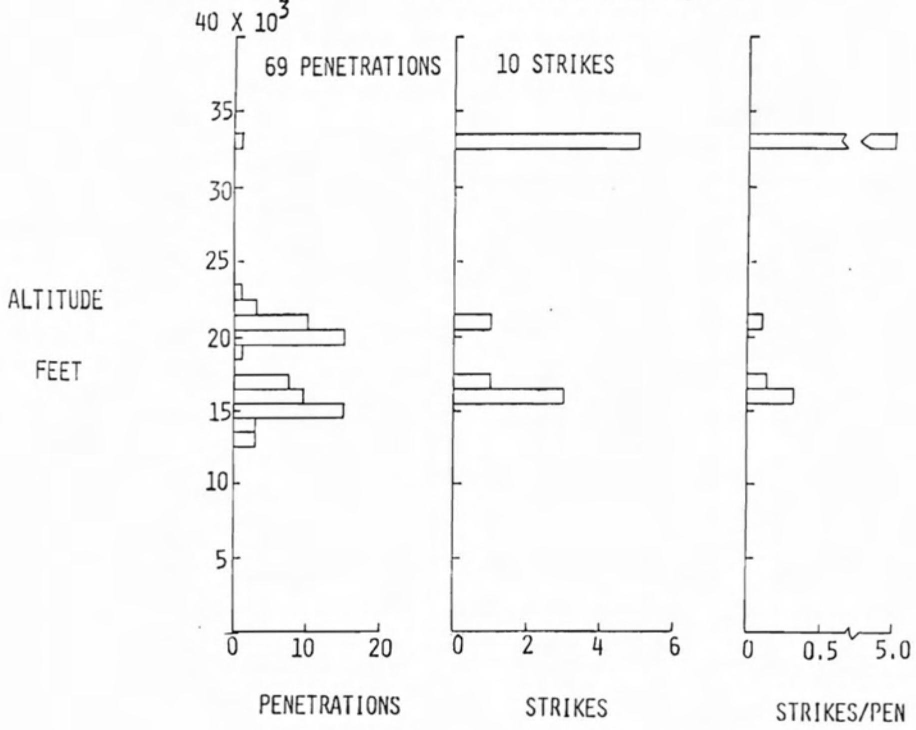


$\dot{D} = \frac{\partial}{\partial t}$ (ELECTRIC FLUX DENSITY)

$\dot{B} = \frac{\partial}{\partial t}$ (MAGNETIC FLUX DENSITY)

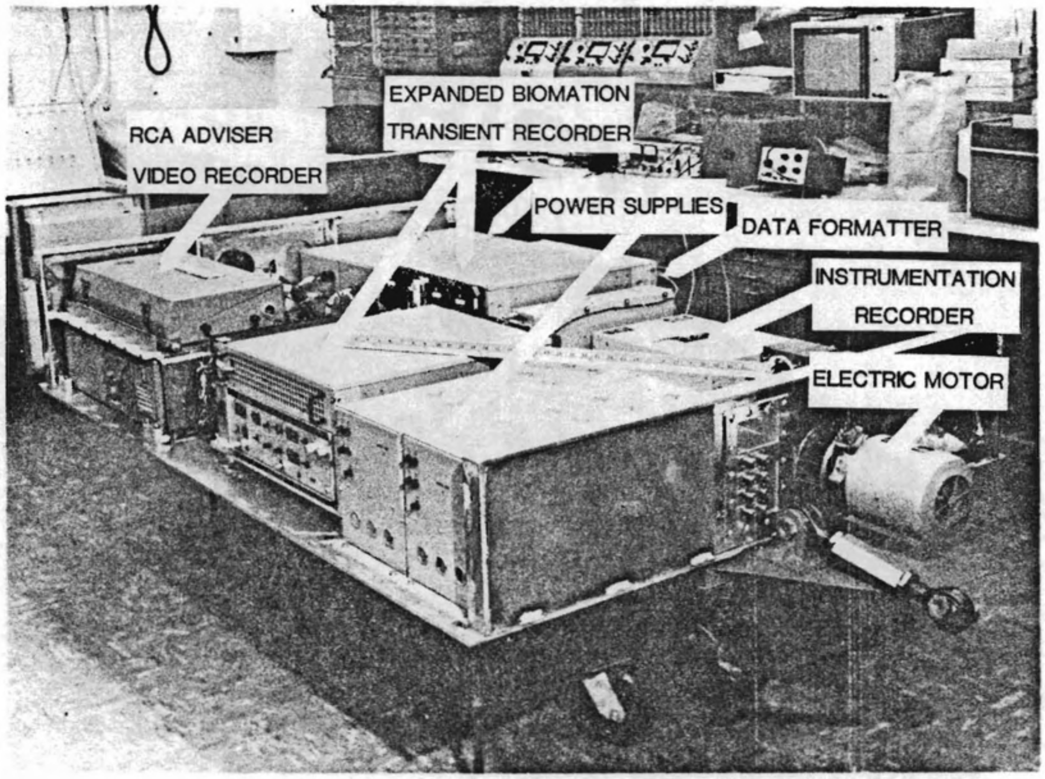
$\dot{I} = \frac{\partial}{\partial t}$ (TOTAL CURRENT)

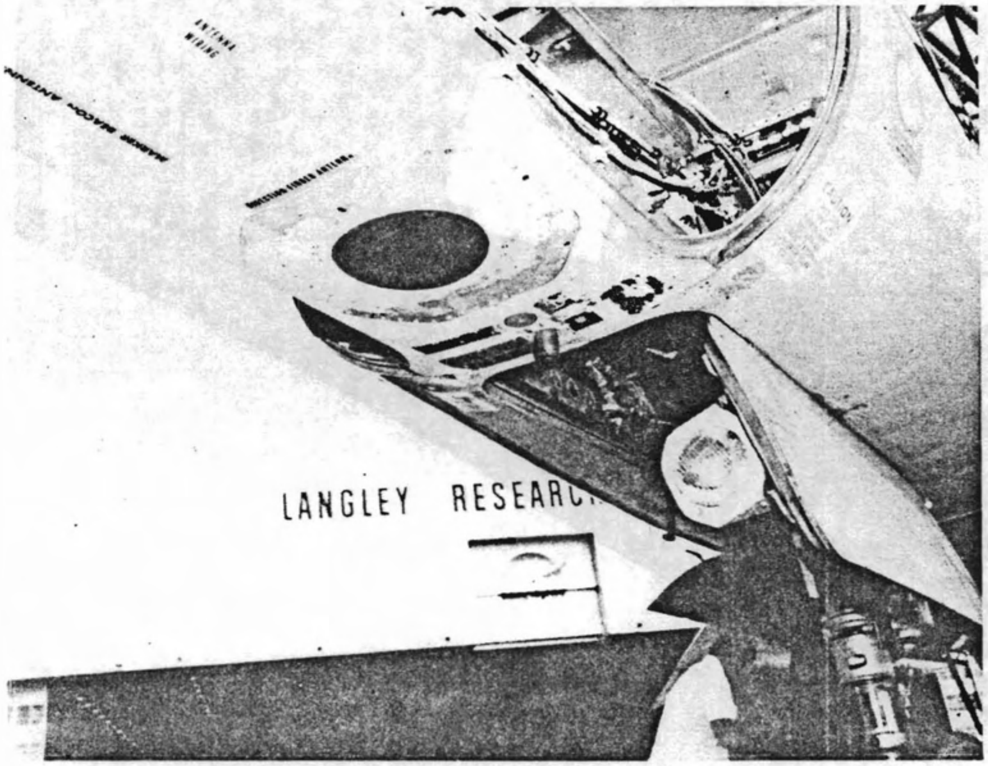
1980 LIGHTNING OCCURRENCES

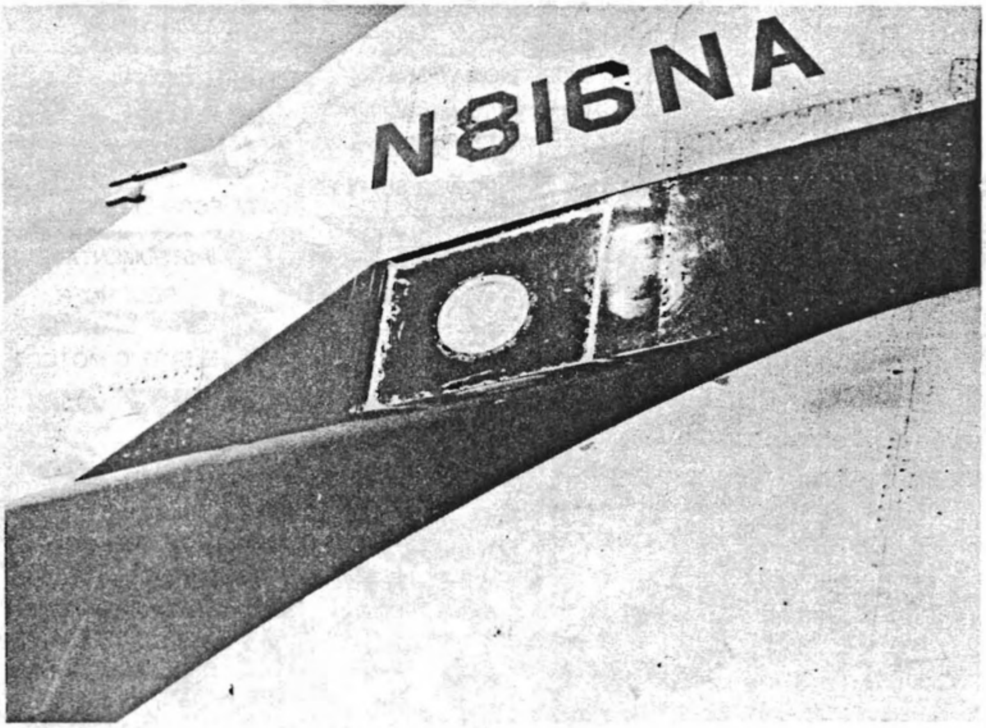


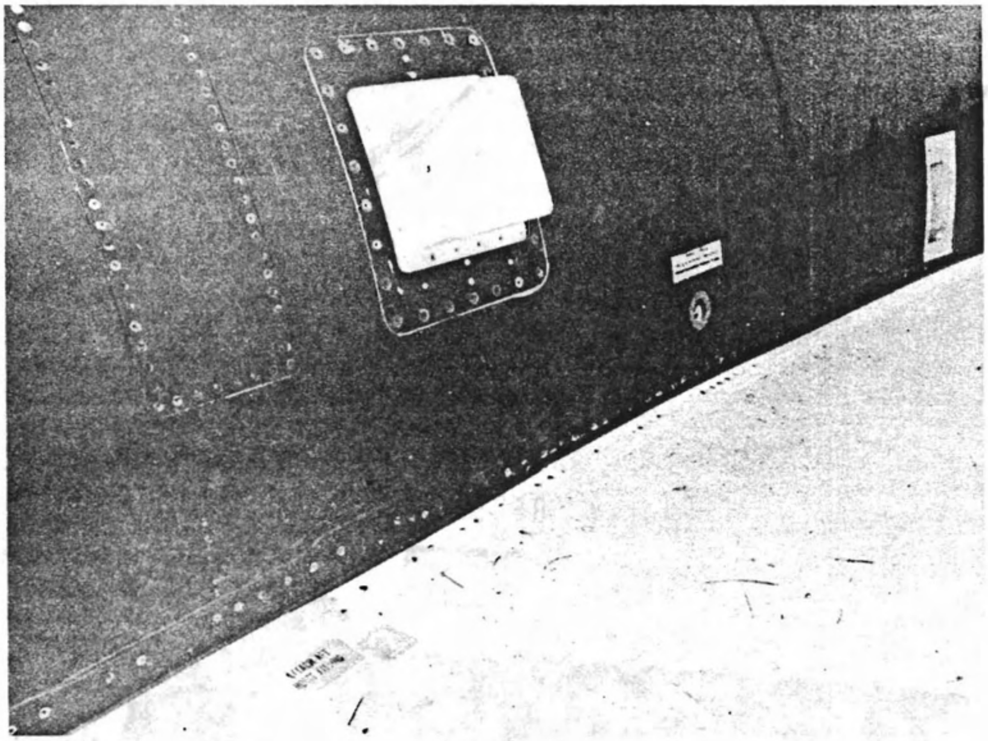
NASA
L-79-5627

INSTRUMENTATION SYSTEM






N816NA



TYPICAL DIRECT STRIKE LIGHTNING RESULTS

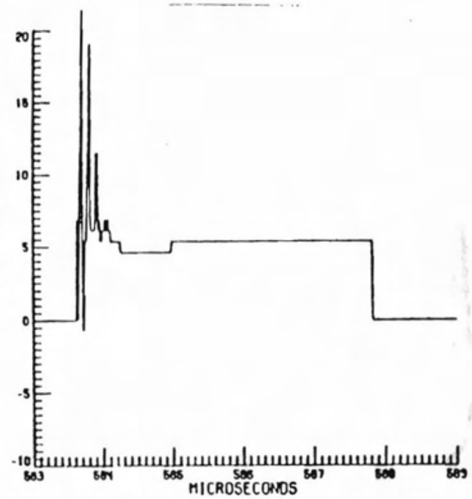


Fig. 10 D-dot sensor (flight #80-018).

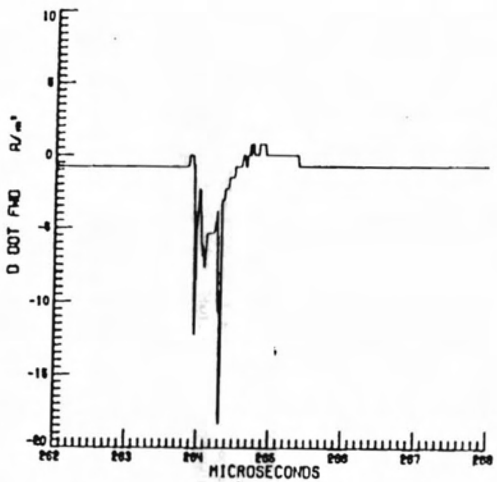


Fig. 11 D-dot sensor (flight #80-036).

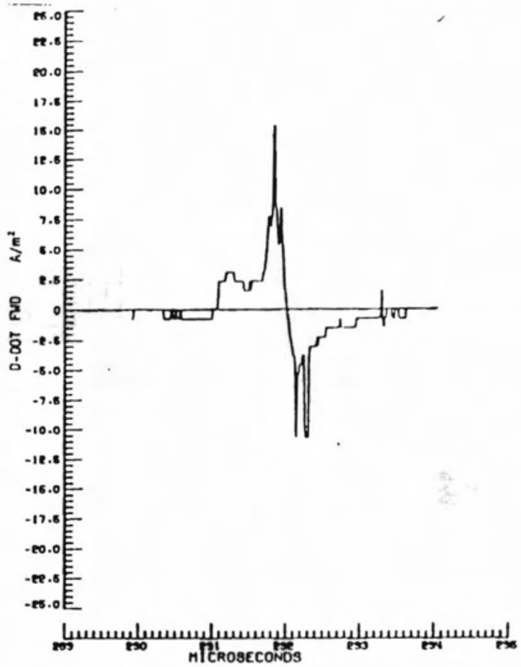


Fig. 12 D-dot sensor (flight #80-038).

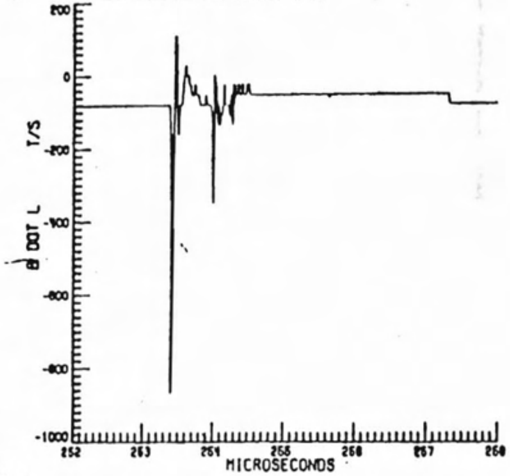


Fig. 13 B-dot sensor (flight #80-036).

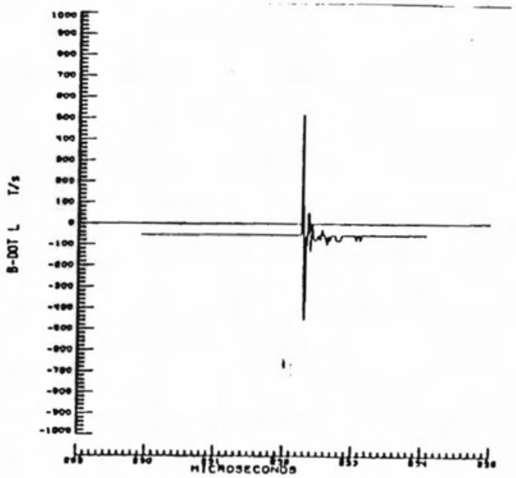


Fig. 14 B-dot sensor (flight #80-038).

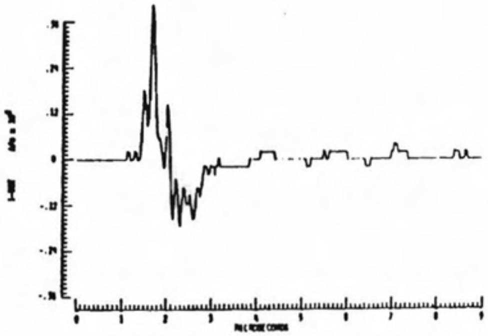
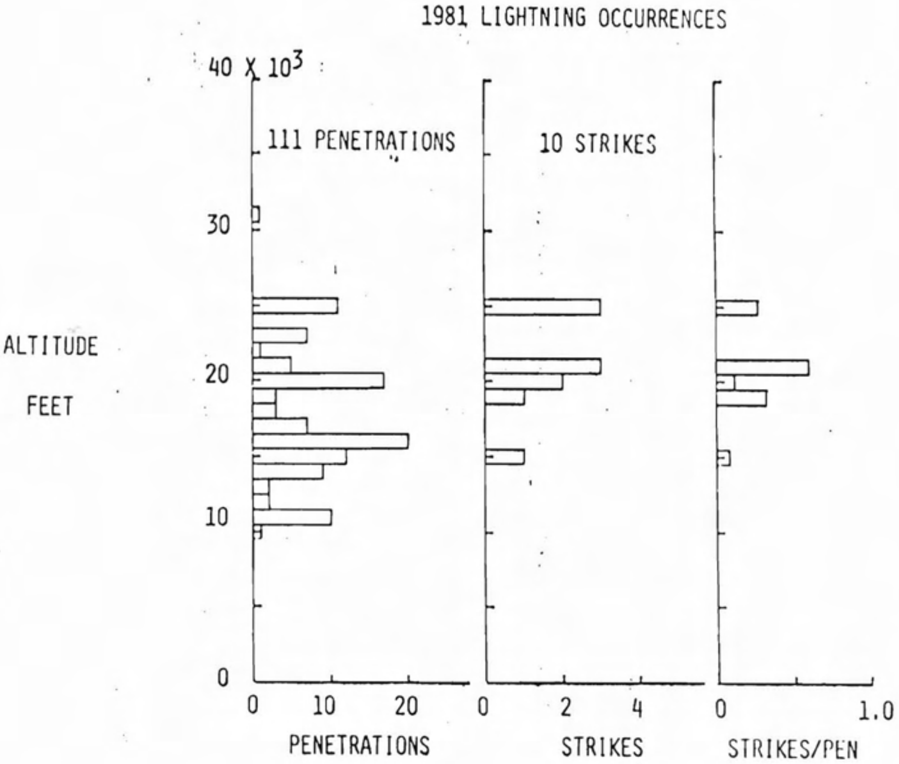
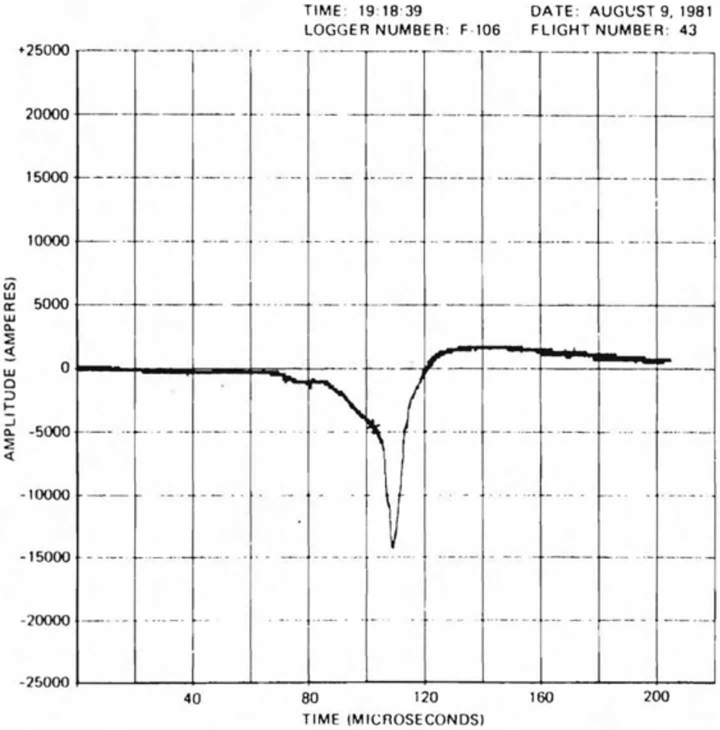


Fig. 15 I-dot sensor (flight #80-038).





X - INDICATES TRIGGER POINT

DATA SUMMARY

- 1980
  - 19 FLIGHTS 69 STORM PENETRATIONS
  - 10 STRIKES 17 TRANSIENTS: (7 $\dot{D}$, 5 $\dot{B}$, 5 $\dot{I}$)
  - RESULTS REPORTED:
    NASA TM 81946 "1980 DIRECT STRIKE LIGHTNING DATA"
    AIAA 81-0083 "E/M MEASUREMENT OF DIRECT LIGHTNING STRIKES TO A/C"
- 1981
  - 24 FLIGHTS 111 STORM PENETRATIONS
  - 10 STRIKES 27 TRANSIENTS
    1 BOOM CURRENT (BOEING)
    16 $\dot{B}$, 10 $\dot{D}$ (DISTANT)
- MAXIMUM MEASURED VALUES

  $\dot{D}$ 30.5 A/m^2 ⟶ 340 KV/0.1 μs
  $\dot{B}$ 1160 T/s ⟶ 2 KA/0.1 μs
  I 15 KA

OTHER F-106 LIGHTNING EXPERIMENTS

- ATMOSPHERIC CHEMISTRY EXPERIMENTS - LaRC
  1980 - SHOWED N_2O ENHANCEMENT NEAR LIGHTNING
  1981 - SHOWED CO ENHANCEMENT NEAR LIGHTNING
- X-RAY EXPERIMENT - U. WASHINGTON
  1980 - SHOWED INCREASED COUNT NEAR LIGHTNING
  1981 - BEING EVALUATED
- OPTICAL SIGNATURE EXPERIMENT - NSSL
  - PROTOTYPE FOR ORBITAL LIGHTNING MAPPER
  - RESULTS BEING ANALYZED AT NSSL
- STORM SCOPE
  - TURBULENCE/LIGHTNING DO NOT ALWAYS CORRELATE
  - LIGHTNING LOCATIONS DISPLAYED TEND TO BE FURTHER FROM AIRCRAFT POSITION THAN RADAR CONTOURS (BUT AT SAME BEARING)
- BOEING DATA LOGGER
  - FIRST BOOM CURRENT RECORDED AUGUST 1981

EXPLORATORY DEVELOPMENT AND RESEARCH ON ATMOSPHERIC ELECTRICITY HAZARDS FOR THE U.S. AIR FORCE

by

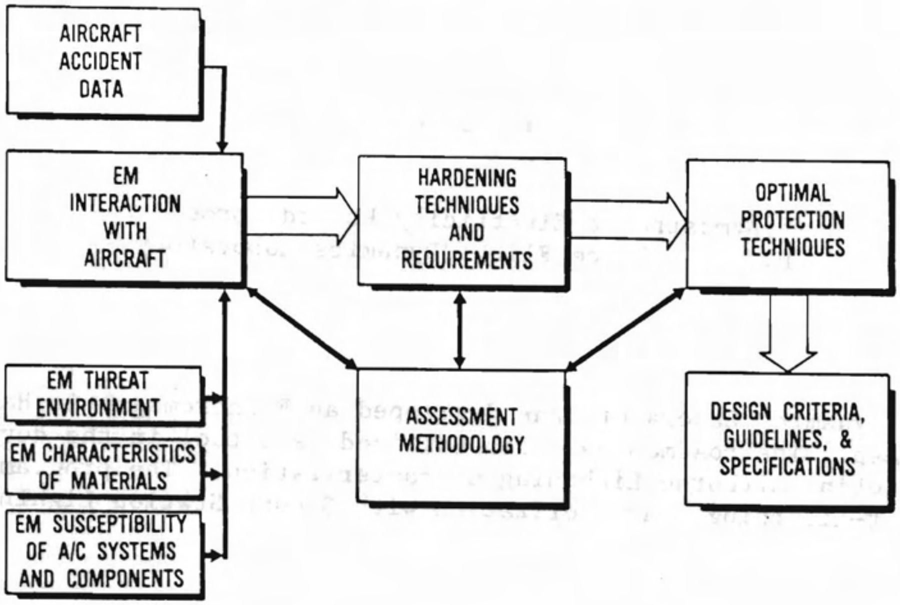
Gary DuBro

Atmospheric Electricity Hazards Group
U.S. Air Force Flight Dynamics Laboratory

Dayton, Ohio

The Flight Dynamics Laboratory has developed an Electromagnetic Hazards Technology roadmap. The roadmap has been utilized as a tool in the development of programs to define Airborne Lightning Characterization. The program correlates/combines Aircraft-Lightning characterization with Ground Station Lightning-Locator Information.

EM HAZARDS TECHNOLOGY ROADMAP



AIRBORNE LIGHTNING CHARACTERIZATION PROGRAM

OBJECTIVE:

ACQUIRE QUANTITATIVE DATA ON THE ELECTROMAGNETIC CHARACTERISTICS OF THE LIGHTNING ENVIRONMENT ENCOUNTERED BY AN AIRCRAFT IN FLIGHT:

- RADIATED ELECTRIC AND MAGNETIC FIELD TRANSIENTS PRODUCED BY A LIGHTNING FLASH
- AIRCRAFT SKIN CURRENT AND SURFACE CHARGE DISTRIBUTION RESULTING FROM FIELD TRANSIENTS AND DIRECT STRIKES
- INDUCED TRANSIENTS IN REPRESENTATIVE AIRCRAFT WIRING

APPROACH:

EMPLOY INSTRUMENTED AIRCRAFT AND GROUND SENSOR NETWORK TO COLLECT DATA DURING THUNDERSTORMS:

- AIRCRAFT-LIGHTNING CHARACTERIZATION DATA
- GROUND STATION-LIGHTNING LOCATION INFORMATION

CORRELATE/COMBINE GROUND MEASUREMENTS & OTHER AIRBORNE MEASUREMENTS AS APPROPRIATE

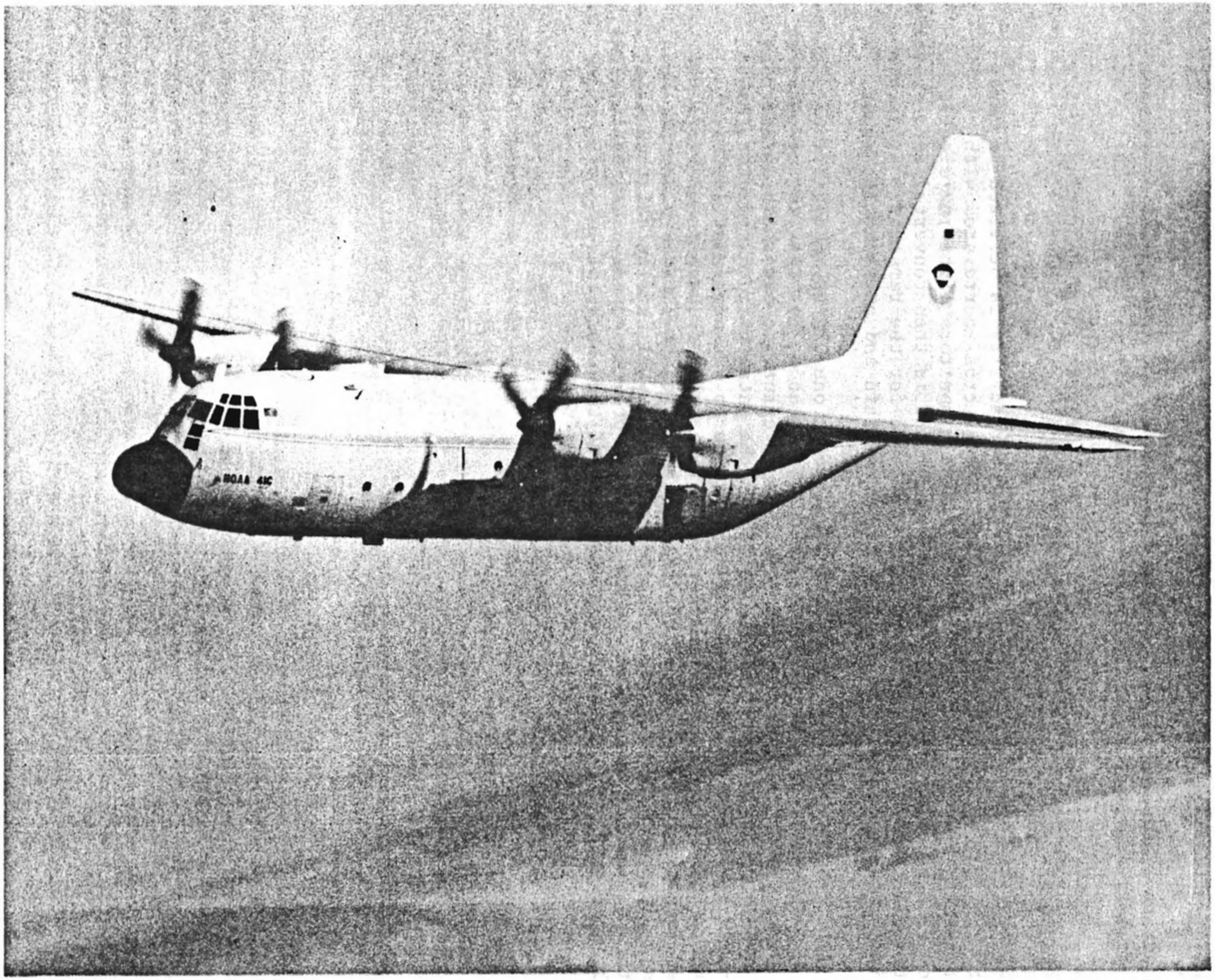
FUNDING:

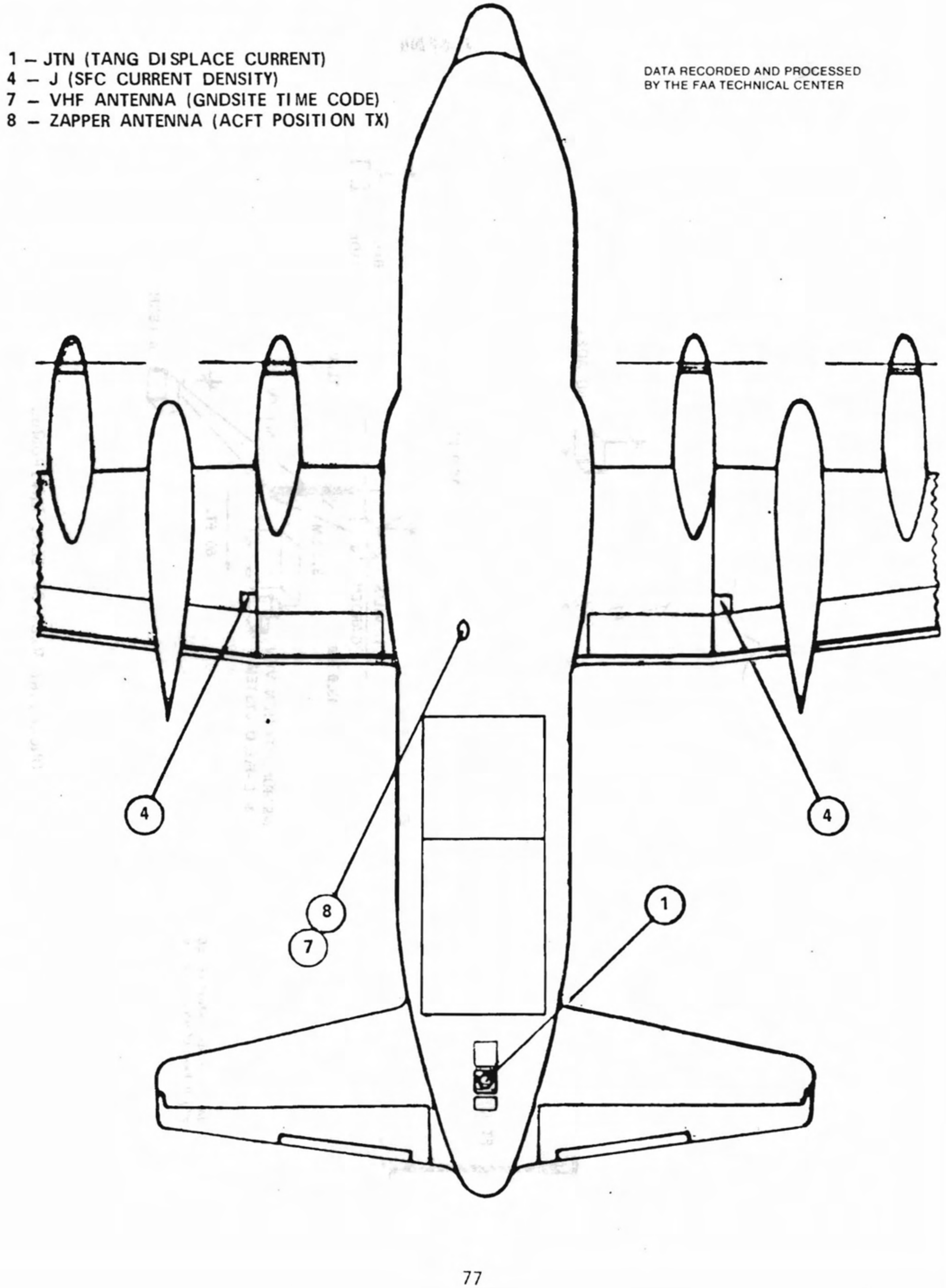
FY 81	FY 82	FY 83	FY 84
316K	163K	45K	45K

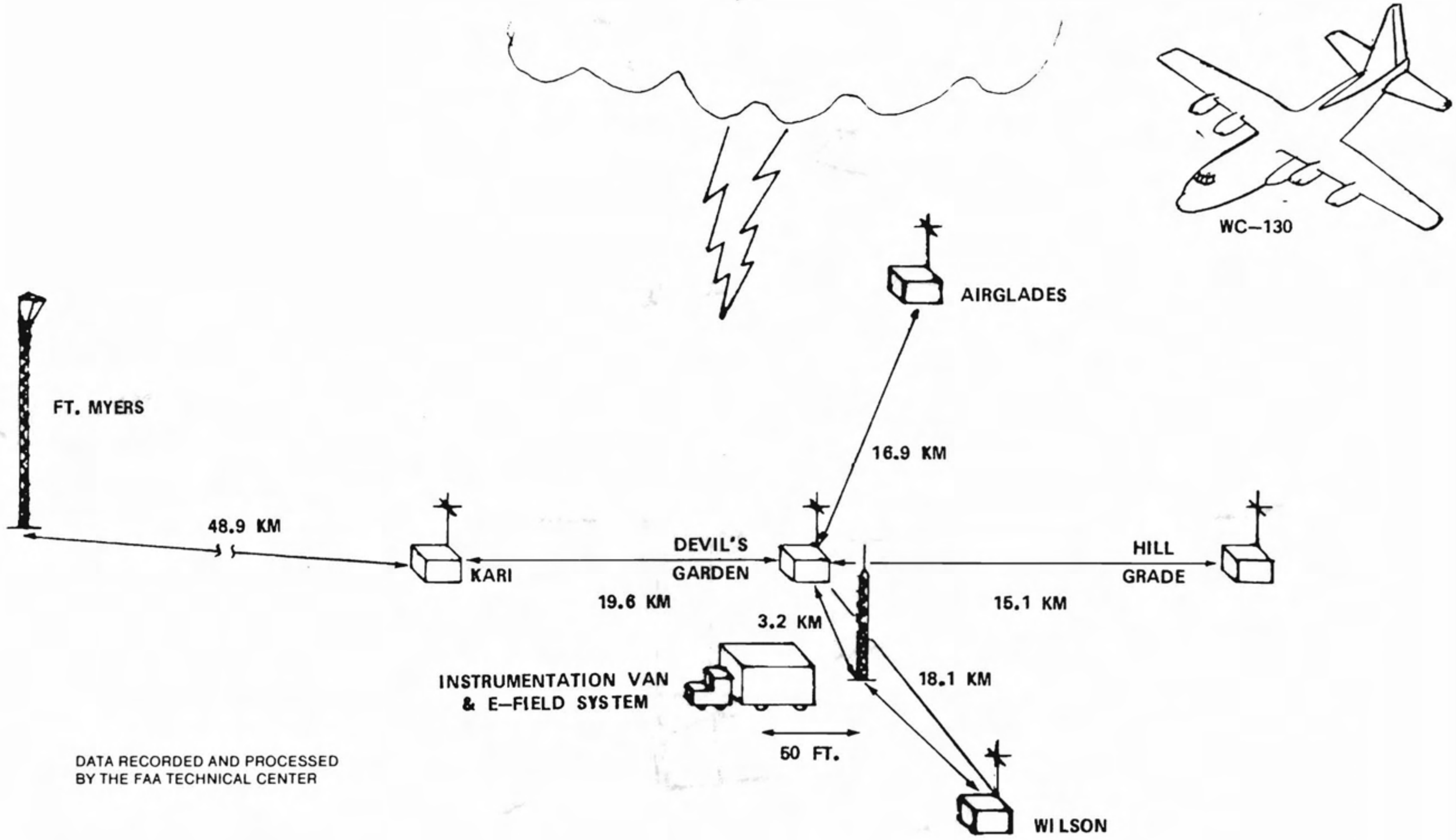
Our major thrust has been in the lightning characterization program. We utilize the NOAA C-130 aircraft as a testbed, and conduct the lightning research program in Southern Florida. In the past, the aircraft did not penetrate the thundercell but remained approximately 5 kilometers from the edge of the cell. This year, the program has been modified by a memorandum of agreement to have the aircraft penetrate directly into the thundercell. The aircraft instrumentation system has been upgraded to retrieve this data.

In conjunction with the C-130 program, a ground facility is utilized to make electrical field measurements. This data is then cross-correlated with the aircraft data. The ground station retrieval system monitors lightning/electrical field strength data in both range and azimuth, and is then converted into relative position to the aircraft. This program is funded for the remainder of the year, and is related to other research efforts both within and outside the agency.

Data reduction and analysis has historically been one of the most difficult tasks encountered. To aid in this effort, our group is about to finalize the contract of a 2-year effort to perform this task. In an effort to establish an adequate data base, the data reduction will encompass the data obtained from the F-106B program, French Ivory-Coast program, in addition to the aforemention C-130 program. This analysis will include information from Dr. Baum's and Prof. C. Moore's program in addition to the data obtained from Dr. Krider's and Dr. Uman's ground measurement programs. In short, the effort will utilize all the valid lightning information available in an effort to provide a reasonable statistical sample size which will enhance the competency of the analysis.

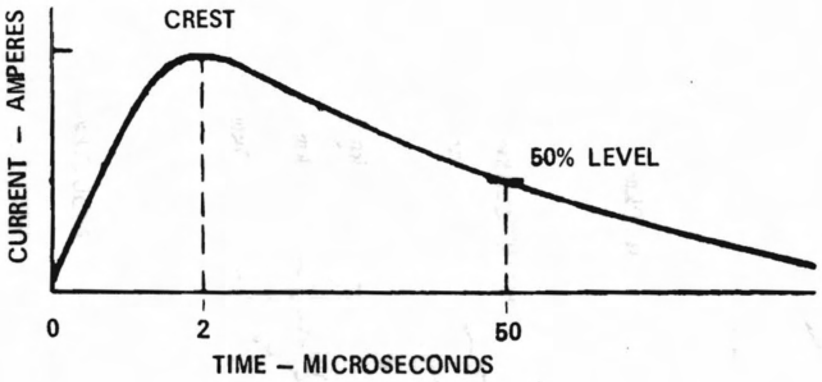

NOAA 43C


1 – JTN (TANG DISPLACE CURRENT)
4 – J (SFC CURRENT DENSITY)
7 – VHF ANTENNA (GNDSITE TIME CODE)
8 – ZAPPER ANTENNA (ACFT POSITION TX)
DATA RECORDED AND PROCESSED BY THE FAA TECHNICAL CENTER
4
4
8
7
1

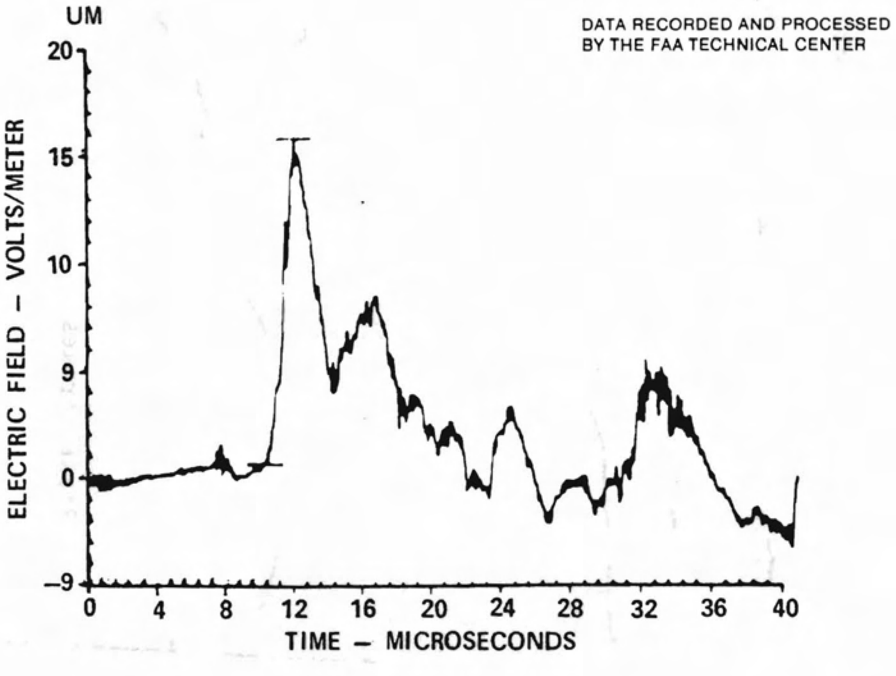


DATA RECORDED AND PROCESSED
BY THE FAA TECHNICAL CENTER

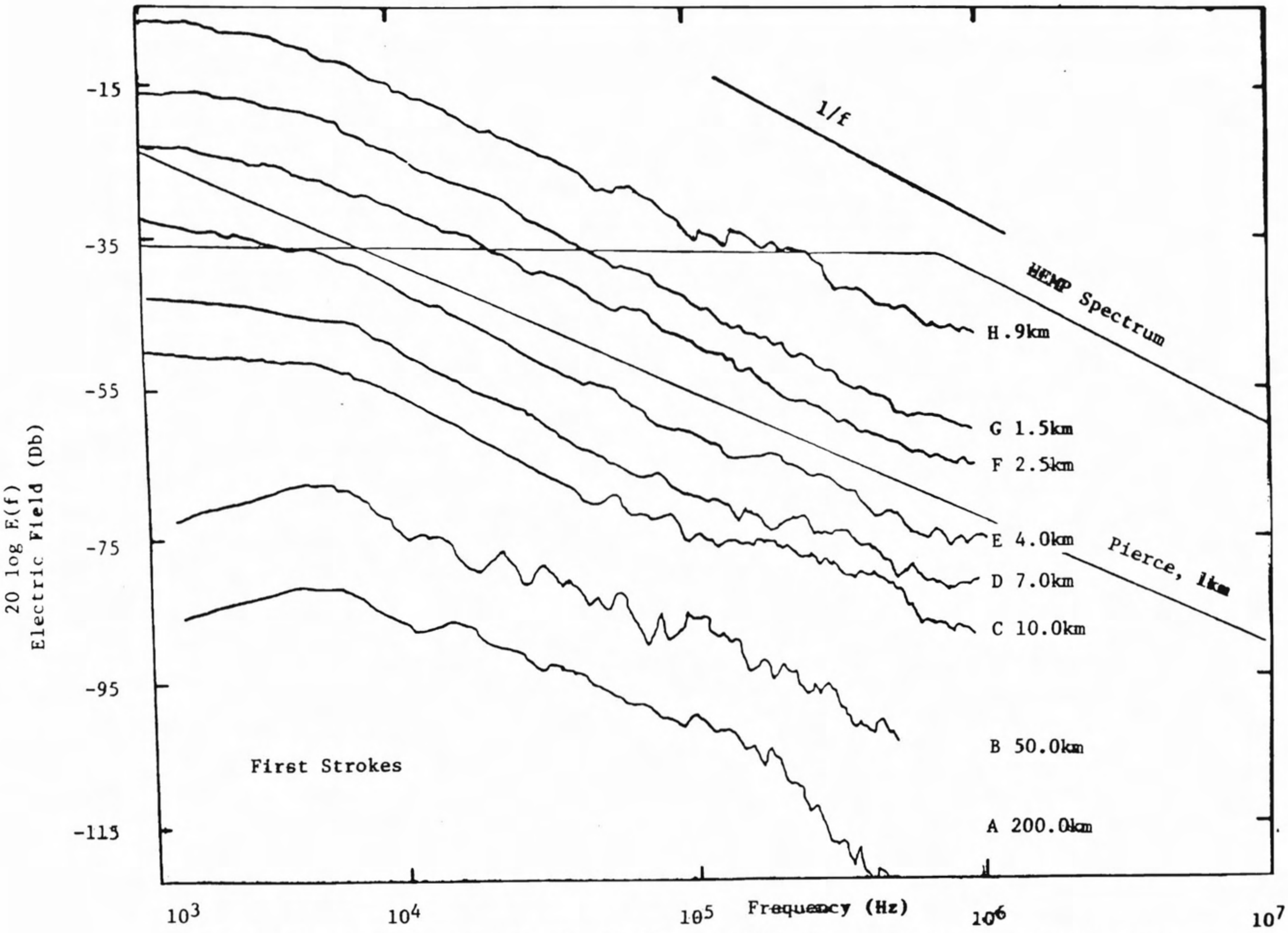
CONCEPTUAL VIEW OF TEST ENVIRONMENT



STANDARD LIGHTNING TEST WAVEFORM 2 X 50 MICROSECONDS

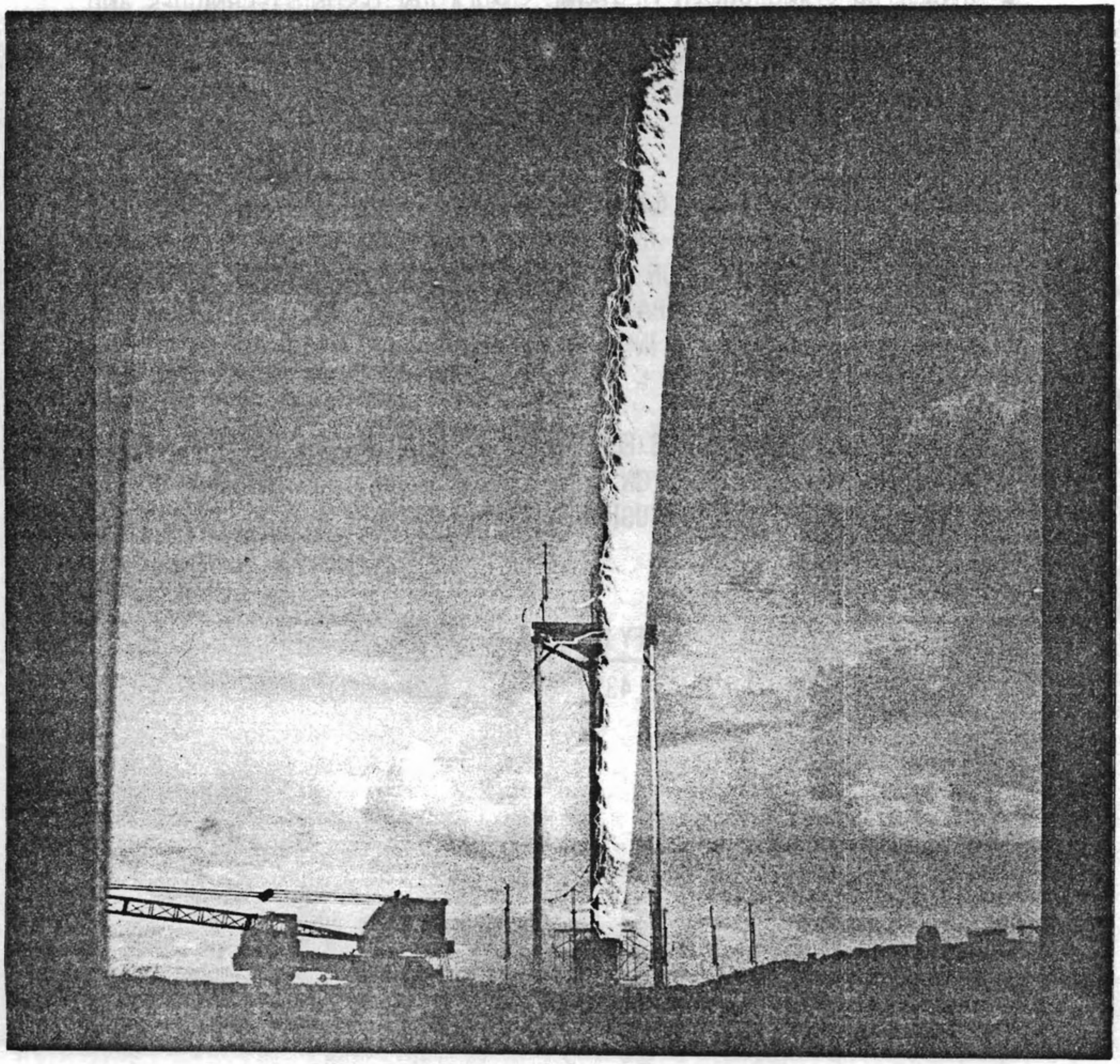


OBSERVED IN–FLIGHT LIGHTNING ELECTROMAGNETIC FIELD



Comparison of Return Stroke LEMP and HEMP Spectral Content at Various Ranges from the Stroke (LEMP Measured from G.I. Serhan, M.A. Uman, D.G. Childers, and Y.T. Lin)

A second project to be discussed is the Rocket Triggered Lightning Experiment (RTLI) which is being conducted as a joint effort with the University of Mexico Institute of Mining and Technology and the Office National d'Etudes et de Recheiches Aerospatiales (ONERA). The purpose of this project is to evaluate the streamering effect associated with aircraft. The rocket will simulate the streamering effects. The French have a lightning triggering capability of about 90 percent. The people involved with the MX missile have shown interest in this project because the lightning strike object physically resembles a rocket. The rocket will only travel about 200 feet into the air. The French have had very good success triggering lightning with this system.



The third project the group is involved in is the development of Standarized Lightning Simulation test and techniques. This program will continue thru 1984.

OBJECTIVE:

- TO DEVELOP STANDARDIZED LIGHTNING SIMULATION TESTING TECHNIQUES AND ANALYTICAL TOOLS FOR AEROSPACE VEHICLES AND SUBSYSTEMS AT THREAT LEVELS.

APPROACH:

TESTING:

- DEFINE AIRCRAFT NATURAL E-M RESONANCES; INCORPORATE LATEST WAVEFORM DEFINITION (FAST RISETIME); INCORPORATE NONLINEAR EFFECTS (I.E., STREAMERS, ARCING AT JOINTS); ISOLATION OF MONITORING INSTRUMENTATION AND TEST EQUIPMENT; CORRELATE/COMPARE WITH ANALYSIS AND INFLIGHT MEASUREMENTS. ACCOMPLISH PRIMARILY VIA INHOUSE EFFORT.

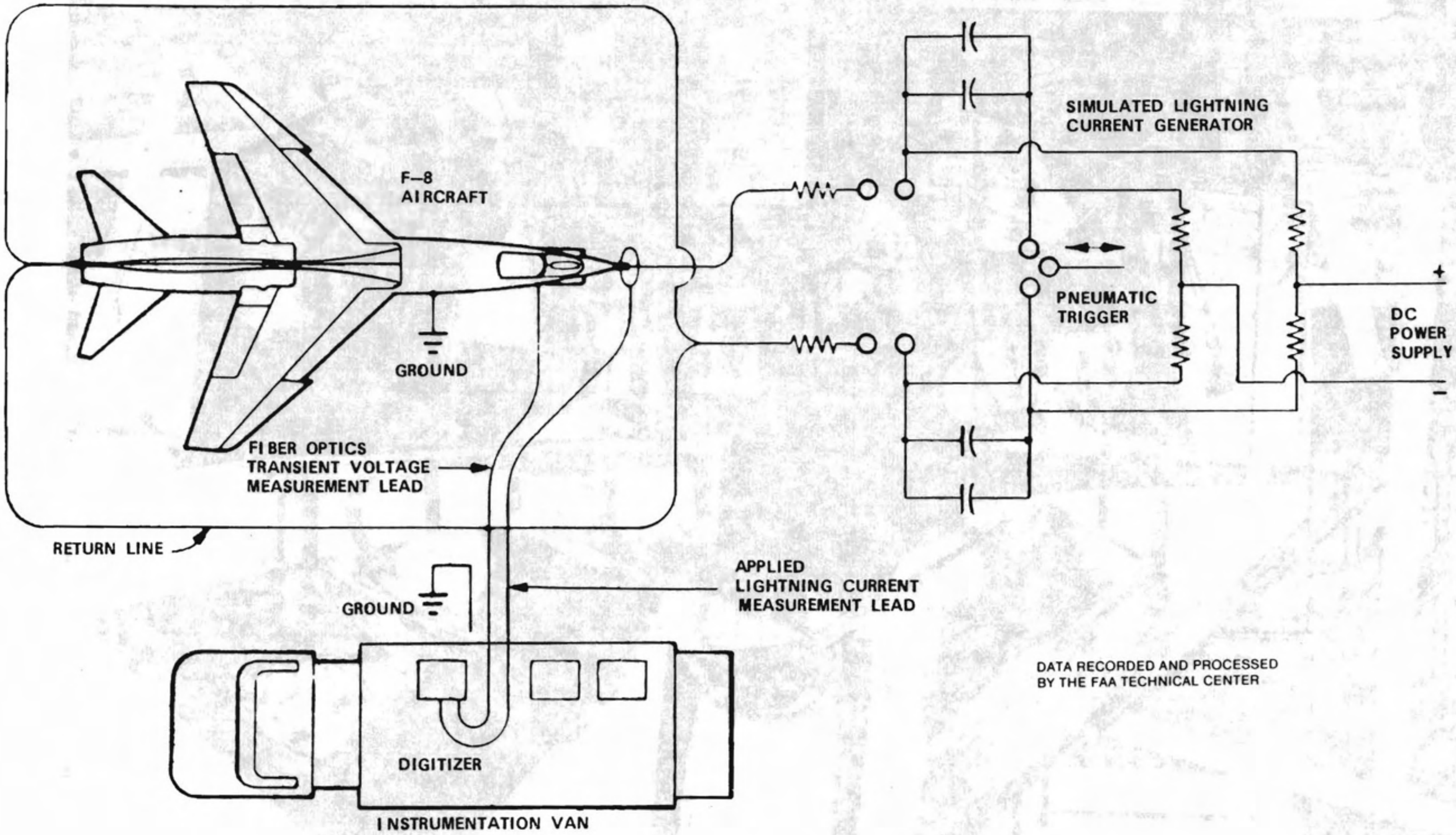
ANALYSIS:

- DEVELOP ANALYTICAL MODELS FOR THE LIGHTNING CHANNEL PHYSICS, EVALUATION TESTING PROCEDURES, BUILD ON NEMP ANALYSIS FOR E-M COUPLING MODELING. ACCOMPLISH PRIMARILY THROUGH CONTRACTED EFFORT.

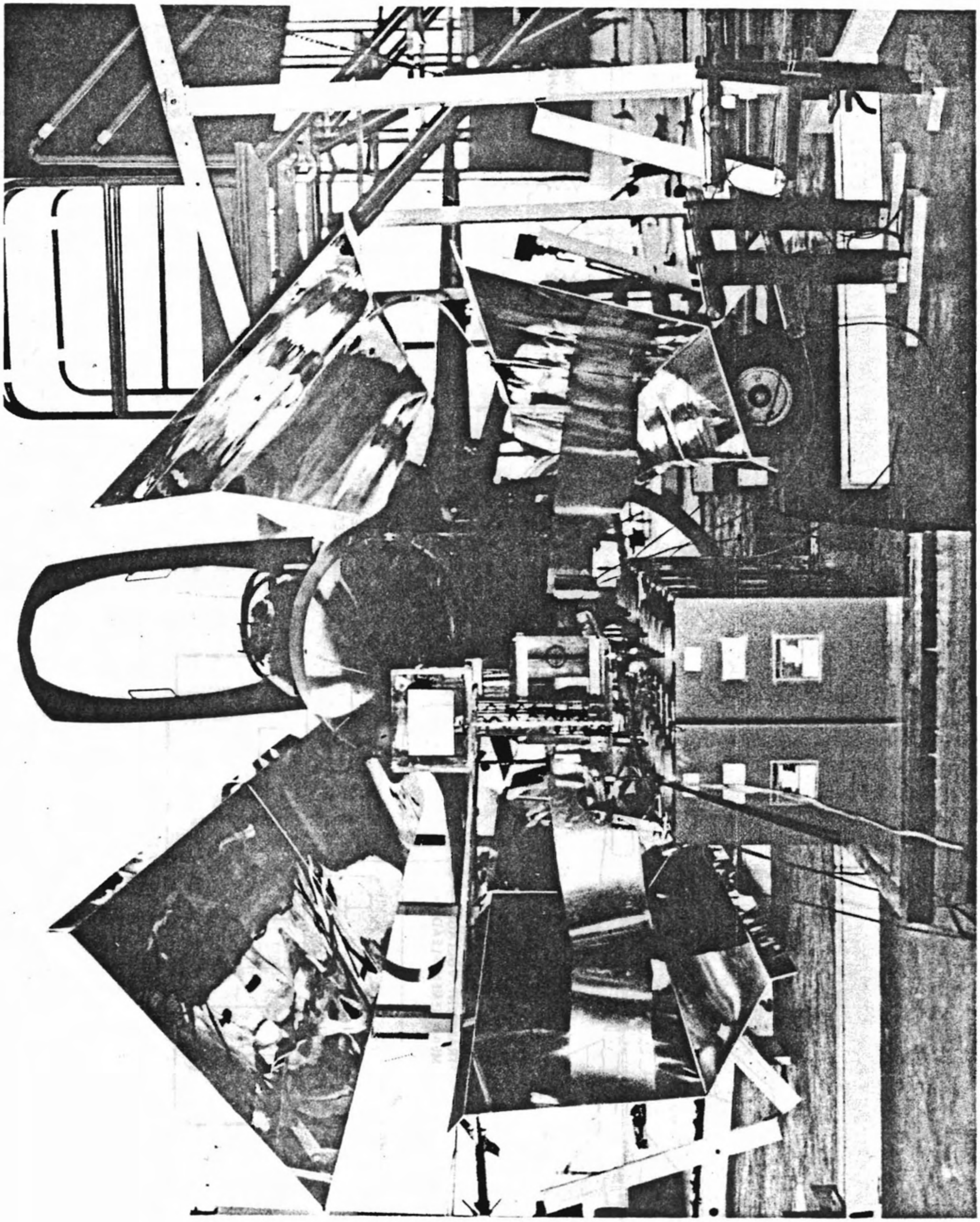
FUNDING:

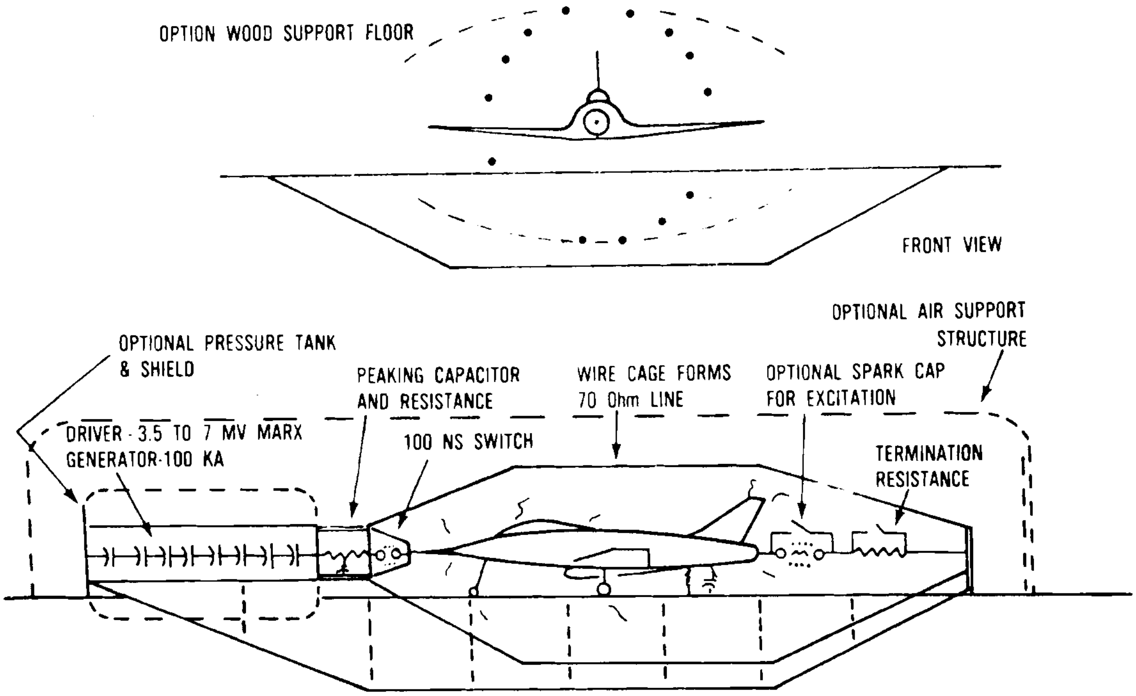
FY 81	FY 82	FY 83	FY 84
112	220	435	520

LIGHTNING SIMULATION TEST DEVELOPMENT PROGRAM
(INHOUSE/CONTRACT)



DATA RECORDED AND PROCESSED BY THE FAA TECHNICAL CENTER





PROPOSED TEST METHOD FOR LIGHTNING INDIRECT EFFECTS TESTING OF AEROSPACE VEHICLES

AEHP INTERFACES

NATIONAL INTERAGENCY COORDINATING GROUP (NICG)

AIR FORCE
NAVY
FAA
NASA
(ARMY)
(NOAA)
(DNA)

MEMORANDUMS OF AGREEMENT

AFWL
NOAA
DNA
NAVAIR
FAA
NASA

SOCIETY OF AUTOMOTIVE ENGINEERS COMMITTEE ON AEROSPACE ELECTRO-MAGNETIC COMPATIBILITY

(SUBGROUP ON LIGHTNING) SAE-AE4-L
INDUSTRY, GOVERNMENT ADVISORY GROUP

INTERNATIONAL AGREEMENTS & LIAISON

FORMAL AGREEMENTS: FRANCE, UK
LIAISON: GERMANY, SWEDEN, SWITZERLAND, ITALY

LIGHTNING CHARACTERIZATION PROGRAM

NOAA
BOEING
MCDONNELL
LIGHTNING LOCATION & PROTECTION, INC.
ONERA
NASA LANGLEY RESEARCH CENTER

AEHP ADVANCED DEVELOPMENT PROGRAM

AIR FORCE
NAVAIR
NADC
NASA LANGLEY RESEARCH CENTER
DNA
FAA TECHNICAL CENTER

ANALYTICS

AREAS OF WORK:

- LIGHTNING ARC CHANNEL/AIRCRAFT INTERACTION MODELING
- AIRCRAFT/LIGHTNING INTERACTION TEST SIMULATION
- INDIRECT LIGHTNING EFFECTS COUPLING MODELING

The final project is to determine the susceptibility of fiber optic communication systems to the EM threat associated with lightning.

FIBER OPTICS PROGRAM

OBJECTIVE

TO DETERMINE SUSCEPTIBILITY OF GENERALIZED FIBER OPTIC SYSTEMS TO THE LIGHTNING THREAT

APPROACH

PERFORM LABORATORY LIGHTNING SIMULATION TETS ON A TESTBED HOUSING A REPRESENTATIVE FIBER OPTICS SYSTEM. THIS EFFORT WILL BE INTERFACED WITH RESULTS OF OTHER FIBER OPTICS PROGRAMS ELSEWHERE

PAYOFF

WILL PROVIDE INFORMATION ON THE UTILITY OF FIBER OPTICS AS A HARDENING TOOL AND GUIDELINES ON THE REQUIREMENTS FOR INTEGRATION INTO AVIONICS SYSTEMS WHICH MAY BE EXPOSED TO ADVERSE ELECTROMAGNETIC HAZARDS

REVIEW OF ATMOSPHERIC ELECTRICITY HAZARDS SIMULATION TEST FACILITIES

by

Larry Walko

Atmospheric Electricity Hazards Group
U.S. Air Force Flight Dynamics Laboratory

Dayton, Ohio

The information in this presentation is the most comprehensive available on Atmoshperic Electricity Hazards Simulation Test Facilities.

As this document has limited distribution, the presentation in its entirity has been transfered to appendix A to facilitate utiliaztion by the entire lightning community.

ELECTROMAGNETIC DESIGN AND SYNTHESIS (EMDAS)

by

Dr. John Birken

Naval Air Systems Command

Washington, D.C. 20361

The U.S. Navy has been investigating the complexity of using advanced composite materials in its future generation aircraft.

Concern for the vulnerability of aircraft "flight-critical" and "flight-essential" systems to both aircraft generated and atmospheric electricity hazards has increased substantially over the past years. Two primary factors have contributed extensively to a potentially increased threat to derivative and new generation aircraft: (1) Increasingly widespread use of sensitive microelectronics in flight-critical electronic and electrical systems; and (2) the reduced electromagnetic shielding afforded by many advanced aircraft structural materials.

Atmospheric electricity interaction with aircraft can result in numerous types of damage. For the case of lightning, the most obvious is that of physical damage resulting from a direct attachment to the aircraft. Such damage is characterized by burning, eroding, blasting, etc., and is the consequence of either the extreme heat loading and accompanying acoustic shock wave, or deforming magnetic forces associated with the high current aspect of lightning. A second type effect results from the fast changing electric and magnetic fields produced by the high currents associated with eithr a direct or near strike. In both cases, these fields can couple voltage transients into the internal aircraft wiring and subsequently to the flight control and avionics systems.

This paper was printed in its entirity in the "Proceedings and Minutes of the National Interagency Coordination Group Meeting" document No. NAVAIR 518-6, FAA-CT-81-195, April 23, 1981.

STATUS OF THE ADVANCED DEVELOPMENT PROGRAM

by

Rudy Beavin

U.S. Air Force Flight Dynamics Laboratory

Dayton, Ohio

The advanced development program is an integrated program which encompasses many governmental agencies in addressing the protection of aircraft against the adverse effects associated with atmospheric electricity. This program is one of the primary functions of the NICG as it directly involves the integration of the participating agencies by consummating their resources into a single effort. The program will culminate the efforts from each participating agency in this highly complex technological area.

The following is the updated presentation of the Atmospheric Electricity Hazards Protection (AEHP) of Advanced Technologhy Aircraft.

OVERVIEW

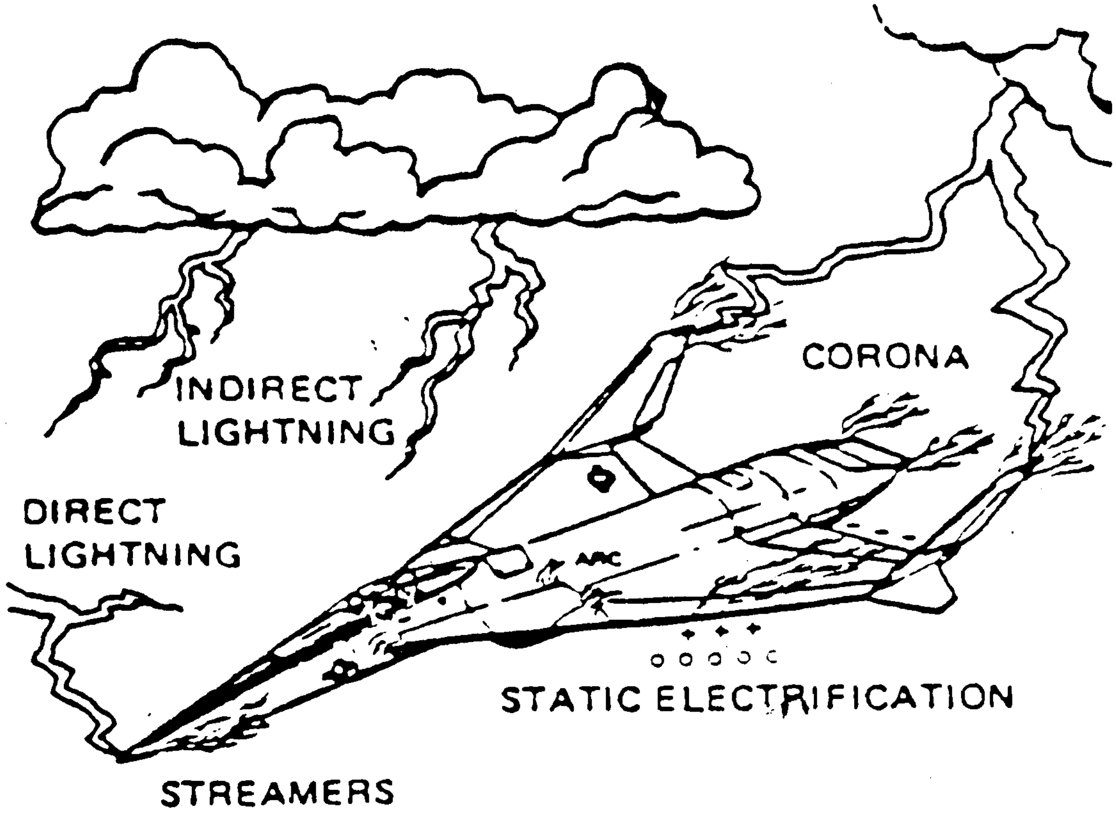
- LIGHTNING THREAT
- AEHP ADP
  - -- OBJECTIVE/APPROACH
- JOINT SUPPORT

LIGHTNING

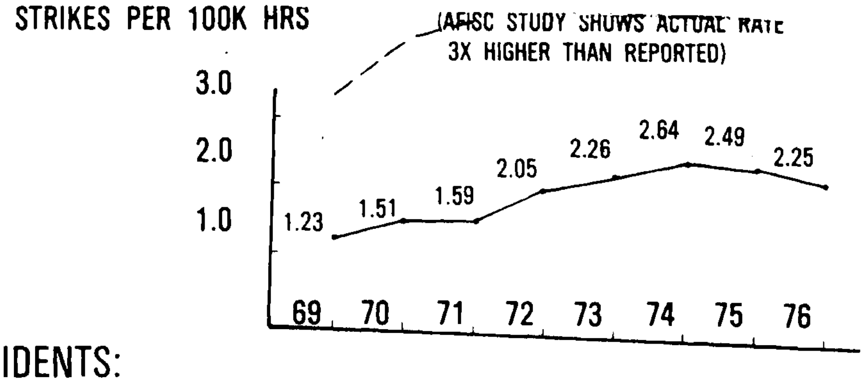
TYPES	--	CLOUD, CLOUD-GROUND, POS, NEG
VOLTAGE	--	30 - 100 MILLION VOLTS
CURRENT	--	20 - 200 THOUSAND AMPS
POWER	--	10^{13} WATTS
ENERGY	--	5.10^{8} JOULES (200 # TNT)/STROKE
EXTENT	--	3 - 30 KM/STROKE
DURATION		
STROKE	--	100 MICRO SEC
FLASH	--	0.2 SEC (1 - 20 STROKES)

HAS BEEN AROUND FOR YEARS

WHY THE SUDDEN INTEREST?



USAF LIGHTNING STRIKE EXPERIENCE



- STRIKE RATE REPORTED (3 YR SMOOTHED AVG)

- TEN YEAR HISTORY OF INCIDENTS: CATASTROPHIC -9, MAJOR -7, MINOR -153

- COST FOR FIVE YEARS ENDING IN 1977 EXCEEDS $21,000,000

- 1978: F-111F LOST 29 MAR 78, LAKENHEATH, UK; 2 FATALITIES
  C-130E LOST 30 NOV 78, CHARLESTON, SC; 6 FATALITIES

- 1980: C-130H LOST 14 MAR 80, INCIRLIK, TU; 14 FATALITIES

- MIL STD MIL-B-5087B -

  200 KA PEAK
  2 X 50μSEC WAVESHAPE; r.t. = 2μSEC
  100 KA / μ SEC RATE OF RISE

- 1979 IEEE INTERNATIONAL SYMPOSIUM (SAN DIEGO, CA)
  CLIFFORD-KRIDER-UMAN
  FIRST RETURN STROKE - 10-90% r.t. = 200 n SEC MEAN
  SUBSEQUENT RETURN STROKE - 10-90% r.t. = 150 n SEC MEAN

- 1980 LIGHTNING TECHNOLOGY CONFERENCE (NASA LANGLEY)
  - WEIDMAN-KRIDER
    RETURN STROKE "FAST TRANSITION" - 10-90% r.t. = 90 n SEC MEAN
  - BAUM-BREEN-O'NEIL-MOORE-HALL
    RETURN STROKE "CHARACTERISTIC" r.t. = 50 n SEC

- MX LIGHTNING WAVEFORM SPECIFICATION 100KA PEAK - 10-90% r.t. = 200 n SEC
  - 100KA PEAK - 10-90% r.t. = 200 n SEC

G→

LIGHTNING RETURN STROKE CHARACTERISTICS

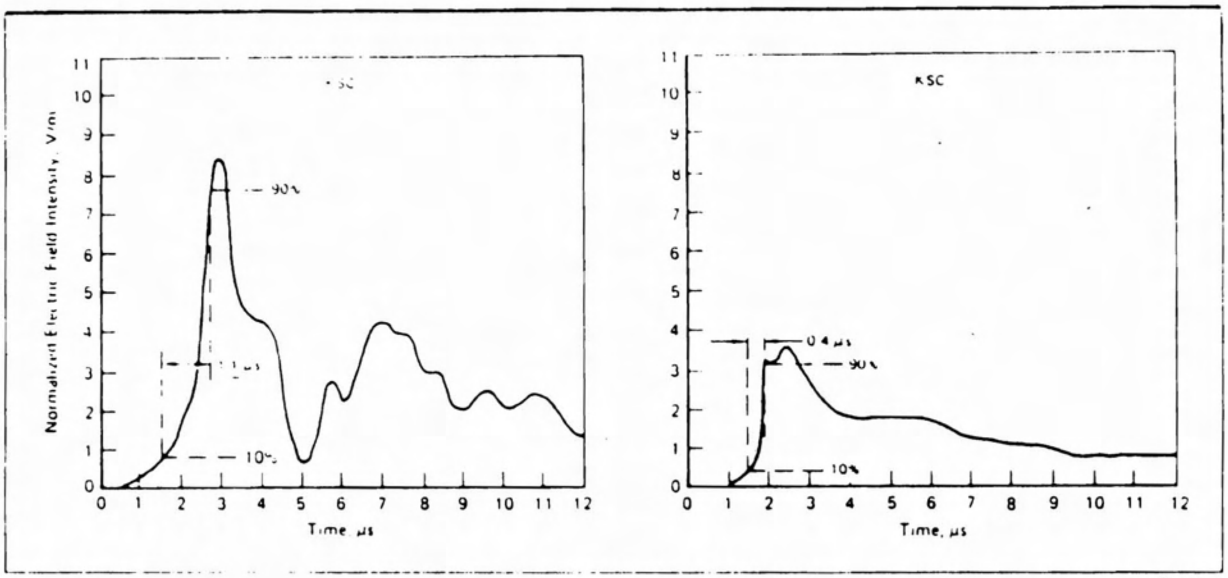


FIGURE 5
ELECTRIC FIELDS FROM A FIRST STROKE (LEFT) AND A SUBSEQUENT STROKE (RIGHT) AS OBSERVED AT KSC. 10 TO 90% RISETIMES ARE SHOWN ON THE FIGURE. BOTH STROKES OCCURRED 15 TO 25 KM SE OF THE KENNEDY SITE. THE PLOTTED FIELDS ARE NORMALIZED TO A DISTANCE OF 100 KM USING THE INVERSE DISTANCE RELATION APPROPRIATE TO RADIATION FIELDS AND ASSUMING THE STROKE DISTANCES TO BE 15 KM FROM REFERENCE 15

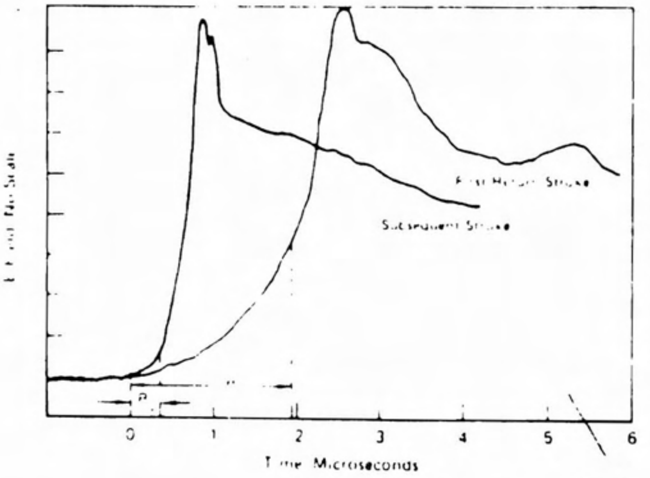


FIGURE 6
CHARACTERISTIC OF FIRST RETURN STROKE FRONT RAMP (R_f) AND SUBSEQUENT STROKE FRONT RAMP (R_s) AS MEASURED BY WEIDMAN AND KRIDER (6). E-FIELD AMPLITUDES ARE NOT TO SCALE. WAVEFORMS ARE BASED ON MEAN VALUES OF HISTOGRAMS

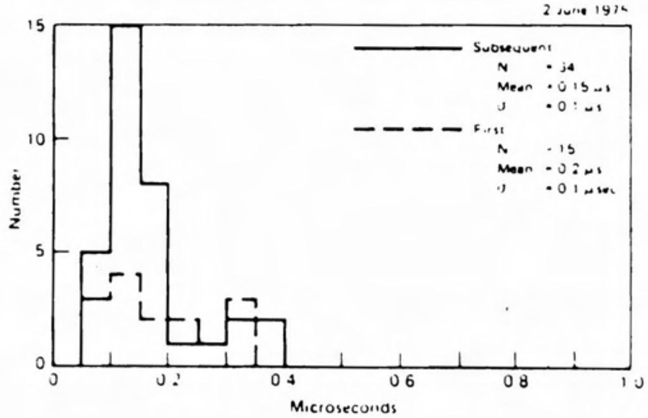


FIGURE 7
HISTOGRAMS OF THE 10 TO 90% RISETIMES OF THE FAST FIELD TRANSITION IN FIRST AND SUBSEQUENT STROKE FIELDS IN FLORIDA AT A DISTANCE OF 15 TO 30 KM OVER SEA WATER. REFERENCE 6.

APPLICATION TO AIRCRAFT INDUCED-COUPLING STUDIES

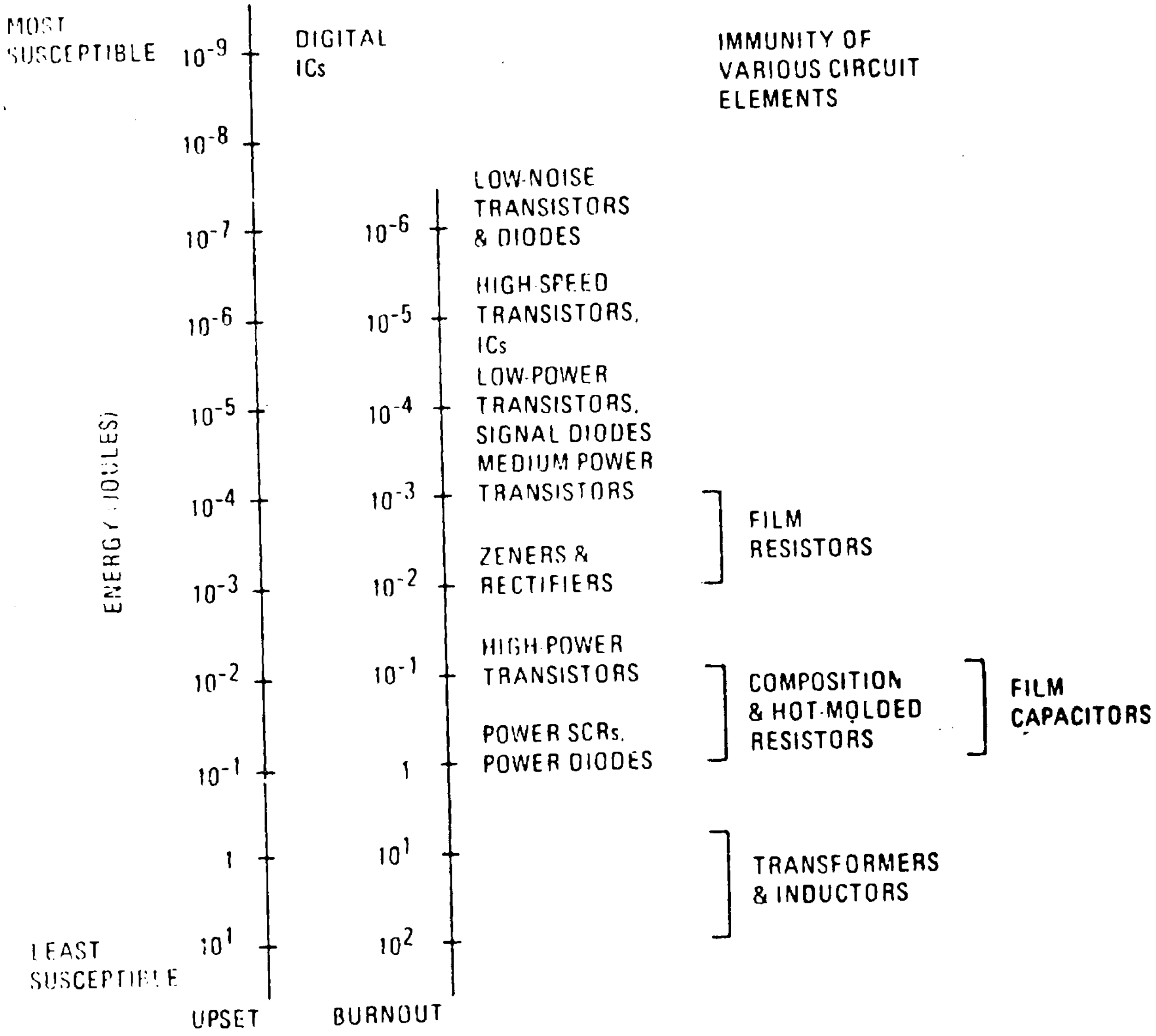
"A CASE FOR SUBMICROSECOND RISE-TIME LIGHTNING CURRENT PULSES FOR USE IN AIRCRAFT INDUCED-COUPLING STUDIES" (CLIFFORD, KRIDER, UMAN 1979)

AVIONICS PLANNING CONFERENCE
(AF/RDP MSG 122215Z JUN 79)

- AF/RDP AND ASD/AX HOSTED HARDENING SUBPANEL MEETING 25-27 JUN 79, KIRTLAND AFB
  - -- AVIONICS STANDARDIZATION
- DISCUSSION ITEMS:
  - -- SIMILARITY OF LIGHTNING AND NEMP-CAUSED TRANSIENTS (TEST DATA)
  - -- HEMP THREAT MEASUREMENT STATUS, TEST RESULTS, PROTECTION COST
  - -- AFWL DRAFT USAF HEMP PROGRAM PLAN (TO AFSC/DLW, MAY 79)
  - -- - ADDRESSES INTEGRATION OF HEMP/LTG/EMI/EMC PROTECTION
  - -- AFFDL AEHP PROGRAM AND PROPOSED ADTP
  - -- DRAFT AFFDL/AFWL MOA
- ACTION ITEMS:
  - -- CONCLUDE AFFDL/AFWL MOA FOR AEHP/NEMP TEST/ANALYSIS INFO EXCHANGE AND COORDINATION
  - -- DRAFT PRELIM BLACK BOX HARDENING STANDARD, INTEGRATING AEHP AND HEMP RQMTS INTO EXISTING EMI/EMC MIL-STD (OPR: ASD/ENAMA WITH AFFDL & AFWL)
  - -- IDENTIFY MISSION-ESSENTIAL AVIONICS
  - -- EXAMINE OPNL CAPABILITY GAINS FROM AVIONICS HARDENING

HAZARD	CAUSE	HAZARD CRITICALITY
MALFUNCTION / FAILURE OF ELECTRONIC CONTROL SYSTEMS	LOW TOLERANCE TO ELECTRICAL TRANSIENTS CAUSED BY DIRECT / INDUCED LIGHTNING OR STATIC ELECTRIFICATION EFFECTS. MAY SIMULTANEOUSLY AFFECT PARALLEL 'REDUNDANT' SYSTEM.	MINOR TO CATASTROPHIC
FUEL TANK FIRE OR EXPLOSION	FUEL VAPOR IGNITION CAUSED BY STATIC ELECTRICITY OR LIGHTNING EFFECTS.	MINOR TO CATASTROPHIC
LOSS OF ENGINE POWER	POSSIBLE LIGHTNING ACOUSTIC SHOCK AT ENGINE INLET, OR ELECTRICAL TRANSIENT EFFECTS ON ENGINE CONTROLS.	MINOR TO CATASTROPHIC
INADVERTENT RELEASE / IGNITION OF EXTERNAL STORES	PREMATURE ACTIVATION CAUSED BY LIGHTNING OR STATIC ELECTRIFICATION EFFECTS	SERIOUS TO CATASTROPHIC
RADOM, CANOPY, AND WINDSHIELD DAMAGE	DIRECT LIGHTNING STRIKES; ARC DISCHARGE CAUSED BY STATIC ELECTRICITY BUILDUP.	MINOR TO SERIOUS
INSTRUMENTATION PROBLEMS / COMMUNICATIONS, NAVIGATION & LANDING SYSTEM INTERFERENCE	TRANSIENT EFFECTS CAUSED BY STATIC ELECTRICITY BUILDUP & DIRECT AND NEARBY LIGHTNING STRIKES.	MINOR TO CATASTROPHIC
STRUCTURAL DAMAGE	DIRECT LIGHTNING ATTACHMENT TO AIRCRAFT	MINOR TO SERIOUS
PHYSIOLOGICAL EFFECTS ON CREW	FLASH BLINDNESS & DISTRACTING OR DISABLING ELECTRICAL SHOCK CAUSED BY DIRECT & NEARBY LIGHTNING STRIKES.	MINOR TO CATASTROPHIC

ATMOSPHERIC ELECTRICITY THREATS TO AIRCRAFT



NOTE: PULSE WIDTHS IN THE MICROSECOND REGION

-*Typical Upset and Burnout Energies*

LIGHTNING THREAT TO NEW AIRCRAFT

- ADVANCED AIRCRAFT MICROELECTRONICS ARE INHERENTLY MORE SUSCEPTIBLE TO LIGHTNING AND STATIC ELECTRICITY EFFECTS
- ADVANCED STRUCTURES PROVIDE LESS ELECTRICAL PROTECTION
- INCREASINGLY CRITICAL APPLICATIONS AND ALL-WEATHER REQUIREMENTS ARE PLANNED
- PRESENT MIL-SPECS, STANDARDS AND GUIDES ARE INADEQUATE
- BOTH MILITARY AND CIVIL AIRCRAFT ARE AFFECTED

HAZARD / THREAT MATRIX

HAZARD	THREAT	DOCUMENT (OR SOURCE)	TYPICAL VALUES
LIGHTNING	DIRECT STRIKE	SAE COMMITTEE AE4L	200 KA
	SWEPT STROKE		100 KA
	LEMP (INDIRECT)		200 KA
EMI	ONBOARD EMITTERS	MIL-HDBK-235	5 akV/m
	OUTSIDE EMITTERS	MIL-STD-461A	
HEL	DEFOCUSED BEAM	FTD POSTULATED AIRBORNE LASER	0.5 kW/cm^2
	FOCUSED BEAM		5.0 kW/cm^2
NEMP	LOW FREQUENCY	SAB-TN-75-5 (AFWL)	50 kV/m
	HIGH FREQUENCY		

AEHP ADVANCED DEVELOPMENT TECHNOLOGY PROGRAM

- GOAL
  - -- OPTIMAL PROTECTION CRITERIA FOR ELECTRICAL/ELECTRONIC SUBSYSTEMS IN ADVANCED A/C STRUCTURES
- APPROACH
  - -- TWO-PHASE CONTRACTED DEMONSTRATION PROGRAM
  - -- JOINT EFFORT WITH USN, USA, NASA, FAA
- PAYOFF
  - -- SAFE, ECONOMICAL, DESIGNED-IN PROTECTION ASSURED BY UP-TO-DATE DESIGN GUIDES, MIL-STDS, CERTIFICATION TESTS

AEHP ADP USER ASSESSMENT

ASD

- '...HIGH PRIORITY... PROGRAM IS READY FOR TRANSITION TO ADP EFFORT... DIRECTLY APPLICABLE TO NEW SYSTEMS CURRENTLY BEING CONSIDERED IN BOTH STRATEGIC AND TACTICAL AREAS... DEVELOPMENT OF... LIGHTNING HARDNESS OF ADVANCED SYSTEMS IS ESSENTIAL... WARRANTS PROGRAM COST.' *[ATF, CX, HX; ALCM]

AFISC (DIRECTORATE OF AEROSPACE SAFETY)

- '...THE AIR FORCE NEEDS THE TECHNOLOGY PLANNED TO ASSURE ADVANCED AIRCRAFT CAN SAFELY OPERATE IN THE EXISTING HAZARDS... THE APPROACH TAKEN IS WELL ORGANIZED AND VERY OBJECTIVE... WE FULLY SUPPORT THE OBJECTIVES OF THIS PLAN.'

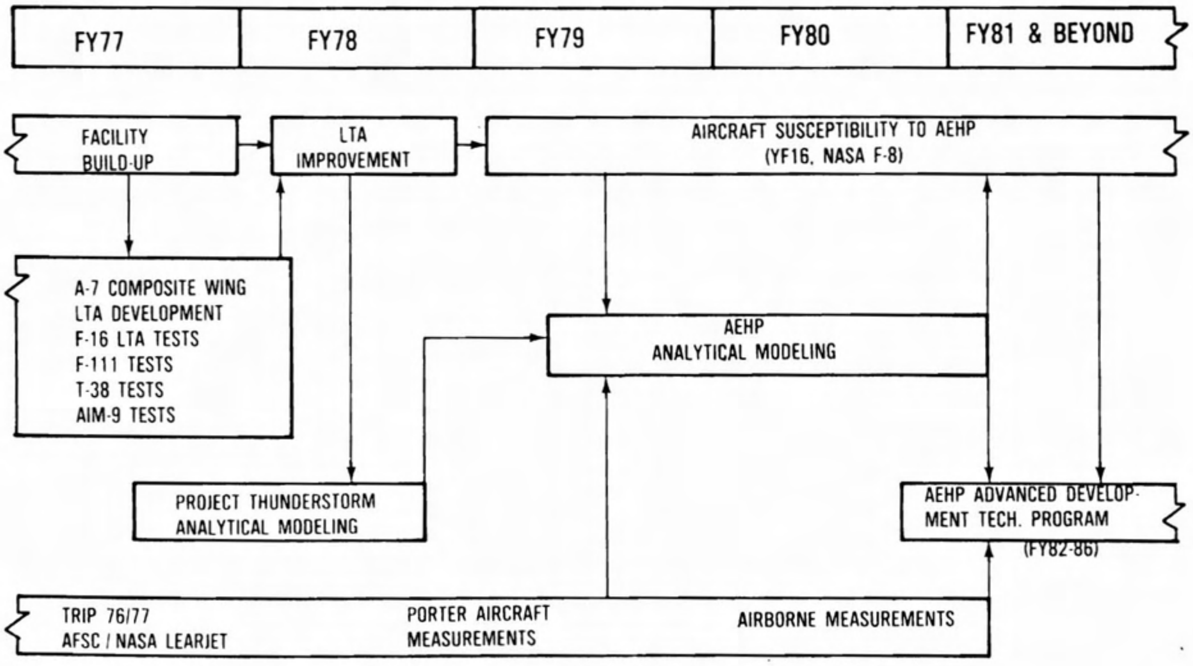
HQ NASA

- '...THE CONSENSUS CONCERN ABOUT LIGHTNING HAZARDS... UNDERSCORES THE URGENCY OF A PROMPT, COORDINATED COLLABORATIVE R&D EFFORT TO ENSURE CONTINUED SAFE AIRCRAFT OPERATION AND MISSION INTEGRITY.'

AFFDL RESPONSIBILITIES AND ACTIVITIES

- AFSC FOCAL POINT LAB FOR LIGHTNING/STATIC ELECTRICITY PROTECTION RESEARCH SINCE 1975
- DIRECTED TO:
  - DEVELOP OVERVIEW AND ROADMAP PLAN (1976)
  - CARRY OUT PROGRAMS TO:
    - DEFINE THE LIGHTNING THREAT
    - DEVELOP PROTECTION TECHNIQUES
    - DEMONSTRATE PROTECTION EFFECTIVENESS
- COMPREHENSIVE ATMOSPHERIC ELECTRICITY HAZARDS PROTECTION (AEHP) PROGRAM:
  - LIGHTNING CHARACTERIZATION
  - ASSESSMENT METHODOLOGY
    - SIMULATION TESTING (HIGH VOLTAGE GENERATORS, INSTRUMENTATION, TEST TECHNIQUES)
    - ANALYTIC MODELING (ADAPT NUCLEAR EMP MODELS)
  - ADVANCED DEVELOPMENT DEMONSTRATION PROGRAM (IN PROCUREMENT) (BOEING, GENERAL DYNAMICS, LOCKHEED, McDONNELL)

ATMOSPHERIC ELECTRICITY HAZARDS PROTECTION (AEHP) PROGRAM



FY77 | FY78 | FY79 | FY80 | FY81 & BEYOND

FACILITY BUILD-UP

LTA IMPROVEMENT

AIRCRAFT SUSCEPTIBILITY TO AEHP (YF16, NASA F-8)

A-7 COMPOSITE WING
LTA DEVELOPMENT
F-16 LTA TESTS
F-111 TESTS
T-38 TESTS
AIM-9 TESTS

AEHP ANALYTICAL MODELING

PROJECT THUNDERSTORM ANALYTICAL MODELING

AEHP ADVANCED DEVELOPMENT TECH. PROGRAM (FY82-86)

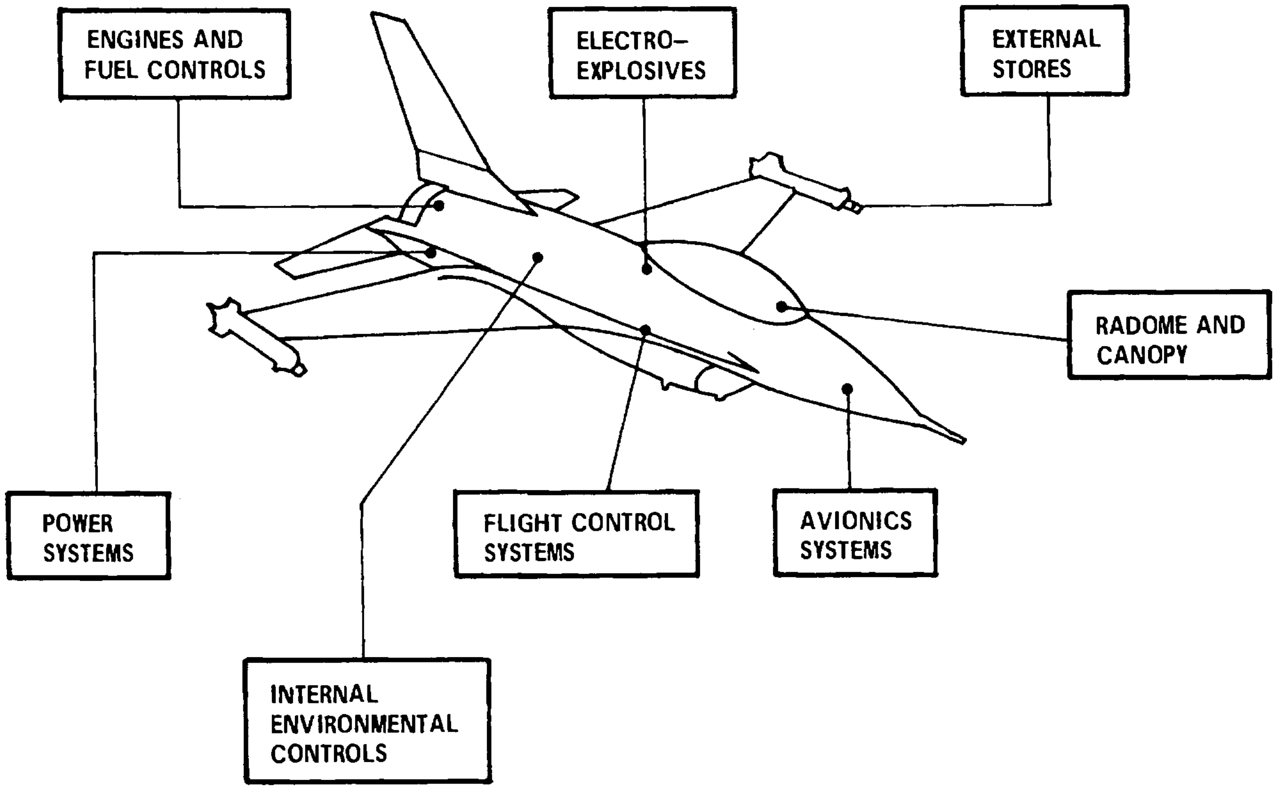
TRIP 76/77 AFSC / NASA LEARJET

PORTER AIRCRAFT MEASUREMENTS

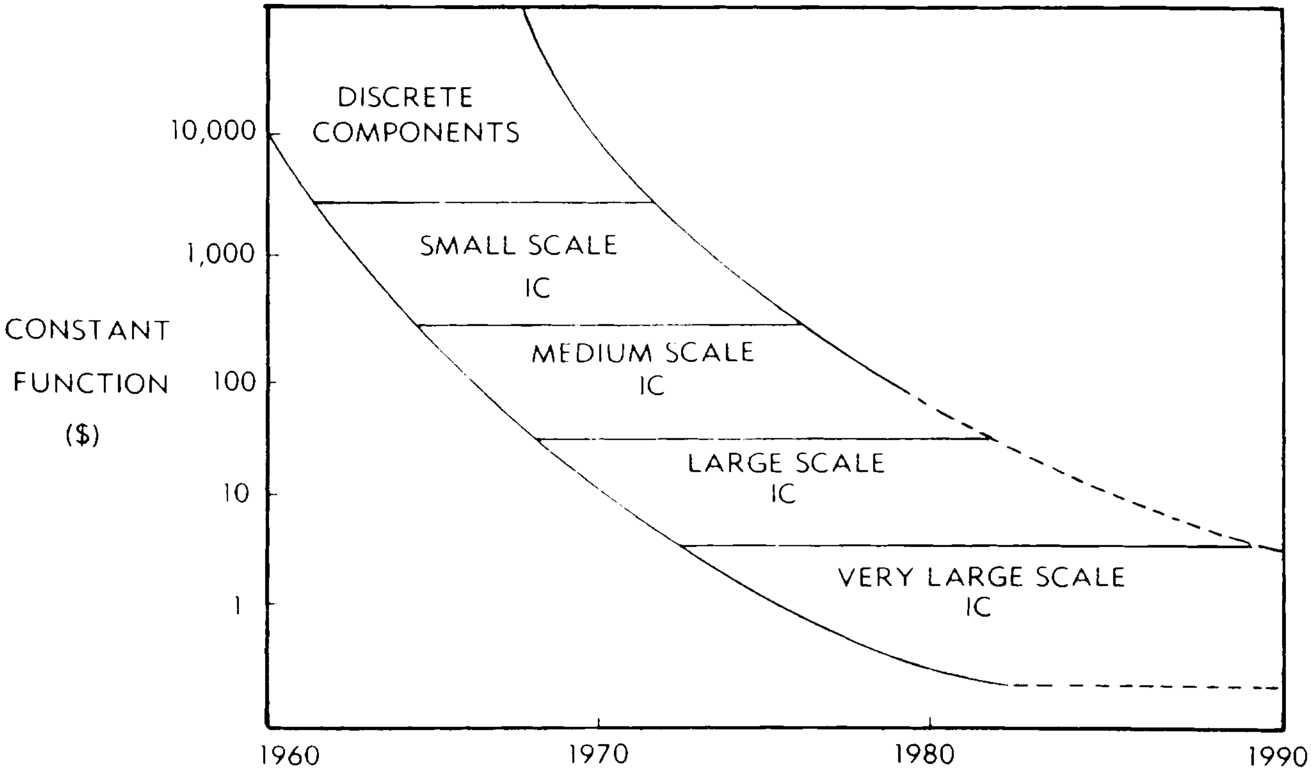
AIRBORNE MEASUREMENTS

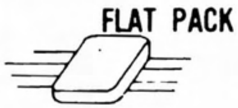
☐ RESEARCH ☐ EXPLORATORY DEVELOPMENT ☐ ADVANCED DEVELOPMENT

SYSTEMS SUSCEPTIBLE TO ATMOSPHERIC ELECTRICITY HAZARDS



ELECTRONIC FUNCTION COSTS

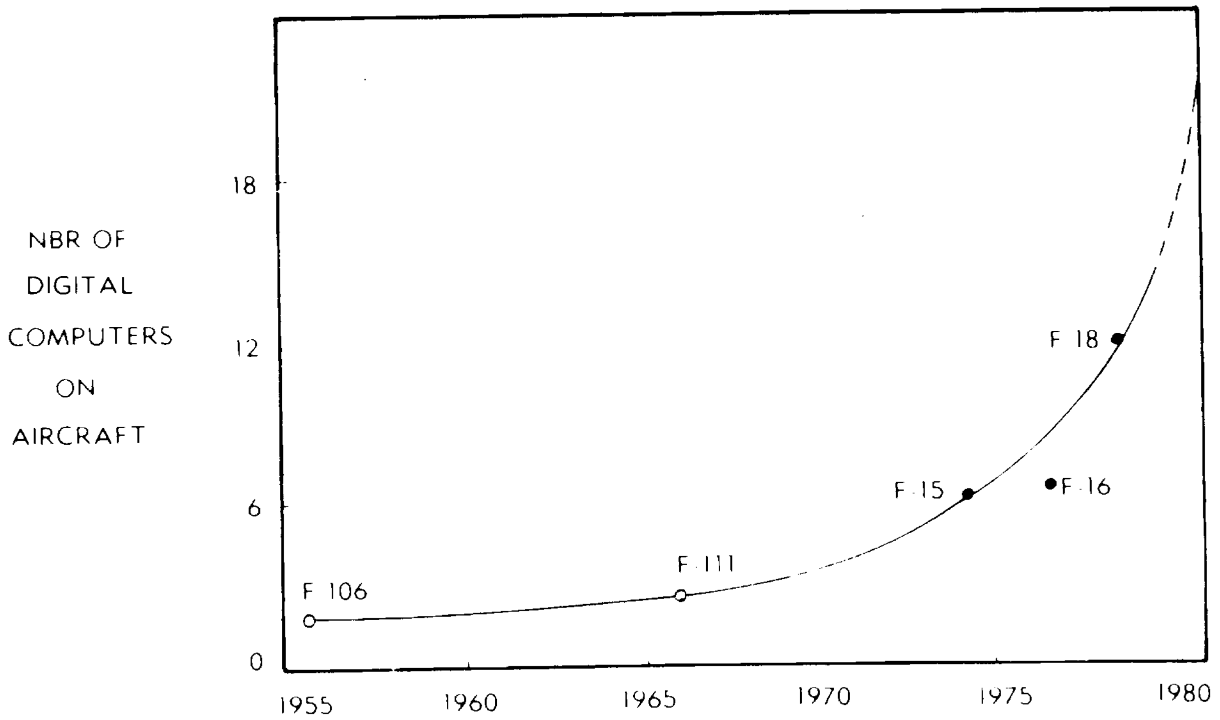


TUBES	DISCRETE TRANSISTORS	INTEGRATED CIRCUITS (IC)	LARGE SCALE INTEGRATED CIRCUITS (LSI)	VERY LARGE SCALE INTEGRATED CIRCUITS (VLSI)
 250V 1 WATT/DEVICE	 12V–24V $10^{-1} - 10^{-2}$ WATTS/DEVICE	 5V–12V $10^{-2} - 10^{-3}$ WATTS/TRANS	 5V–7V $10^{-3} - 10^{-4}$ WATTS/TRANS	 1.5V–3V $10^{-5} - 10^{-6}$ WATTS/TRANS
GLASS/ METAL/ CERAMIC	METAL/ CERAMIC	METAL/ CERAMIC/ EPOXY	METAL/ CERAMIC/ EPOXY	CERAMIC/ EPOXY
F–9, F–100, F–106	F–4, F–111	F–14, F–15	F–16, F–18	VSTOL, AFTI, FSW
ALUMINUM	ALUMINUM	ALUMINUM/TITAN	GRAPHITE–EPOXY ALUMINUM	GRAPHITE–EPOXY ?
PRE–1950'S	1950'S	1960'S	1970'S	1980'S

TECHNOLOGY TRENDS

- **ASD-HOSTED MEETING ON 22 JUN 79 (GOVT / IND) AND 23 JUN 79 (GOVT ONLY)**

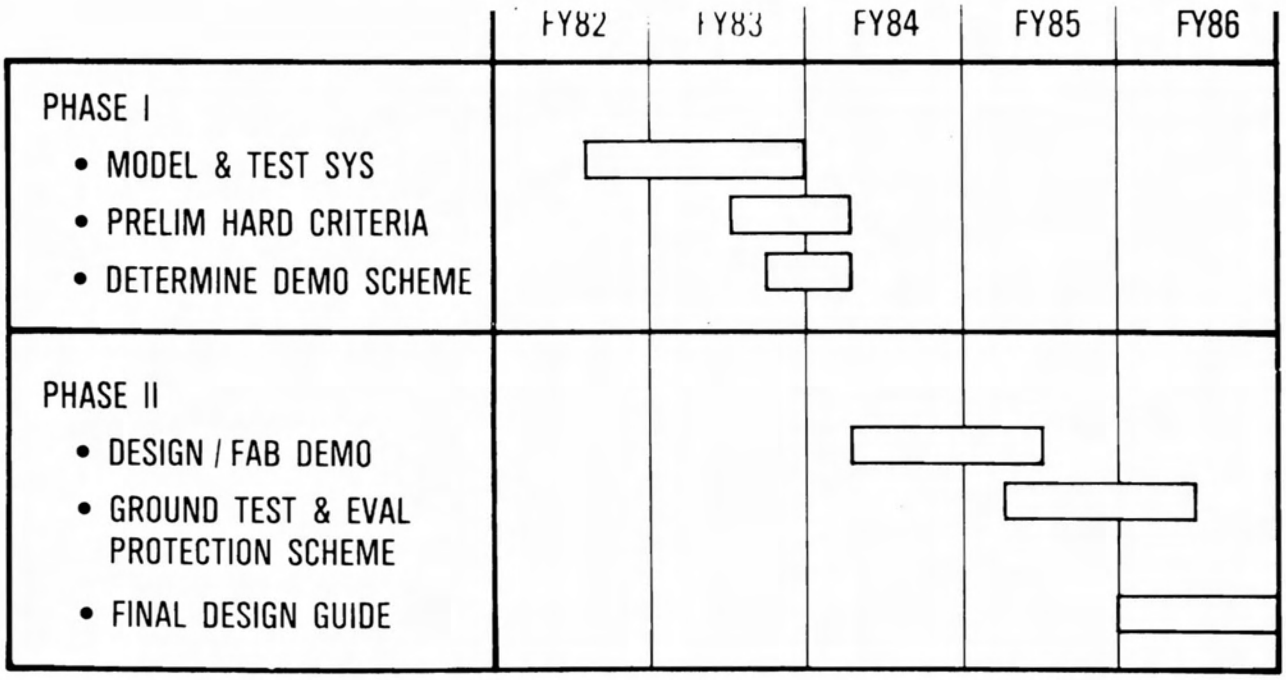
- **PRELIMINARY CONSENSUS (FROM DETAILED QUESTIONNAIRE):**
  - NO FUNDAMENTAL BARRIERS, BUT SYSTEMS LEVEL PROTECTION PROGRAMS ARE NEEDED TO REALIZE BENEFITS
  - MAJOR PROBLEM CAUSES ARE LIGHTNING INDUCED EFFECTS, EMI / EMC, NEMP
  - ARE DUE TO DIFFICULTY IN PROVIDING: DURABLE, CONDUCTIVE JOINTS AND SEAMS; FULL EM SHIELDING; PROTECTION FOR COMPOSITE FUEL TANKS
  - PROBLEMS ARE DRIVEN BY SENSITIVE ELECTRONICS AND TRENDING UPWARD FOR BOTH METAL AND COMPOSITE AIRFRAMES


DIGITAL PROCESSING APPLICATIONS

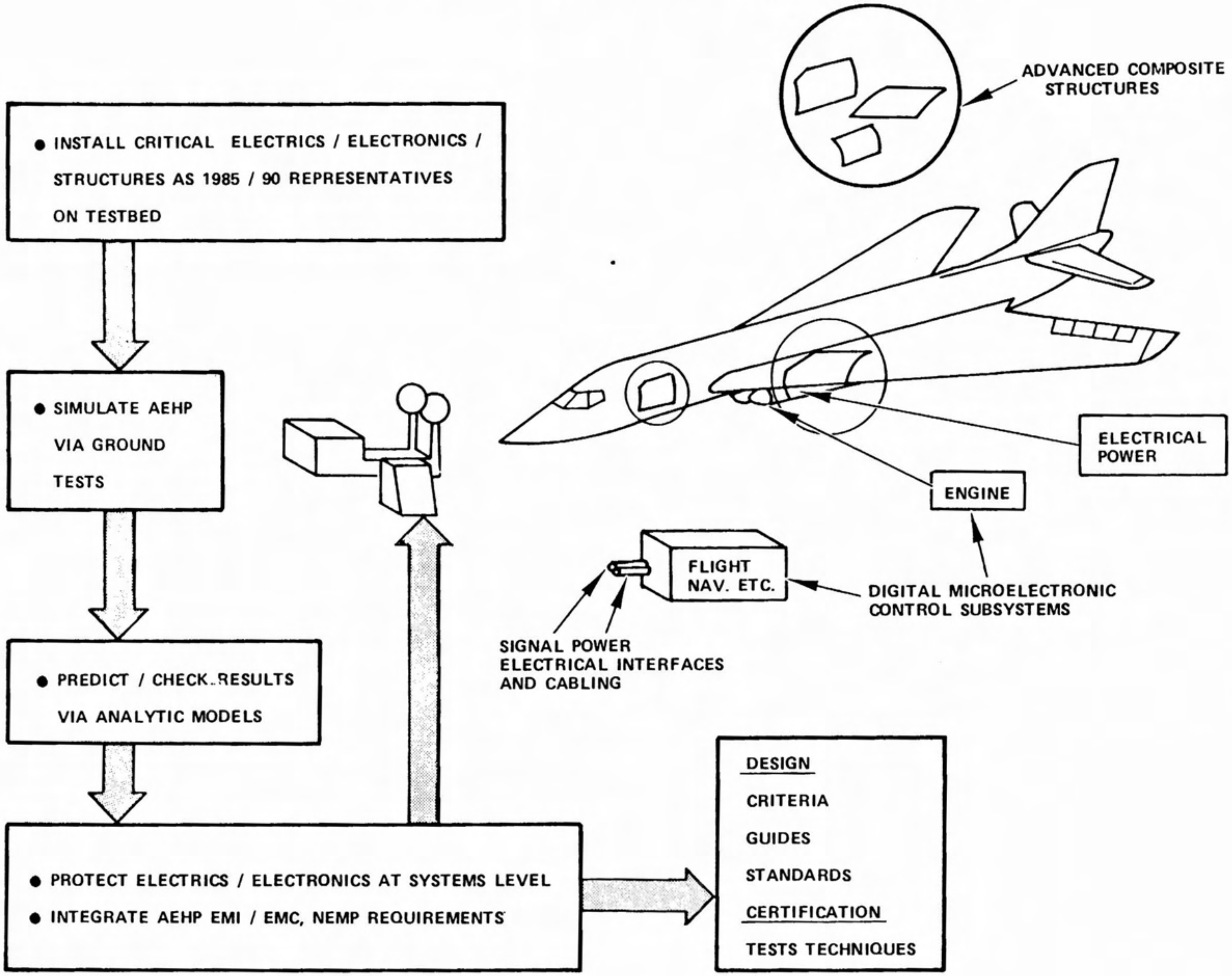
ADP PROTECTION PHILOSOPHY

- DENY HIGH CURRENTS TO INTERIOR OF AIRCRAFT
- TRADE STRUCTURES, INTERFACE AND SUBSYSTEM HARDENING FOR BEST SYSTEMS LEVEL MIX
  - SELECTIVELY INTEGRATE LIGHTNING, EMI/EMC, NEMP PROTECTION METHODS
- CONCENTRATE ON CRITICAL ELECTRICAL AND MICROELECTRONIC CONTROL SYSTEMS AFFECTING SAFETY AND MISSION
  - FLIGHT CONTROL
  - ENGINE CONTROL
  - STORES MANAGEMENT
  - ELECTRICAL POWER SYSTEMS
- USE GROUND SIMULATION TESTS AND ANALYTIC TOOLS FOR HARDNESS EVALUATION
  - EMPLOY BEST EXISTING LIGHTNING CHARACTERIZATION
  - BOUND KEY PARAMETERS TO DEFINE SAFETY MARGINS
- PRODUCE PRACTICAL PROTECTION GUIDELINES AND SPEC'S FOR GENERIC AIRCRAFT EMPLOYING MICROELECTRONIC SUBSYSTEMS AND ADVANCED COMPOSITE STRUCTURES

ADP WORK SCHEDULE



ATMOSPHERIC ELECTRICITY HAZARDS PROTECTION (AEHP)
ADVANCED DEVELOPMENT TECHNOLOGY PROGRAM



- INSTALL CRITICAL ELECTRICS / ELECTRONICS / STRUCTURES AS 1985 / 90 REPRESENTATIVES ON TESTBED
- SIMULATE AEHP VIA GROUND TESTS
- PREDICT / CHECK RESULTS VIA ANALYTIC MODELS
- PROTECT ELECTRICS / ELECTRONICS AT SYSTEMS LEVEL
- INTEGRATE AEHP EMI / EMC, NEMP REQUIREMENTS

DESIGN

CRITERIA

GUIDES

STANDARDS

CERTIFICATION

TESTS TECHNIQUES

PHASE ONE

PRELIMINARY ANALYSIS AND PROTECTION DESIGN

ATMOSPHERIC ELECTRICITY ENVIRONMENTAL ASSESSMENT

FLIGHT VEHICLE STRUCTURE IMPACT

ELECTRONICS SUSCEPTIBILITY

VULNERABILITY ASSESSMENT

EFFECTIVENESS TRADEOFFS

– INTERIM DESIGN CRITERIA

– PHASE II PROGRAM DEFINITION AND APPROVAL

– PHASE I FINAL REPORT

PHASE TWO

PROTECTION VALIDATION

– TEST VEHICLE PREPARATION

PROTECTION EVALUATION

DESIGN CRITERIA AND GUIDES

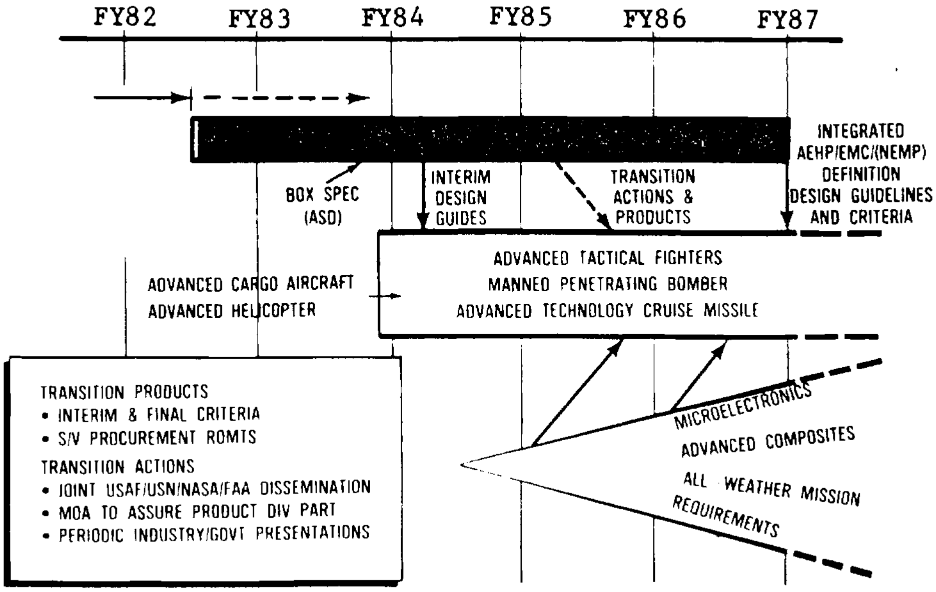
PHASE II FINAL REPORT

QUALIFICATION TEST PROCEDURES

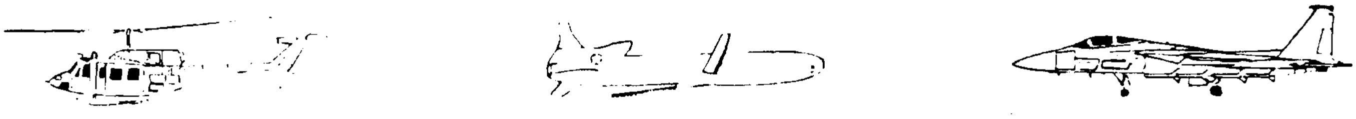
- SIMILARITY OF LIGHTNING AND NEMP-CAUSED TRANSIENTS
- GENERAL APPLICABILITY OF BASIC EMI/EMC HARDENING METHODS
  - BOND, GROUND, SHIELD, LIMIT, FILTER, ETC.
  - SYSTEMS LEVEL STRATEGY
- RECOGNITION OF LIGHTNING AS SEVERE THREAT
- HIGH COST OF CURRENT EM RADIATION PROTECTION RQMTS
  - EM PROTECTION
- LACK OF ADEQUATE LIGHTNING OR NEMP STANDARDS
  - CRITERIA AND SOLUTIONS AD HOC FOR EACH A/C
- AIR FORCE AVIONICS STANDARDIZATION GOALS

FACTORS PROMOTING INTEGRATED LIGHTNING, EMI/EMC, NEMP PROTECTION

AEHP ADTP TRANSITION OPPORTUNITIES/WINDOWS



INTER-AGENCY ADP SUPPORT



ARMY

NAVY

AEHP

FLIGHT DYNAMICS LABORATORY

FAA

DNA

NASA

- INTERAGENCY MGT PLAN (SIGNED BY FAA, USAF, USN, NASA OCT 80)
  - ESTABLISH NATIONAL AEHP PROGRAM (NAEHP)
  - ESTABLISH NAEHP INTERAGENCY COORD GP (NICG)
    - COMPOSED OF AGENCY FOCAL PTS
    - INDORSE PGMS FOR JOINT SUPPORT
- JOINT PROGRAM MGT SUPPORT PLAN
  - USAF–PGM MGR, ADPO, FUNDING, TEST ARTICLES / BED
  - USN–TEST / BED, PROGRAM REVIEW
  - NASA–DIGITAL UPSET ANALYSIS, LTNG, CHAR.
  - FAA–APPROPRIATE FUNDING AND SUPPORT
  - JOINT–STEER PGM VIA NICG
- REMAINING ACTIONS
  - APPROVE PLANS AND MOA IN EACH AGENCY
  - SECURE RESOURCES TO MEET REQMTS AND SCHEDULE
    - FAA / FDL IA APPROVED ($600K SHARE)
    - DNA / FDL MOA APPROVED ($1.3M FOR AEHP / NEMP CROSS FLOW)
    - HELICOPTER DEMO ($3.1M ARMY SHARE PROPOSED)
    - NAVY PHASE II SUPPORT (PROPOSED)

LIGHTNING STRIKE
QUALIFICATION TESTING
OF
US ARMY HELICOPTERS

David L. Albright
US Army Aviation Research and Development Command
St. Louis, Missouri

The UH-60A (BLACK HAWK) is the first Army aircraft to undergo complete lightning strike qualification testing. It was selected because of the substantial use of non-metallic components, the complexity of its flight control system, and the requirement to operate in adverse environmental conditions.

The lightning strike qualification testing consisted of three key elements:

a. Full scale tests of the main and tail rotor blades.

b. Streamering tests of selected non-metallic surfaces of the aircraft.

c. Conducted-current tests of a total air vehicle.

Significant results of each of the above are as follows:

a. Both the main and tail rotor blades failed the component tests; but design changes have been incorporated which will enable them to survive a severe (200,000 ampere) lightning strike. These design changes are similar to those incorporated in the Navy LAMPS blades and have a production effectivity of the 94th aircraft.

b. Streamering tests, which consist of the application of intense electric fields to non-metallic surfaces covering flight critical circuitry and flight crew personnel, demonstrated that internal sparking occurred off the helmet and foot pedal areas, which was defined as being hazardous to the flight crew. Corrections for these items in the crew station area consist of adding conductive material on or near the cockpit overhead canopy and conductors across each cockpit lower window near the foot pedals. These changes were effective with the 72nd production aircraft. With these changes, the liklihood of crew injury due to internal sparking is considered an acceptable risk.

c. The total system "conducted-current test" consisted of a strike to a fully operational aircraft on the ground (rotor hubs turning, rotor blades removed, subsystems operating) at a level of 5000 amperes, which was intended to be non-destructive. This test resulted in damage to 21 subsystems and components, the most significant of which are: flight control system computer, electrical system bus relays, hydraulic modules, caution and warning system, trim servos, and lesser important systems. It is important to recognize that the average strength of a full scale strike is 20,000 amperes with a small percentage in excess of 200,000 amperes, all of which have fast rise times. The simulated lightning current waveform was a damped sinusoid type at a frequency of approximately 25kHz. Since many subsystems failed the 5000 amperes test, the program was terminated at this point. A considerable number of very low level (400 amperes) strikes was applied and data taken for use in defining future design fixes.

There is currently no formal, funded program to initiate design fixes for the full scale conducted-current lightning strike failures; however, proposals for same have been submitted. The current Operator's Manual restriction reads, "WARNING: AVOID FLIGHT IN OR NEAR THUNDERSTORMS ESPECIALLY IN AREAS OF OBSERVED OR ANTICIPATED LIGHTNING DISCHARGES. AS A RULE OF THUMB, THE AIRCRAFT SHOULD REMAIN AT LEAST ONE CLOUD HEIGHT (PEAK CLOUD ALTITUDE) AWAY FROM THE EDGE OF THE CLOUD." In addition, descriptive information on the consequences of a lightning strike are included in the manual.

Full scale vehicle tests of the CH-47 aircraft have not been considered; however, lightning tests of the composite main rotor blade were successful. In light of the current BLACK HAWK data and the full IMC capability of the CH-47 such total vehicle testing is highly desirable.

The situation with the AH-1S is virtually the same as the CH-47. The composite main rotor blade was tested; and although it initially failed the lightning test, a redesigned version passed. Streamer and full scale conducted-current tests would also be desirable (pending availability of funds.)

Comparable lightning strike protection demonstration requirements were included in the Engineering Development Phase qualification testing program for the YAH-64 for the same reasons as for the UH-60A. However, lightning strike tests have not been conducted except for component testing on the tail rotor blade and the external fuel tank. Results are not yet conclusive in that fatigue testing of the damaged tail rotor blade is still required and details of the fuel tank test results are forthcoming. The status of the full scale streamering and conducted-current tests remain in question due to nonavailability of test assets and funding limitations required to complete the program. An analysis in lieu of full scale tests has been performed by the contractor with numerous design changes being considered as a result of this analysis. Full scale main rotor blade tests will be conducted on the composite blade.

Lightning strike tests on the Near Term Scout Helicopter include the mast mounted sight, the mount installation, and the main and tail rotor blades. Funding limitations preclude incorporation of full scale vehicle tests at this time.

With regard to the general issue of thunderstorm avoidance warnings in Operator's Manuals, all advise against flying into or near thunderstorms, primarily because of considerations of turbulence, poor visibility, and heavy rains. Only two mention lightning, the UH-60A and the UH-1; and of the two, only the UH-60A provides a circumvention distance, namely, the"cloud-height-away" rule of thumb. The rule-of-thumb approach was used so as to not unduly restrict helicopter flight; and it recognizes that helicopters generally fly beneath the clouds and the fact that they can make an emergency landing almost anywhere, whereas a fixed wing aircraft cannot.

A search of the US Army Safety Center's data bank for the past ten years indicates that Army helicopters have not had many recorded lightning strikes, primarily because of the Operator's Manuals' cautioning of avoiding thunderstorms; which is generally easy to accomplish during peacetime operations. The aircraft for which lightning strikes have been recorded during flight are the two which are IMC rated. Most of the recorded lightning strikes occurred when the aircraft were on the ground. These were probably caught by surprise before they could be hangared.

Of all the lightning strikes reported, none resulted in catastrophic failures, primarily because most were ground strikes. The degree of subsequent inspection and teardown analyses reported varied considerably; and any detailed analysis usually resulted in replacement of a number of dynamic components. The one strike to a UH-60A was not a direct strike; however, two tail rotor blades, retention plate assemblies, and the tail rotor gearbox were replaced.

- MINOR DESIGN CHANGES INCORPORATED TO ENHANCE CREW SAFETY RESULTED FROM STREAMERING TEST
- NUMEROUS SYSTEMS DAMAGED DURING TOTAL SYSTEM CONDUCTED CURRENT TEST @ 5000 AMP LEVEL
  - ELECTRICAL SYSTEM BUS RELAYS
  - FLIGHT CONTROL SYSTEM COMPUTER
  - HYDRAULIC MODULES
  - TRIM SERVOS
  - CAUTION & WARNING SYSTEM
  - OTHER LESSER IMPORTANT SYSTEMS

UH-60A STREAMERING & TOTAL SYSTEM TEST RESULTS

	AH-1S	CH-47D	UH-60
● STD/COMPOSITE M/R BLADE TESTED	COMP	COMP	STD
● T/R BLADE TESTED	NO	N/A	YES
● STREAMERING TEST CONDUCTED	NO	NO	YES
● CONDUCTED - CURRENT TOTAL SYSTEM TEST CONDUCTED	NO	NO	YES

LIGHTNING QUALIFICATION TESTS

IN FLIGHT

- UH-1H ('74)
- CH-47C ('78)
- CH-47C ('80)

THESE ARE IMC RATED

GROUND

- UH-1D ('71)
- AH-1G ('73)*
- UH-1H ('74)
- AH-1G ('75)*
- UH-1H ('76)*
- OH-58A ('77)
- OH-58A ('77)
- UH-1H ('77) *
- CH-47 ('79)
- CH-54A ('79)
- UH-1H ('79)
- TH-55A ('79)
- OH-58 ('79)
- OH-58 ('80)
- UH-1H ('80)
- UH-1H ('80)
- AH-1S ('81)
- UH-60A ('81)

* NOT INCLUDED IN SAFETY CENTER DATA.

NOTES:

1. PEACE-TIME DATA - THUNDERSTORMS - IMC AVOIDED.
2. STRIKES NOT REPORTED DURING UNAUTHORIZED IMC FLIGHT.
3. DURING SEVERE WEATHER, AIRCRAFT NORMALLY HANGARED.

DOCUMENTED LIGHTNING STRIKES

- NO CATASTROPHIC FAILURES REPORTED.
- TYPICAL DAMAGE REPORTED:
  - ANTENNAE, TAIL ROTOR BLADES, MAIN ROTOR BLADES.
  - ARC BURNS TO COMPONENTS.
  - COMPONENTS MAGNETIZED.

★ ★ **SPECIFIC INCIDENT:**

UH-1H - IN WHICH A MAIN TRANSMISSION SEIZURE OCCURRED SEVERAL DAYS AFTER STRIKE; INSPECTED AND RELEASED FOR FLIGHT (CIRCUMSTANTIAL EVIDENCE).

ANALYSIS OF LIGHTNING STRIKE DAMAGE REPORTED

ARMY ORGANIZATION FOR RESEARCH AND DEVELOPMENT

Joel L. Terry, Jr.
Applied Technology Laboratory
USARTL (AVRADCOM)
Fort Eustis, VA 23604

Since Army attendance at this meeting represents three distinct areas, I feel the committee would benefit from a short review of the Army's R&D organization.

All three attendees' organizations report to or are a part of the Aviation Research and Development Command (AVRADCOM), which reports through the Army Materiel Development and Readiness Command (DARCOM, Alexandria, VA) to the Department of the Army (Figure 1).

Figure 2 provides a breakdown of AVRADCOM by directorates, laboratories, and activities. Mr. Dave Albright is assigned to the Development and Qualification Directorate in St. Louis, Missouri. One of the more important responsibilities of this Directorate is the establishment of airworthiness substantiation specifications for Army aircraft. Lightning test specifications for the whole aircraft system are therefore of great interest. Mr. Jack Rubin is assigned to the Avionics Research and Development Activity (AVRADA) located at Fort Monmouth, New Jersey. As the name implies, AVRADA has the responsibility for avionics research and development, to include all types of displays. Electromagnetic compatibility of avionics systems is of great interest. Within the Applied Technology Laboratory (ATL)--of the Research and Technology Laboratories (RTL)--where I am assigned, there are a number of technical areas interested in EMI, EMP, and lightning protection. The Structures Technical Area manages the Advanced Composite Aircraft Program (ACAP) and is generally interested in the effects of lightning on composite structures. The Weaponization Technical Area manages the Army helicopter advanced and engineering development programs for both weapons systems and target acquisition and designation systems. EMI, EMP, and lightning protection are extremely important. The Safety and Survivability Technical Area is concerned with vulnerability of helicopters to weapons threats such as nuclear EMP. The Applied Aeronautics Technical Area has the Flight Controls and Subsystems Subarea where I am assigned. The major flight controls program is the Advanced Digital/Optical Control System (ADOCS) which is a fly-by-light system designed to virtually eliminate electrical interference in the flight control system. Effects on all other basic aircraft subsystems are a concern of this subarea.

I have been designated as point of contact (POC) for the AEHP Advanced Development Program (ADP), primarily because of ATL's interest in electrical interference in flight controls systems and the need for a funding line location within the RTL complex. I feel that the POC for the AEHP ADP is appropriately placed at ATL. I also feel that the proper location of the POC for the National Interagency Coordinating Group of the AEHP should be in a directorate of AVRADCOM. This location can provide oversight for production helicopter considerations in addition to all technologies within the AVRADCOM laboratories and activities.

COMMAND RELATIONSHIPS

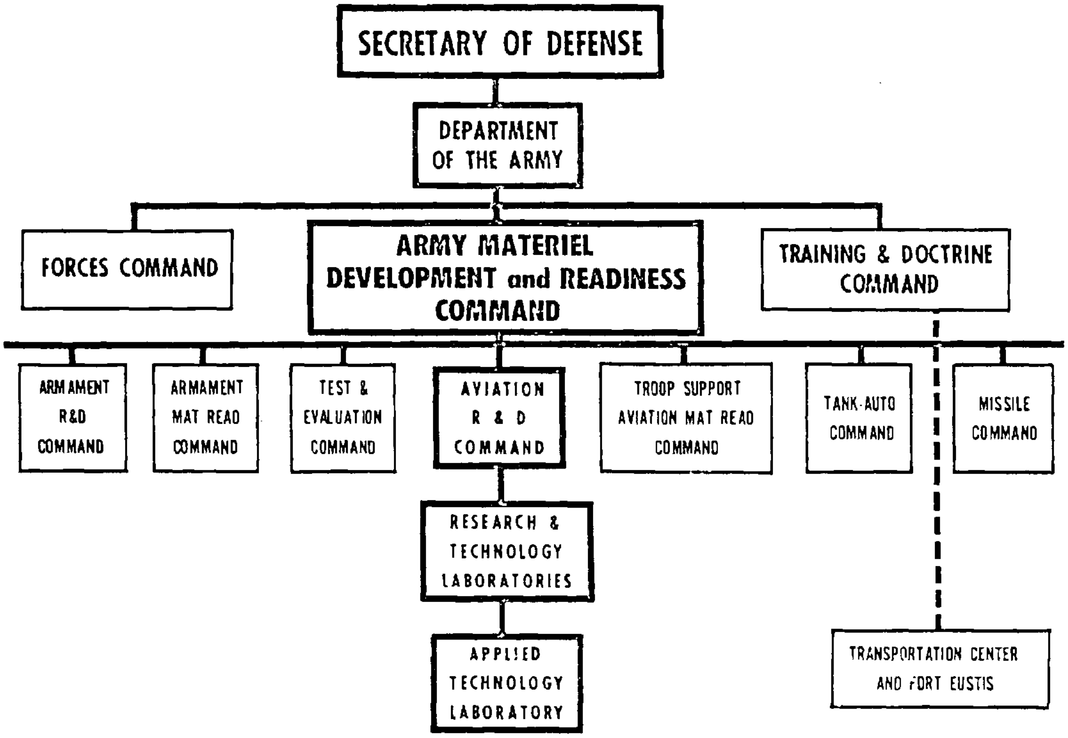
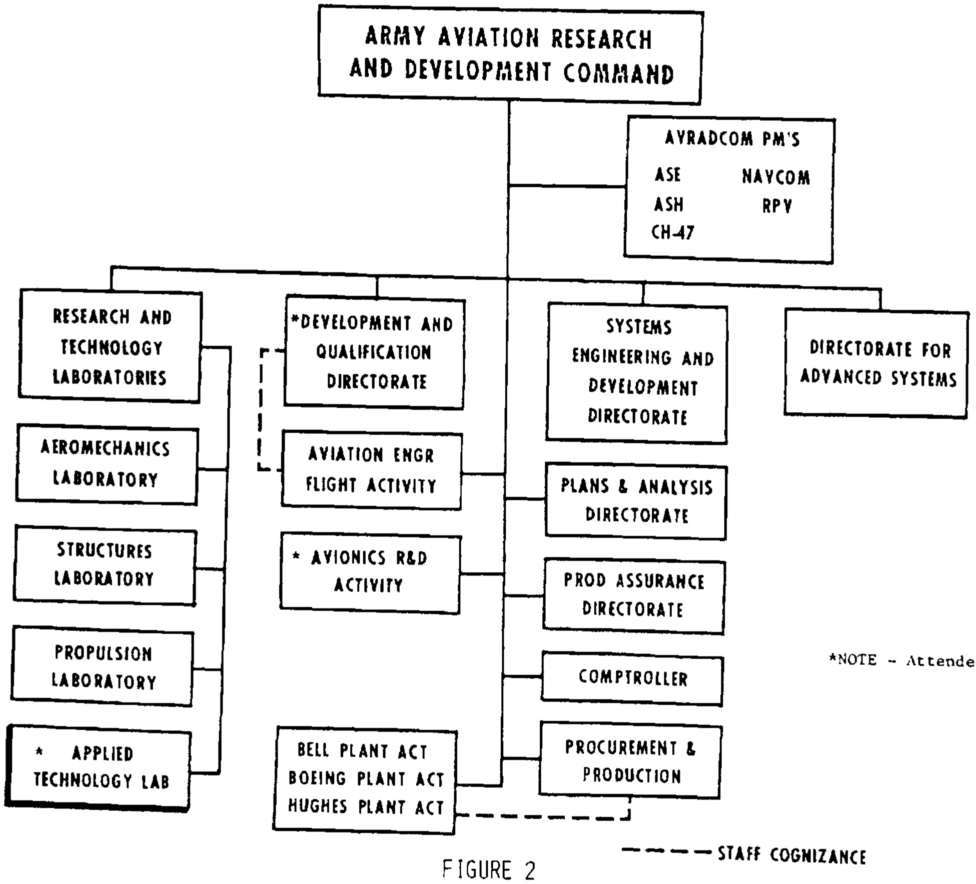


FIGURE 1



*NOTE - Attendees' organizations.

FIGURE 2

SUMMARY.

The formal meeting of the NICG for Atmospheric Electricity Hazards Protection for Aircraft was held at the Bergamo Conference, Dayton, Ohio, December 8-9, 1981. This was the third formal meeting of the group, and was hosted by the USAF with Mr. Gary DuBro (USAF) as chairman.

Representatives from the U.S. Army (USA), U.S. Coast Guard (USCG), and the National Oceanic and Atmospheric Administration (NOAA) were invited as observers in addition to the charter members from the USAF, USN, NASA, and the FAA. Unfortunately, the representatives from the USCG were unable to attend.

The primary purpose of the meeting was the following:

1. Review the minutes from the previous meeting (Crystal City, Va; April 22-23, 1981).

2. Determination of the need for a dedicated national airborne lightning laboratory to supplement the F-106B (NASA-Langley Research Center) aircraft.

3. Disposition of the Management Support Plan of the National Atmospheric Electricity Hazards Protection (NAEHP) Program.

4. Feasibility of establishment of a national ground lightning test facility which includes location, capability, and area of responsibility. Also, to provide committee members with a better insight into existing atmospheric electricity hazards simulation test facilities and capabilities, the following presentations were conducted:

   Sandia Lightning Simulator capabilities.
   Research conducted by the National Severe Storm Laboratory.
   Review of atmospheric electricity hazards simulation test facilities.

5. Sponsorship, responsibilities, etc., associated with the International Aerospace and Ground Conference on Lightning and Static Electricity to be held in the United States in the spring of 1983.

6. Agency updated overview of existing concerns and status of both ongoing and proposed projects.

7. New business.

REVIEW OF MINUTES.

The meeting commenced with a brief review of the minutes from the previous meeting. Mr. Gary DuBro (USAF) made a motion to accept the minutes as written; Mr. Felix Pitts (NASA) seconded the motion and the motion carried.

DEDICATED NATIONAL AIRBORNE LABORATORY.

The determination of the need for a dedicated national airborne lightning laboratory to supplement the F-106B (NASA-Langley Research Center) aircraft was discussed. Mr. Felix Pitts stated that the F-106 program was progressing at a satisfactory rate, except that additional in-strike data are required. He stated that an additional 10 aircraft would be required to supply a sufficient quantity of data in a timely manner.

Mr. DuBro was given an action item (Crystal City, Va; meeting) to define exactly what "decommission of the NOAA C-130 aircraft" means and determine the availability of said aircraft for use as a dedicated lightning measurement laboratory to supplement the F-106B aircraft. Mr. DuBro said the C-130 has been sent to an Air Force Reserve unit and cannot be utilized for lightning research. Mr. Rasch was given an action item (Crystal City, Va; meeting) to determine the possibility of the FAA Technical Center bailing the C-130 from the Air Force.

Mr. Rasch met with the Director of the FAA Technical Center to discuss the feasibility of the Center maintaining and operating the C-130 test aircraft. This would increase the FAA fleet and existing logistic problems. A negative response was obtained due to the impact it would have upon the limited resources available at the Technical Center.

This concluded the discussion on utilizing the C-130 aircraft to supplement the F-106B testbed for lightning research.

The USAF has been investigating the feasibility of coordinating with the French to utilize their C-160 aircraft in Florida. This program would commence in 1984. Dr. D. Rust inquired about the practicality of using either a NOAA or Navy P-3 aircraft for this research. This could be accomplished on a cost-sharing basis. Mr. DuBro was given an action item to investigate the feasibility of the USAF utilizing one or both of these aircraft.

DISPOSITION OF MANAGEMENT SUPPORT PLAN.

The joint demonstration program for atmospheric electricity hazards protection of advanced technology aircraft, "Management Support Plan," was discussed very briefly. After reviewing the minutes from the previous meeting, it was apparent that the differences between the U.S. Navy (USN) and USAF could not be readily resolved.

The committee interpreted the "Management Support Plan" as a document to support the ADP. As that program is ongoing, the true value of the support plan has been greatly diluted. Mr. Rasch made a motion that the "Management Support Plan" be deleted. Mr. Pitts seconded the motion. The motion carried to delete the "Management Support Plan."

NATIONAL LIGHTNING TEST FACILITY.

The feasibility and practicality of having a dedicated national aircraft lightning test facility was discussed very briefly. The discussion was deferred to permit the committee to review the atmospheric electricity hazards simulation test facilities information presented by Mr. L. Walko (USAF).

Action items were given to Mr. DuBro to determine what additional facilities (physical plan) would be required for this lightning test facility and to conduct a survey to define the annual operating cost (manpower and money).

CONFERENCES.

An announcement was made that Culham Laboratory will host the 1982 International Aerospace Conference on Lightning and Static Electricity at St. Catherine's College in Oxfordshire, England, March 23-25, 1982. A total of 61 papers are to be presented as follows:

Phenomenology - 19 papers
Hazards Assessment - 7 papers
Lightning Testing, Exp. Tech - 13 papers
Aerospace Electrostatics - 8 papers
Protection of Aerospace Vehicles - 8 papers
Ground Systems - 6 papers

This is truly an international conference as papers are being presented from eight different countries.

The NICG will host the 1983 International Aerospace and Ground Conference in concert with the FIT. This conference is tentatively scheduled for April 1983 at a site to be determined. Mr. Rasch will participate as chairman for this conference.

Dr. Corbin (USAF) indicated that the USN was planning an international lightning conference in November 1982. As the Navy sponsored conference would seriously impact both the Culham conference and the NICG sponsored conference (April 1983), Mr. Rasch was given an action item to coalesce the USN and NICG conferences.

AGENCY OVERVIEWS.

In a continued effort to enhance communications within the NICG agencies, overviews were presented as follows:

Sandia Lightning Simulator Facilities, Mr. J. C. Bushnell (Sandia National Laboratory)

Research on Electrical Properties of Severe Thunderstorms on the Great Plains, Dr. Dave Rust (NSSL)

F-106 Direct Lightning Strike Program, Mr. F. Pitts (NASA)

Exploratory Development and Research on Atmospheric Electricity Hazards for the US Air Force, Mr. G. DuBro (USAF)

Review of Atmospheric Electricity Hazards Simulation Test Facilities, Mr. L. Walko (USAF)

Full-Scale Aircraft VAlidation of NAVAIR Aircraft Electromagnetic Design and Synthesis, Dr. J. Birkin (USN)

Atmospheric Electricity Hazards Protection of Advanced Technology Aircraft, Mr. R. Beavin (USAF)

Lightning Strike Qualification Tests of US Army Helicopters, D. Albright (USA)

Army Organization for Research and Development, Mr. J. Terry, Jr. (USA)

NEW BUSINESS.

Mr. DuBro, meeting chairman, querried about the practicality of having a permanent chairman in place of the present status of having the hosting agency participate as the chairman. This was discussed and tabled in favor of not having a formal organizational structure. The hosting agency will continue to participate as the chairman.

Mr. Rasch will continue to participate as the NICG Secretariat for the next 2 years. After that period, the position will be reassigned.

Mr. Al Hall (NASA) stated that the frequency of the meetings were too short. He recommended that the Interagency Management Plan be revised to have the NICG meetings held annually with provisions for emergency meetings as required. Mr. Jack Rubin (USA) made a motion to have the Interagency Management Plan revised to reflect the annual meeting schedule. Mr. Rudy Beavin (USAF) seconded the motion. The motion carried. Mr. Rasch was assigned an action item to modify the Interagency Management Plan to reflect the change.

The U.S. Army representatives are very interested in having the Army join the NICG as full members. They indicated that they would make a maximum effort to have the Army solicit the NICG for membership prior to the January 1983 meeting.

The next meeting has been scheduled for January 1983 to be held at the NASA-Langley Research Center with Mr. Felix Pitts to participate as chairman.

APPENDIX A

REVIEW OF ATMOSPHERIC ELECTRICITY HAZARDS SIMULATION TEST FACILITIES

TABLE OF CONTENTS

APPENDIX A

REVIEW OF ATMOSPHERIC ELECTRICITY HAZARDS SIMULATION TEST FACILITIES

by

Larry Walko

Atmospheric Electricity Hazards Group
U.S. Air Force Flight Dynamics Laboratory

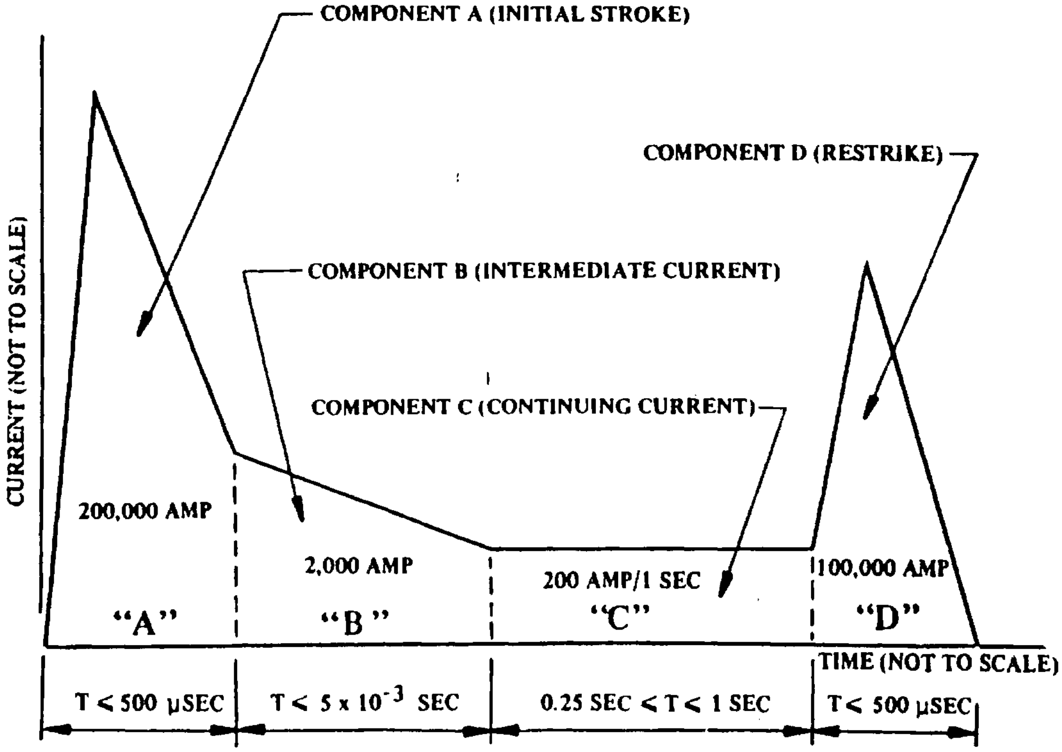
Dayton, Ohio

The information presented herein is the most comprehensive available on Atmoshperic Electricity Hazards Simulation Test Facility. The information encompasses details and facilities from Airframe Manufactures, Private Laboratories and Universities throughout the free world.

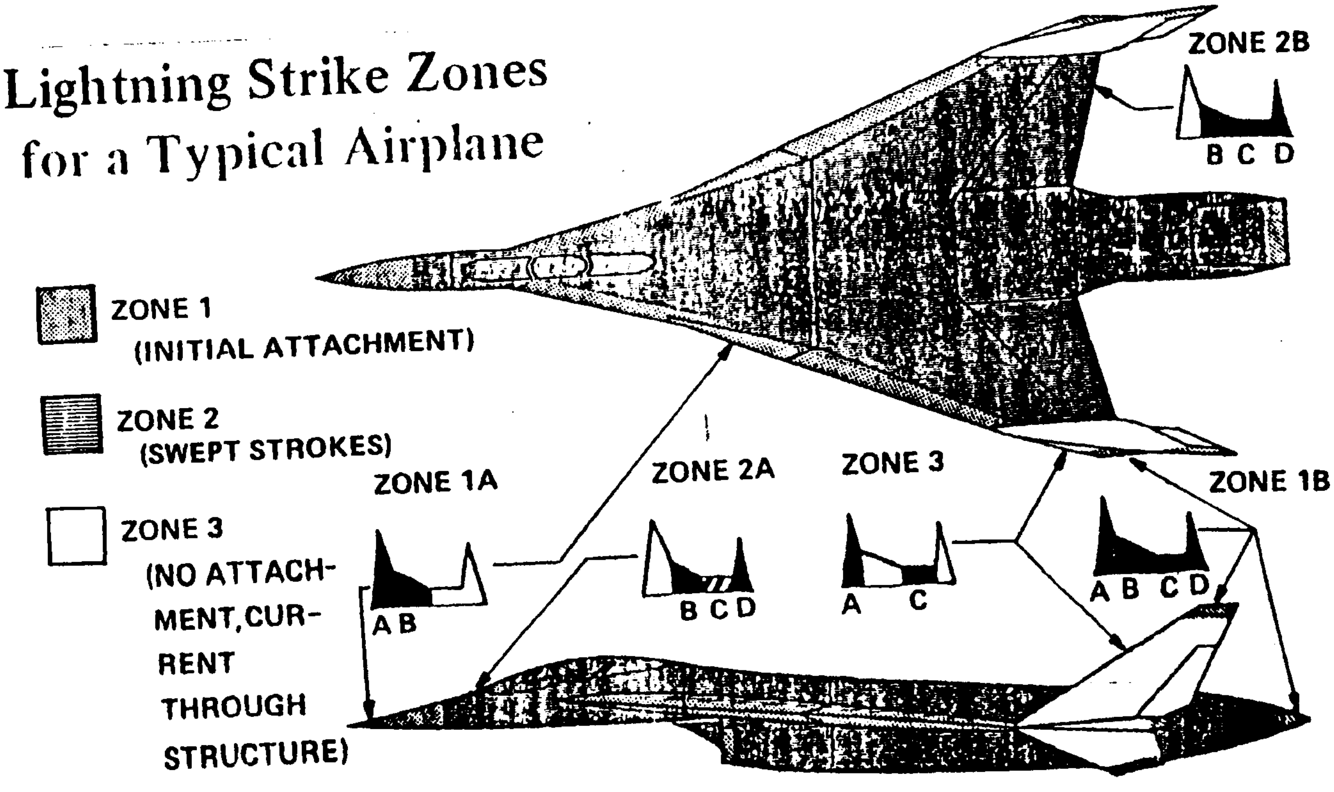
REVIEW OF ATMOSPHERIC ELECTRICITY HAZARDS SIMULATION TEST FACILITIES

- UNITED STATES AND FOREIGN
- GOVERNMENT FACILITIES
- AIRFRAME MANUFACTURERS
- PRIVATE LABORATORIES
- UNIVERSITIES AND COLLEGES

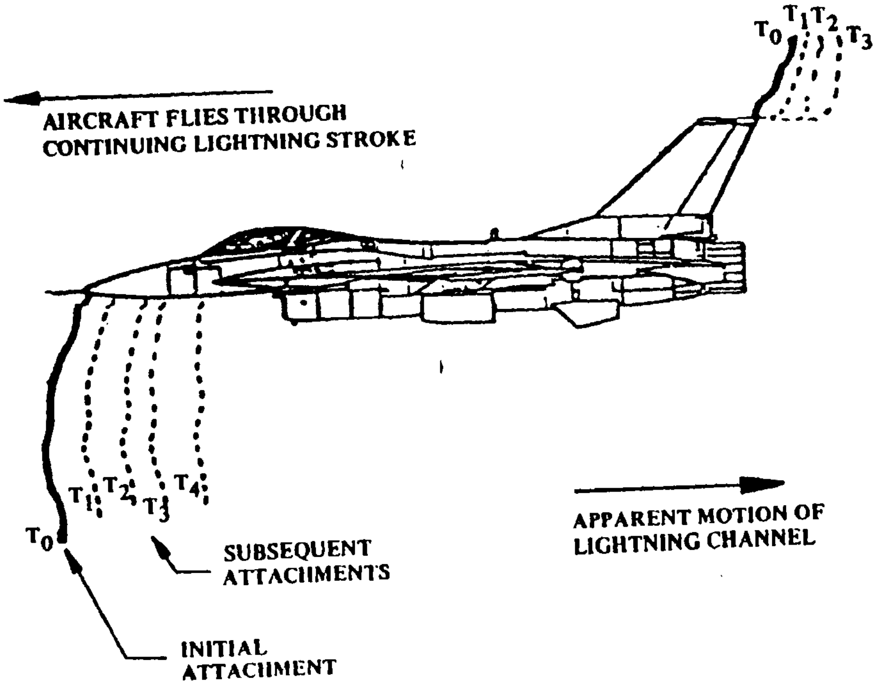
Lightning Test Waveforms



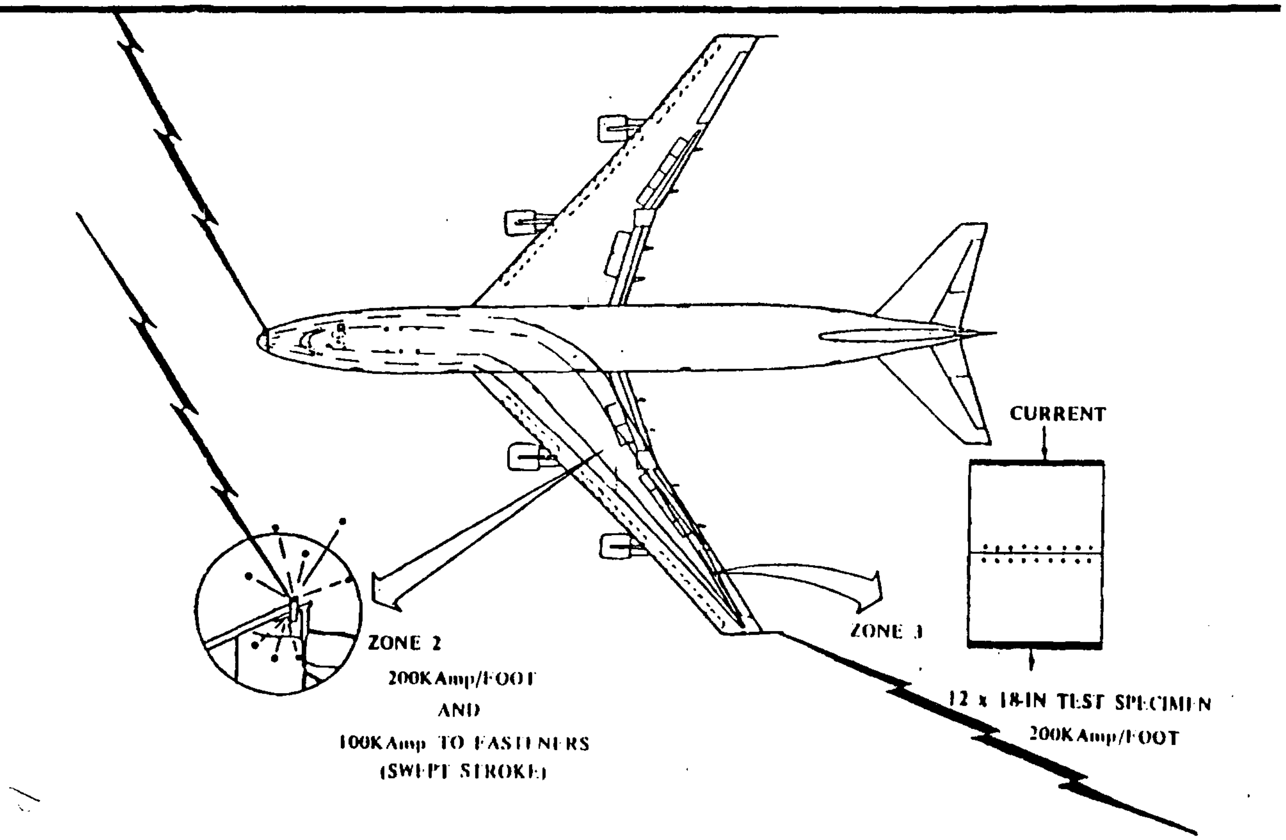
Lightning Strike Zones for a Typical Airplane



Lightning Attachment and "Swept-Stroke Phenomona"



Lightning Current Flow and Test Criteria



U.S. AIR FORCE - ATMOSPHERIC ELECTRICITY HAZARDS RESEARCH FACILITY

- HIGH VOLTAGE AND HIGH CURRENT IMPULSE CAPABILITY
- INDUCED EFFECTS TESTING - CURRENT INJECTION
- LIGHTNING CHARACTERIZATION MEASUREMENT CAPABILITY
- FAST RISETIME GENERATOR DEVELOPMENT

Generators

High Voltage Capabilities

Voltage	Energy	Maximum Arc Length	Applications
300 KV	250 joules	10 inches (0.3 meters)	General laboratory use and high current bank trigger
1.5 MV	26.3 Kj	6 feet (2 meters)	ARC attachment of aircraft component parts and models. Instrumentation cal. and measurement evaluation
6 MV	192 Kj	21 feet (6.5 meters)	Long arc attachment to full scale aircraft components. Arc propagation and induced transient evaluations

High Current Capabilities

Current	Maximum Charging Voltage	Energy	Applications
1 KA	50 KV	2.0 Kj	Transient analysis of aircraft (low level)
10 KA	100 KV	24 Kj	Transient analysis of aircraft (intermediate range) skin current measurement
30 KA	200 KV	36 Kj	Simulation of average lightning current stroke for testing
100 KA	5-50 KV	62.5 Kj	High energy to assess structural damage and high current induced studies
250 KA	100 KV	300 Kj	High energy to assess structural damage and induced energy coupling effects
600 A	100 V	60 KW	Continuous current generation to simulate swept stroke parameters

AIR FORCE WEAPONS LABORATORY LIGHTNING SIMULATION CAPABILITY

- * AFWL MATERIAL RESPONSE IMPACT FACILITY
- * HIGH ENERGY STORAGE SYSTEM - 8 MODULES, 22 MAXWELL SERIES H CAPACITORS PER MODULE
- * TOTAL SYSTEM STORAGE CAPACITY - 500 kJ
- * LOW INTERNAL INDUCTANCE - 8nH PER MODULE
- * RECONFIGURATION OF SYSTEM EASY DUE TO MODULAR NATURE OF BANK

NAVAL AIR TEST CENTER, PATUXENT RIVER, MD

* HIGH VOLTAGE IMPULSE GENERATOR - 2 MV, 33 KJ

* HIGH CURRENT IMPULSE GENERATOR - 160 μF, 25 KV
  CAPABLE OF 120 KA PEAK CURRENT

SANDIA NATIONAL LABORATORIES, ALBUQUERQUE, NM

- SANDIA LIGHTNING SIMULATOR

  PEAK CURRENT 200 KILOAMPS

  RATE OF RISE 100 KILOAMPS/USEC

  NUMBER OF PULSES PER FLASH 1 TO 4

  CHARGE TRANSFER PER FLASH 300 COULOMBS

  ACTION INTEGRAL PER FLASH 3×10^6 A^2SEC

BOEING LIGHTNING AND ELECTROSTATIC TEST FACILITY

* FACILITIES TO DUPLICATE ALL HIGH PEAK CURRENT SIMULATED

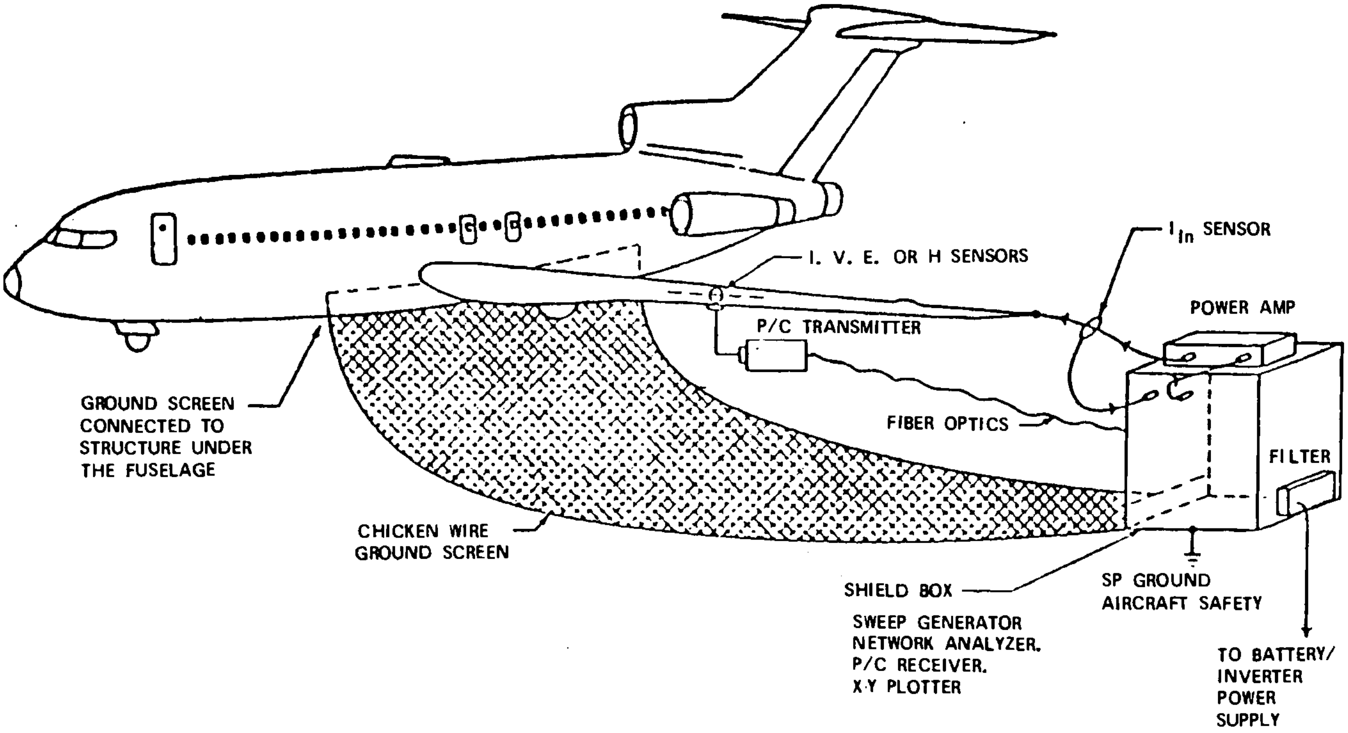
* CAPACITOR BANKS - 1.0 μF TO 5000 μF, OPERATING VOLTAGE UP TO 230 kV

* HIGH COULOMB TRANSFER COMPONENTS - STORAGE BATTERIES, CAPABLE OF 3000 AMPERES FOR 10 MSEC TO 1.0 SECOND DURATION, COULOMB TRANSFER 1.0 TO 3000 COULOMBS.

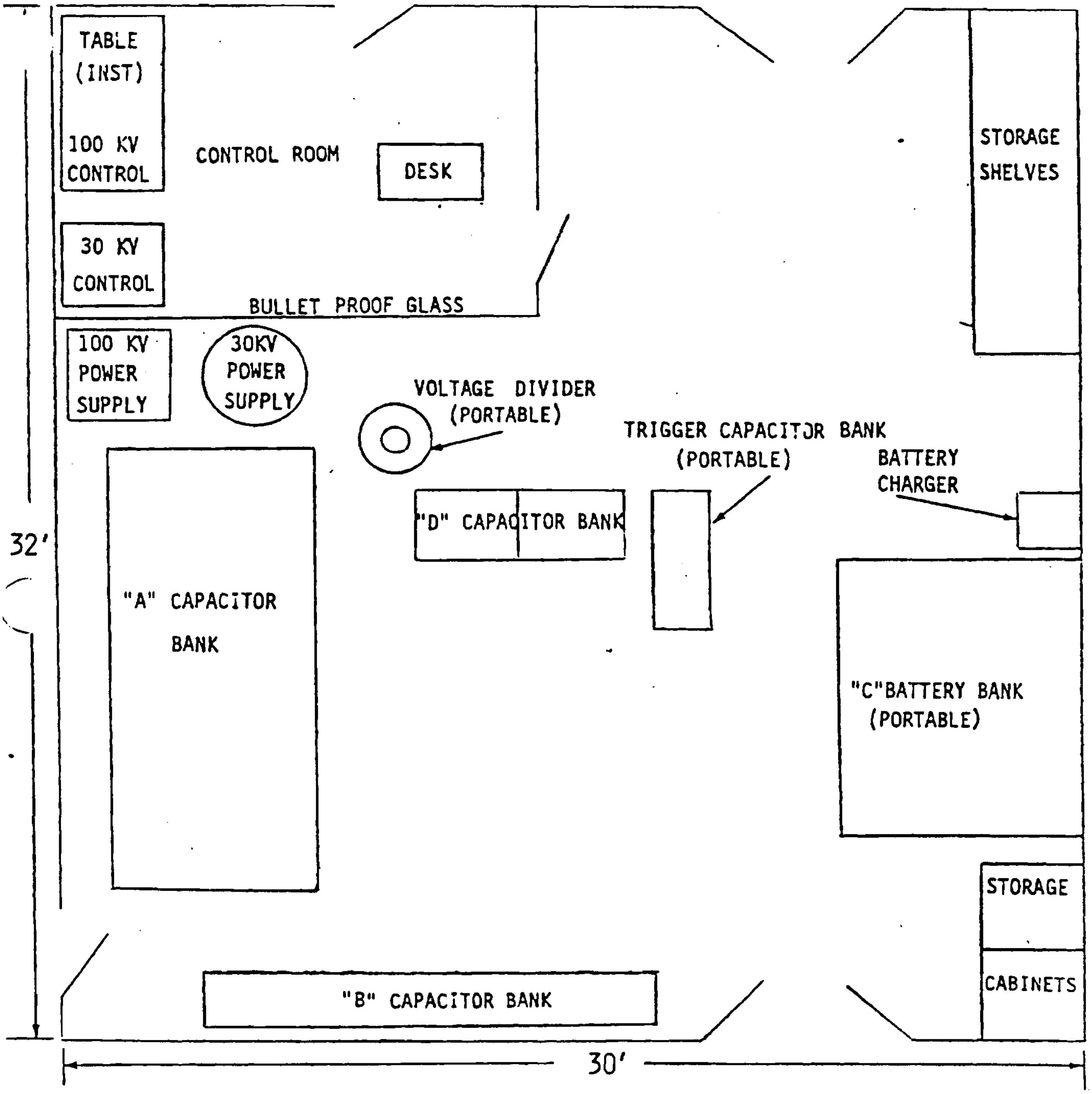
* HIGH ENERGY DISCHARGER - SQUARE WAVE AND RAMP WAVE, PEAK CURRENTS UP TO 28,000 AMPS, DURATION OF 0.1 MSEC TO 18 MSEC; USED FOR CURRENT VS TIME RELATIONSHIPS

* CW OR CONTINUOUS WAVE METHOD OF TEST

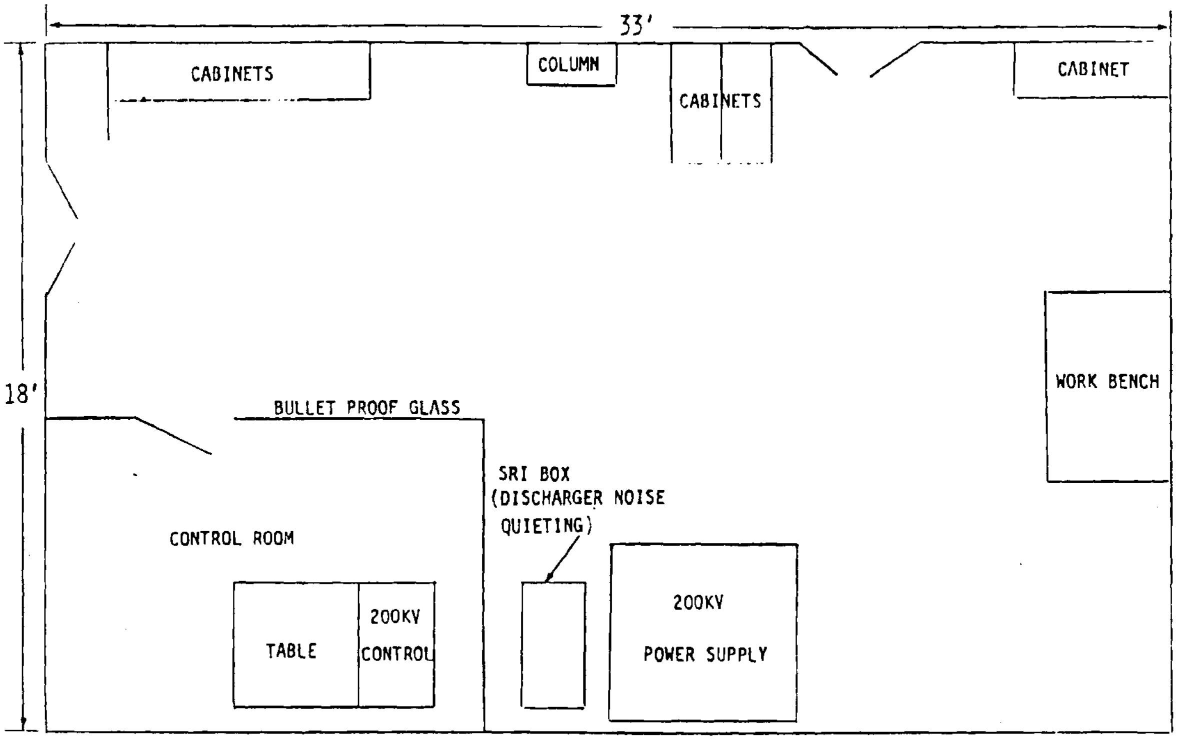
* DC POWER SUPPLIES



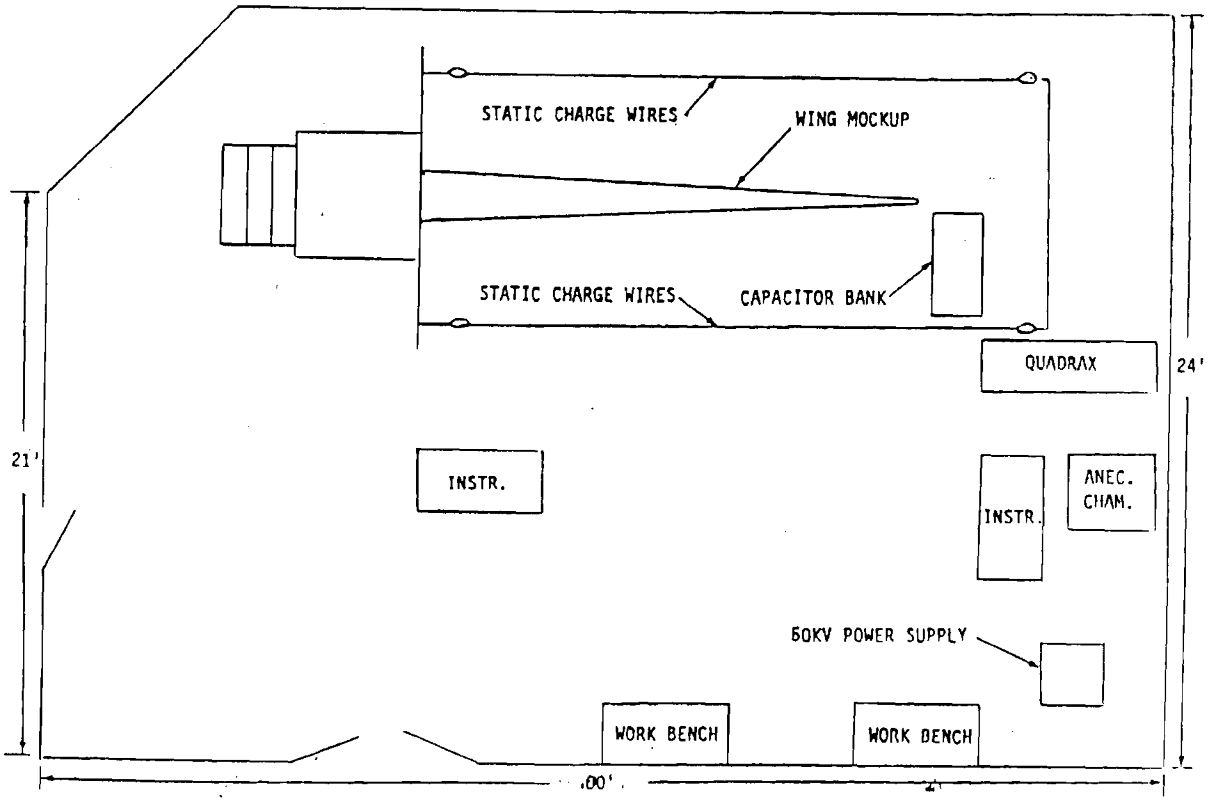
AIRCRAFT SET-UP FOR CW TESTING



LIGHTNING LABORATORY #1



P-STATIC LABORATORY # 2



LAYOUT WING MOCKUP LAB

LOCKHEED-GEORGIA COMPANY TEST FACILITIES

- High Current Impulse Capability - 32 1.6 μF 62.5 kV capacitors connected in parallel, 200 kA, 3 x 10^6 A^2sec, damped oscillatory
- Thorenson 10 mA, 50 kV DC power supply
- Current measured by LTRI designed 0.6 MΩ shunt, coaxial , non-inductive
- Battery Bank - 350 volts, 200 amp level, duration 3 to 5 seconds
- 20 x 20 ft. shielded screen room
- Vaccuum Jar - 30" high, 18" inside dia., used for model attachment studies, can be evacuated to 50,000 ft. equivalent, model size 1 ft.

McDONNELL-DOUGLAS LIGHTNING SIMULATION LABORATORY

* HIGH VOLTAGE IMPULSE GENERATORS - 4.2 MV, 42 STAGE DOUBLE FOLDED MARX; 1.6 MV, TRIPLE FOLDED 66STAGE MARX, ATTACHMENT STUDIES

* HIGH CURRENT IMPULSE GENERATORS - 1MJ MULTIPLE BANK SIMULATOR, INITIAL 200 kA, 100 kA RESTRIKE, INTERMEDIATE COMPONENT; 630 kJ BANK, 300 kA, 240 kV; 15 kJ, 200 kA, 2 μSEC RISETIME

* SHOCK EXCITATION TEST METHOD FOR INDUCED EFFECTS TESTING

* SWEPT STROKE TEST CAPABILITY

Table I
MCAIR lightning simulation laboratory
Major capacitor bank systems

LIGHTNING GENERATOR				DESCRIPTION		PRINCIPLE USAGE				NOTES	FIGURE
NO.	ENERGY KJ	VOLTAGE KV	CURRENT KA	TYPE	PORTABLE	HIGH VOLTAGE PHENOMENON	INDUCED TRANSIENTS MEASUREMENT	HIGH CURRENT DAMAGE TESTING	SWEPT STROKE SIMULATION		
1	42	4200	4	MARX		X				OUTDOOR FACILITY	15, 22, 23
2	4	1650	2	MARX	X	X	X				16, 24
3	1	400	2	MARX	X	X	X			GENERAL LAB USE	3, 14
3'	2.4	1500	10	"	X	X	X				
3"	48	1600	~50	"	X	X	X			COMBINED HIGH PEAK CURRENT, INTERMIDIATE CURRENT, CONTINUING CURRENT. ADJUSTABLE ENERGY AND WAVE SHAPE	
4	~~690~~ 640	240	300	MARX			X	X			6, 28
5	480	12	10	PARALLEL				X			
6	15	100	200	SERIES	X		X	X		FAST RISE-TIME	5
7	60	24	200	SERIES/ PARALLEL	X			X			26
8	30	32	100	PARALLEL	X			X			
9	240	12	1	PARALLEL					X	OUTDOOR FACILITY	27
10	6.25	500	50	MARX	X	X	X		X		21
11	240	480	30	MARX	X	X	X			CAN BE +240V 0 –240V ADJUSTABLE ENERGY AND WAVE SHAPE	20, 24
12	30	25	5	PARALLEL	X		X				
13	72	480	200	MARX	X		X	X	X	FAST-RISE TIME	
14	192	96	150	MARX	X			X			

GP78-0668-20

Table II
MCAIR lightning simulation laboratory
Major power supplies

POWER SUPPLY			DESCRIPTION	PRINCIPLE USAGE	NOTES
POWER RATING	VOLTAGE	CURRENT			
150KW	400 V	500 AMP	D.C. RECT. POWER SUPPLY	HIGH CURRENT DAMAGE TESTING (CONTINUING CURRENT)	PORTABLE
125KW	5,000V	25 AMP	D.C. RECT. POWER SUPPLY	ARC STUDIES	PORTABLE
37KW	25,000V	1.5 AMP	D.C. RECT. POWER SUPPLY	CHARGING SUPPLY FOR 1MJ CAPACITOR BANK	
4KW	400,000V	10 MA	D.C. RECT. POWER SUPPLY	ELECTROSTATIC CHARGING PHENOMENA	
12KW	120,000V	100 MA	D.C. RECT. POWER SUPPLY	CHARGING SUPPLY FOR 4.2MV HIGH VOLTAGE GENERATOR	
BLOWN DUST			AIR DRIVEN	TRIBOELECTRIC CHARGING PHENOMENA	PORTABLE

LIGHTNING SIMULATION SOURCES

HIGH-VOLTAGE GENERATORS

VOLTAGE (KV)	CURRENT (KA)	ENERGY (KJ)	USAGE AND CHARACTERISTICS
4000	15	40	FULL-SCALE COMPONENT AND LARGE MODEL TESTS 20-FOOT SPARK; OUTDOOR
1650	5	4	INDUCED VOLTAGE STUDIES: PORTABLE
1500	10	2.4	REMOTE SITE INDUCED VOLTAGE TESTS; MODULAR CONSTRUCTION
800	25	24	ARC ATTACH POINT TESTS; ADJUSTABLE VOLTAGE RAMP
480	30	240	HIGHER-CURRENT INDUCED VOLTAGE TESTS; PORTABLE
400	2	1	GENERAL LAB USE

HIGH-CURRENT/SWEPTSTROKE GENERATORS

VOLTAGE (KV)	CURRENT (KA)	ENERGY (KJ)	USAGE AND CHARACTERISTICS
240	300	660	*HIGH-PEAK-CURRENT DAMAGE TESTS
96	150	192	*HIGH-PEAK-CURRENT/RESTRIKE TESTS; PORTABLE
480	200	72	*FAST RISE TIME, HIGH-CURRENT TESTS; PORTABLE
12	10	480	*INTERMEDIATE AND CONTINUING CURRENT TESTS
12	1	240	OUTDOOR, 250-KNOT SWEPT STROKE FACILITY; WIND-BLOWN CONTINUING CURRENT AND RESTRIKE TESTS
500	50	6	

NOTES:

1) *GENERATORS CAN BE INTEGRATED TOGETHER TO PROVIDE COMBINED CURRENT COMPONENT A, B, C AND D FULL-THREAT WAVEFORM WITH 2μ SEC RISE TIME.
2) A BUFFALO MODEL 55 BLOWER WITH 100-KNOT WIND STREAM IS AVAILABLE FOR ECONOMICAL LOWER SPEED SWEPT STROKE TESTS.
3) SMALLER HIGH-CURRENT GENERATORS ARE AVAILABLE FOR GENERAL LAB USE.

DC/STATIC ELECTRICITY SOURCES

VOLTAGE (KV)	CURRENT (A)	POWER RATING (KW)	PRINCIPAL USAGE
6	500	3000	CONTINUING CURRENT DAMAGE TESTS (HIGH COULOMB) FOR LARGE COMPOSITE STRUCTURES
0.3	300	90	CONTINUING CURRENT DAMAGE TESTS FOR CONDUCTION TESTS ON SMALL CONDUCTIVE TEST ARTICLES
FRENCH INJECO DEVICE			COMPRESSED AIR CHARGE SPRAY GUN, UP TO 80 µA CURRENT.
BLOW DUST			DRY NITROGEN DRIVEN, TRIBOELECTRIC CHARGING OF PANELS
400 KV DC RECTIFIER			CORONA SPRAY FOR ELECTROSTATIC CHARGING

NOTE: GENERATOR CHARGING POWER SUPPLIES UP TO 120 KV ARE ALSO AVAILABLE.

INSTRUMENTATION AND DATA

PULSE SENSORS

EG&G MGL-S7 (3 EA)	SKIN CURRENT SENSORS
EG&G MGL-6 (3 EA)	FREE FIELD $\dot{B}$ SENSORS
EG&G HSD-4(R)	FREE FIELD $\dot{D}$ SENSOR
EG&G CFD-1	SURFACE $\dot{D}$ SENSOR
EG&G CPM-1	INDUCTIVE $\dot{I}$ SENSOR
PEARSON CURRENT TRANSFORMERS	PEAK CURRENT RATING
MODEL 411 (2 EA)	5 KA
110A	10 KA
1025	20 KA
3025 (2 EA)	20 KA
1049 (4EA)	250 KA
BELL DC CURRENT TRANSFORMER	± 1000 ADC; 150 S RESPONSE TIME
T&M RESEARCH COAXIAL CURRENT SHUNTS	
MODEL F-5000-20	.001 OHM; 5,000 JOULES MAXIMUM
MODEL F-10000-40	.0005 OHM; 10,000 JOULES MAXIMUM

INSTRUMENTATION AND DATA

DATA SYSTEMS

FIBER OPTIC DATA LINKS	SIX CHANNELS: BATTERY POWERED TRANSMITTER; 25 MHZ BANDWIDTH; DIFFERENTIAL, HIGH-IMPEDANCE INPUT; VARIABLE VOLTAGE GAIN TO 150X; RECEIVER DRIVES 50Ω LOAD
TRANSIENT RECORDERS	
BIOMATION 8100	8 BIT RESOLUTION, 2048 DATA POINTS, 10 NS MINIMUM SAMPLING INTERVAL
BIOMATION 6500 (2 EA)	6 BIT RESOLUTION, 1024 DATA POINTS, 2 NS MINIMUM SAMPLING INTERVAL
TEKTRONIX 7612D (2 EA)	2 CHANNELS, 8 BIT RESOLUTION, 4098 DATA POINTS, 5 NS MINIMUM SAMPLING INTERVAL
TEKTRONIX 7912	512 x 512 POINT MATRIX, 200 MHZ BANDWIDTH

INSTRUMENTATION AND DATA

LABORATORY COMPUTERS

HEWLETT PACKARD (HP) 9825 WITH FLOPPY DISK STORAGE, PLOTTER AND PRINTER	64K BYTES OF MEMORY: INTEGRATED WITH FIBER OPTIC AND TRANSIENT RECORDING SYSTEMS TO PROVIDE COMPUTER-CONTROLLED DATA ACQUISITION; MODEM TO DEC PDP 11/40 COMPUTER
HP 9825 WITH PLOTTER AND PRINTER	64K BYTES OF MEMORY: INTEGRATED WITH TRANSIENT RECORDERS FOR AUTOMATED DATA ACQUISITION
NORTH STAR	16K BYTES OF MEMORY: DISK STORAGE

PHOTOGRAPHIC EQUIPMENT

CORDIN MODEL 200	HIGH-SPEED STREAK AND FRAMING; 1μS INTERFRAME INTERVAL
CORDIN MODEL 351/326	STREAK AND FRAMING CAMERA; 25,000 FRAMES/SECOND
IMAGE CONVERTER SYSTEM	ELECTRONIC IMAGE INTENSIFIER CAMERA BOTH STREAK AND FRAMING MODES; (IN PROCUREMENT)
FAIRCHILD HS 401	MOVIE CAMERA, 1800 FRAMES/SECOND
FOUR STILL CAMERAS	4" x 5" FRAME SIZE, NUMEROUS LENSES AND ASSOCIATED EQUIPMENT

NOTE: BESIDES THE ABOVE LISTED SPECIALIZED EQUIPMENT, THE LIGHTNING LABORATORY HAS A LARGE QUANTITY OF GENERAL-PURPOSE TEST EQUIPMENT SUCH AS OSCILLOSCOPES, PULSE GENERATORS, TIME DOMAIN REFLECTOMETERS, ETC.

NORTHRUP CORPORATION LIGHTNING LABORATORY

- 1.2 MV MARX GENERATOR - CAPABLE OF 6 FT ARC, 8000 AMPS CURRENT
  35 STAGE, 40 kV PER STAGE
- RECORDING INSTRUMENTATION IN SCREEN ROOM

28 January 1981

LIGHTNING SIMULATION CAPABILITIES OF NORTHROP CORPORATION

The Northrop Aircraft Corporation is developing the in-house capability to perform full-scale lightning simulation tests. At present (January 1981), the Northrop Lightning Laboratory can perform lightning attachment zone definition studies using scale model aircraft and full size hardware attachment point (Zone 1) testing as described in MIL-STD-1757 (June 17, 1980). These tests are performed using the Pulsar Model 890 high voltage Marx generator, which produces voltage waveform A of the referenced MIL-STD.

Northrop is also presently capable of producing current component A, the initial high peak current component of a simulated lightning stroke. The requirements for this component are a peak amplitude of 200 kiloamperes with an action integral of at least 2 million ampere-squared-seconds at a total time duration not exceeding 500 microseconds. This component is produced by the Pulsar Model 5000 capacitor bank, which can produce peak currents of 260 kiloamperes and action integrals of 3.5 million ampere-squared-seconds. This current component is used in performing direct effects testing of structural components and materials as described in Test Method T02 of MIL-STD-1757. The Model 5000 generator can also produce current waveform D, the "re-strike" waveform, with a peak amplitude of at least 100,000 amperes and an action integral of a least 250,000 ampere-squared-seconds.

Current waveform E as defined in MIL-STD-1757 is produced by the Pulsar Model 790 high current generator. This generator produces up to 100,000 amperes rising at a rate of 100 kiloamperes per microsecond; the minimum requirements for current waveform E are a rate of rise of at least 25 kiloamperes per microsecond for at least 0.5 microseconds and a minimum amplitude of 50,000 amperes. This current component is used for the evaluation of indirect effects such as induction of unwanted signals in control and monitoring circuits in aircraft.

The Lightning Laboratory is also equipped with fiber optic coupled data transmission systems capable of making measurements in circuits which are isolated from ground and are driven to extremely high voltages during lightning testing.

SHAW AERO DEVICES, INC., LONG ISLAND, NY

- HIGH CURRENT IMPULSE CAPABILITY - 200 kA, 15.6 COULOMBS, 6.7 kV
- LIGHTNING TEST CAPABILITIES MEET THE TESTING REQUIREMENTS OF:

MIL-B-5087 BONDING ELECTRICAL & LIGHTNING PROTECTION OF AEROSPACE SYSTEMS

MIL-C-38373 CAP, FLUID TANK FILLER

MIL-F-38363 GENERAL SPECIFICATION FOR AIRCRAFT FUEL SYSTEMS

FAA CIRCULAR AC20-53 PROTECTION OF AIRCRAFT FUEL SYSTEM AGAINST LIGHTNING

LIGHTNING TECHNOLOGIES INCORPORATED (LTI)

- HIGH VOLTAGE IMPULSE - 0.5 MV, 6 kJ, 1 MV/μSEC, 1.5 FT. ARC LENGTH
- HIGH CURRENT IMPULSE - 50 kJ CAPACITOR BANK, COMPONENT A
  COMPONENTS A, B, D IN 1982
- GENERAL ELECTRIC HIGH VOLTAGE LABORATORY FACILITIES

OUTDOOR TEST FACILITY - 6.2 MV, 200 kJ HIGH VOLTAGE IMPULSE GENERATOR
- 1.5 MV 60 Hz RMS TEST SET

INDOOR TEST FACILITY - TWO 5 MV, 84 kJ HIGH VOLTAGE IMPULSE GENERATORS
- TWO 1.5 60 Hz RMS TEST SETS
- 66 kJ, 150 kV HIGH CURRENT IMPULSE GENERATOR, 100 kA UNIDIRECTIONAL, 300 kA OSCILLATORY
- CONTINUING CURRENTS, 400 AMPS, 600 VDC OR 5000 AMPS FOR TENS OF MILLISECONDS

LIGHTNING & TRANSIENTS RESEARCH INSTITUTE (LTRI)

- HIGH CURRENT AND HIGH VOLTAGE IMPULSE TEST FACILITIES
  - MIAMI - 250 kJ BANK, 200 kA PEAK CURRENT
  - ST. PAUL - 100 kJ BANK
- SIX ADDITIONAL CAPACITOR BANKS USED TO PROVIDE MULTIPLE COMPONENT DISCHARGES BY USING ISOLATION REACTORS, RESISTANCES AND SWITCHING SYSTEMS
- ENVIRONMENTAL CAPABILITY FOR PRODUCING TEMPERATURE, HUMIDITY, ALTITUDE CONTROL AND WIND SPEED WITH TWO WIND TUNNELS IN MIAMI AND ST. PAUL
- ACCESS TO UNIVERSITY OF MINNESOTA COMPUTER CENTER

TABLE I

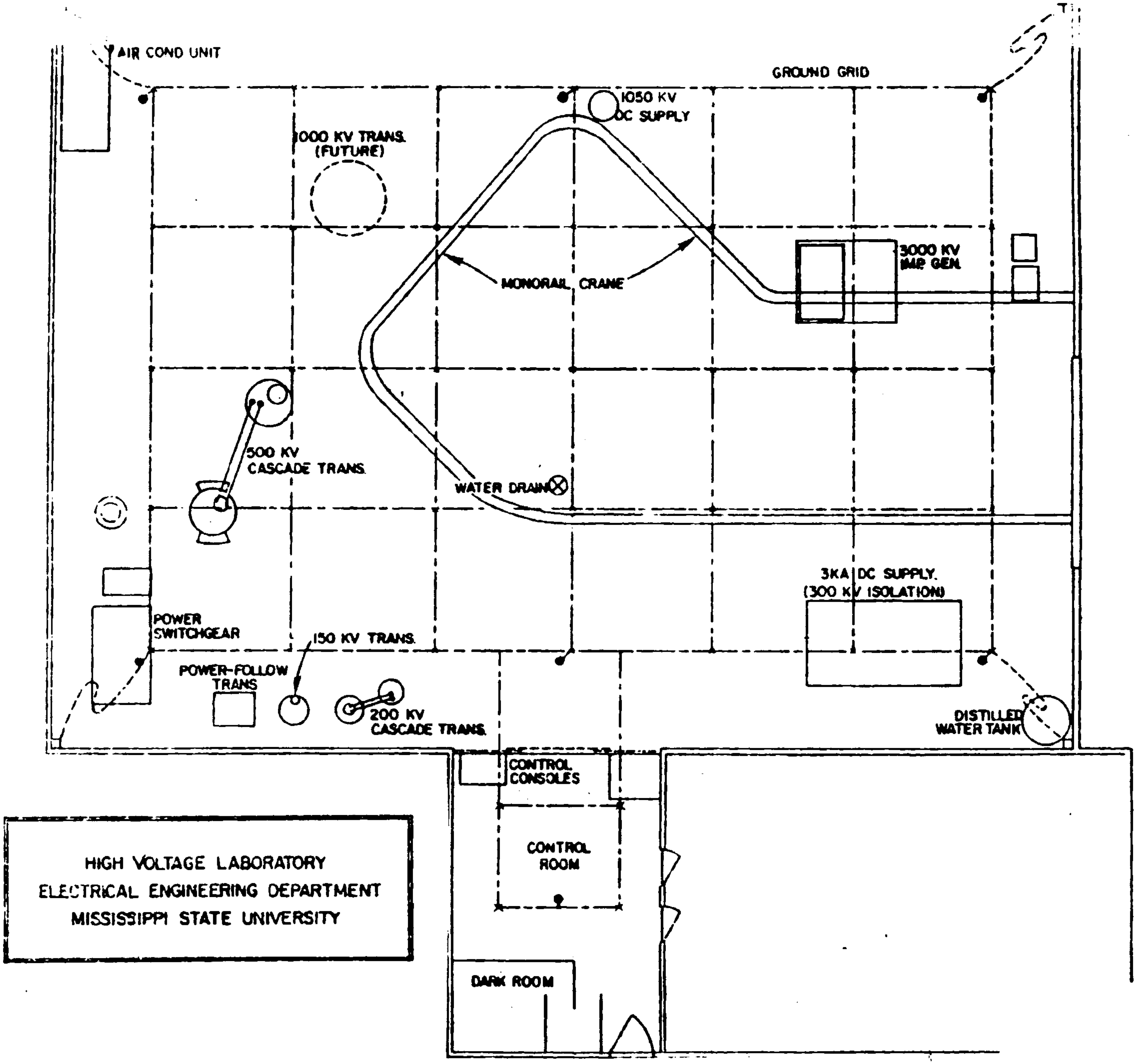
LTRI HIGH VOLTAGE AND CURRENT CAPABILITIES

GENERATOR	CAPACITY MICROFARADS	VOLTAGE KILOVOLTS	CURRENT KILOAMPERES	CURRENT RATE OF RIS AMPERES PER MICROSECOND
ST. PAUL				
LIGHTNING				
High Voltage	0.01	2400	20	20,000
High di/dt	0.068	700	50	110,000
High Current	70	50	270	10,000
High Current	300	20	180	5,000
High Current	140	30	180	5,000
Intermediate Cur.	3000	6.6	5	1
Continuing Cur.	Batteries	—	1	—
Environmental Chamber*	8' x 8' x 15'			
Environmental Chamber*	4' x 4' x 4'			
AC High Voltage*	100 kilovolts	10 KVA		
MIAMI				
LIGHTNING				
High Voltage	0.008	4000	30	30,000
High di/dt	0.1	800	60	110,000
High Current	131	50	250	20,000
Continuing Cur.	Batteries		1	—

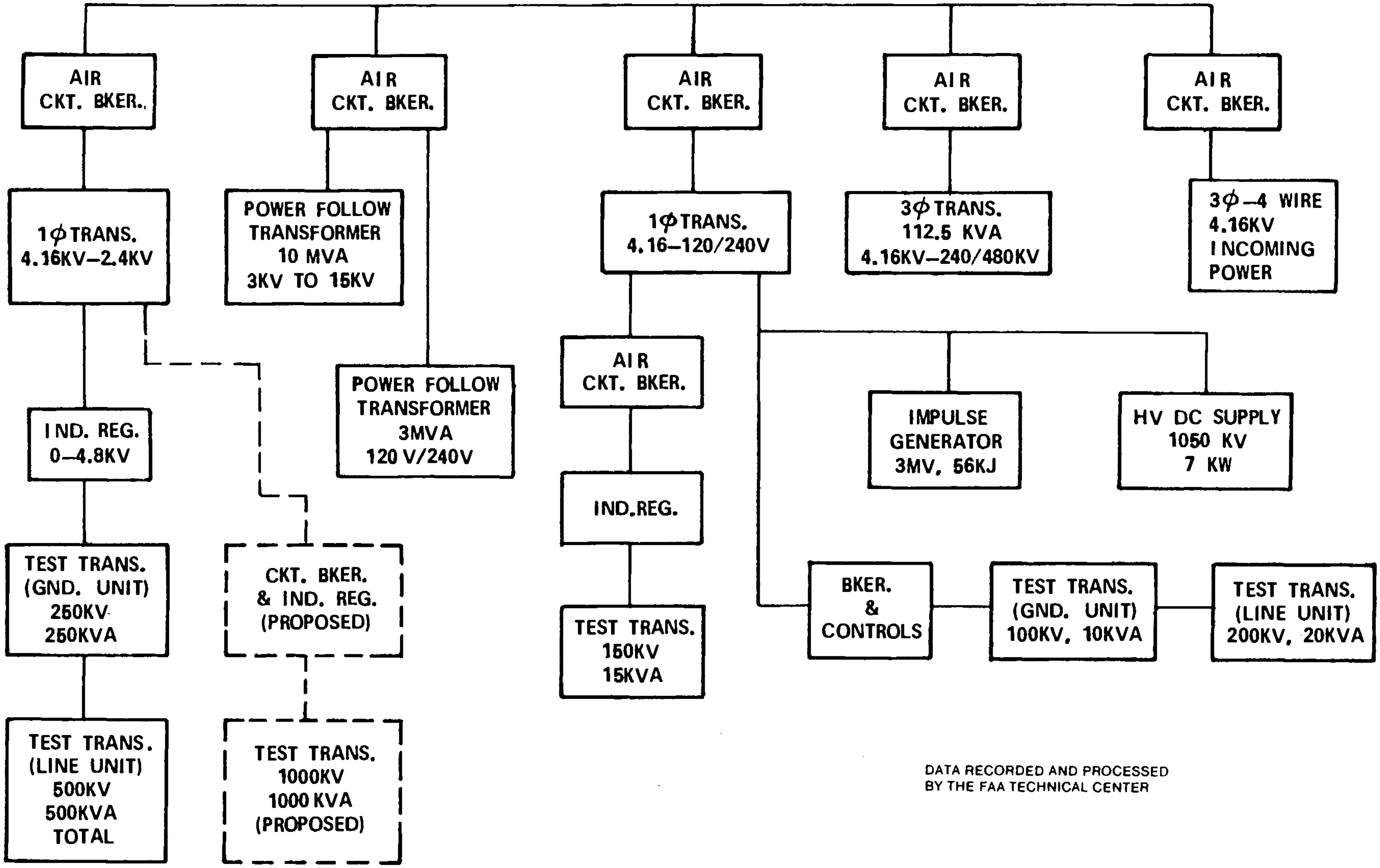
*For AC Wet and Dry Flashover Tests

MISSISSIPPI STATE UNIVERSITY HIGH VOLTAGE TESTING LABORATORIES

- * HIGH VOLTAGE IMPULSE GENERATOR - 3.0 MV, 56 kJ
- * 60 Hz TRANSFORMERS - TWO UNIT CASCADE, 500 kV, 500 kVA
- * DC TEST SET - 1050 kV, 7 kW HIPOTRONICS
- * HIGH CURRENT DC SUPPLY - 3000 AMPS AT 50 VOLTS WITH 300 kV AC ISOLATION
- * POWER FOLLOW TRANSFORMER - 10 MVA SHORT CIRCUIT
- * POWER FOLLOW TRANSFORMER - 120/240 VOLTS, 3 MVA SHORT CIRCUIT



HIGH VOLTAGE LABORATORY
ELECTRICAL ENGINEERING DEPARTMENT
MISSISSIPPI STATE UNIVERSITY



DATA RECORDED AND PROCESSED
BY THE FAA TECHNICAL CENTER

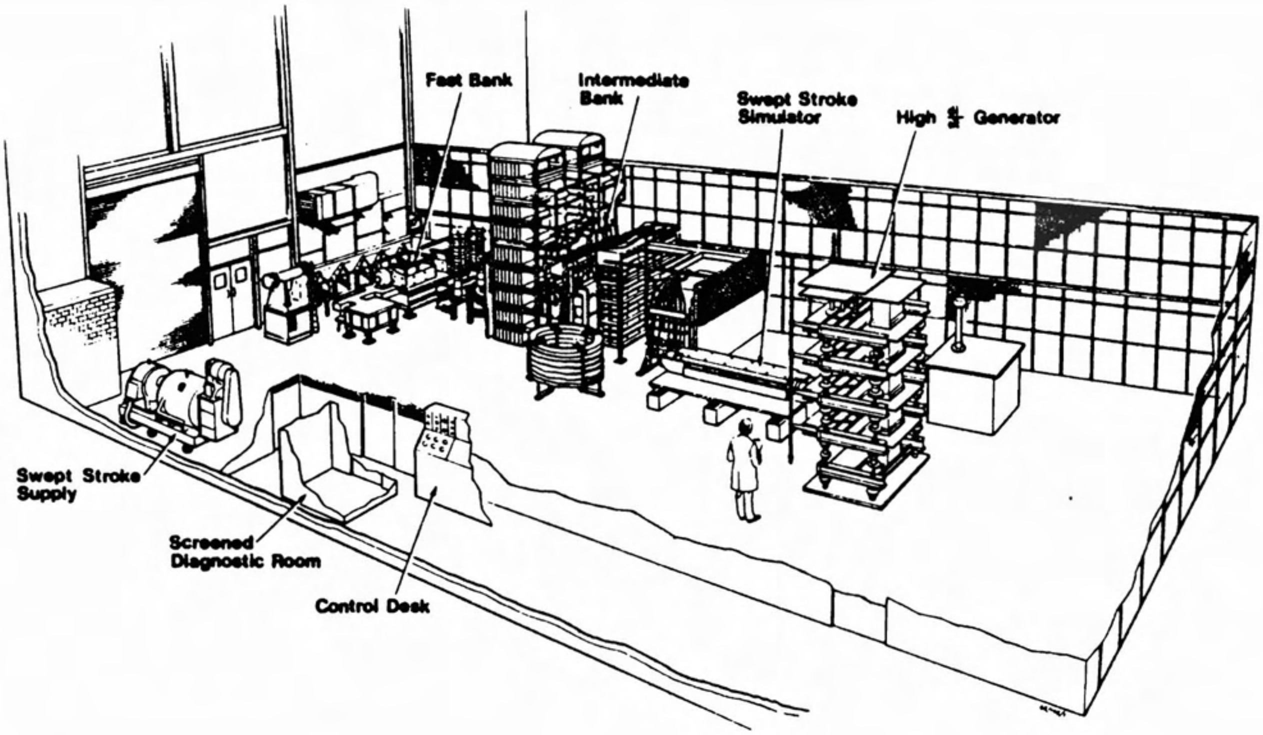
CENTRE D'ESSAIS AERONAUTIQUE DE TOULOUSE (C.E.A.T.)

- HIGH VOLTAGE IMPULSE GENERATOR -
  5 MV, 62.5 KJ, UNDIRECTIONAL WAVESHAPE 1.2x50 µSEC CAPABLE OF 8 METER ARC, USED FOR ATTACHMENT STUDIES

- HIGH CURRENT IMPULSE GENERATOR -
  200 KA PEAK, 100 KJ, 50 KV, 34 KA/µSEC RATE OF RISE IMPULSE WITH ADDITION TRANSFER OF CHARGE OF 500 COULOMBS. USED FOR INDUCED EFFECTS TESTING, COMPOSITE MATERIALS INVESTIGATION, CERTIFICATION TESTS.

CULHAM LABORATORY, ABINGDON, OXFORDSHIRE, UK

- FAST BANK - 140 KJ, 100 KV, 200 KA, 15 µSEC RISETIME, ACTION INTEGRAL $2\times10^6 A^2 s$ INITIAL STROKE
- INTERMEDIATE BANK - 600 KJ, 20 KV, UNIDIRECTIONAL PULSE, 50 TO 100 KA PEAK, CHARGE TRANSFER UP TO 500 COULOMBS, INTERMEDIATE AND CONTINUING CURRENTS
- HIGH RATE OF RISE GENERATOR - 40 KJ, 1MV, 100 KA AT A 100 KA/USEC RATE-OF-RISE SUBSEQUENT RETURN STROKES, INDUCED VOLTAGE MREASUREMENTS
- SWEPT STROKE EQUIPMENT - THE LABORATORY ARC IS DRIVEN ACROSS THE COMPONENT UNDER STUDY BY A TRANSVERSE MAGNETIC FIELD



The *fast bank* (140kJ, 100kV) will produce a 200,000A unidirectional pulse with a rise time of about 15μs with an action integral of 2×10^6 A^2s, and simulates the first stroke of a severe lightning discharge, as well as providing the first component of existing agreed international specifications.

The *intermediate bank* (600kJ, 20kV) will produce a unidirectional pulse of amplitude variable between 50,000 and 100A and a charge transfer of up to 500 coulombs. Thus it simulates the 'intermediate' and 'continuing' currents of a lightning discharge.

The *high rate of rise generator* (40kJ, 1MV) will produce 100,000A at a rate of rise of 100,000A/μs into a 6m component and simulates the maximum peak current and rate of rise of current associated with a subsequent stroke of a lightning flash and is suitable for induced voltage measurements.

With the *swept stroke equipment* the transfer of the lightning attachment point along the aircraft can be simulated. The laboratory arc is driven across the component under study by a transverse magnetic field.

The results of the applied research programme are available to aircraft and component manufacturers who can hire the test facility to carry out simulated lightning tests on components of special interest to them. They also consult Culham staff on design considerations for components that are likely to be damaged by lightning.

The unit has a high international reputation and has contracts from Europe (e.g. Scandinavia) and also from the USA. Work conducted by the unit has not been limited only to aircraft, but has included ships and land installations.

In 1977 the unit, with the backing and encouragement of the Ministry of Defence, the Civil Aviation Authority and the aerospace industry, produced proposals for a testing schedule "Recommended Practice for Lightning Simulation and Testing Techniques for Aircraft" by J Phillpott. These proposals have received international approval and acceptance.

In September 1978 the unit organised a 3-day course on "Lightning Protection to Aircraft" which was attended by 30 engineers and designers from the British and European aerospace industries.

For further information contact Mr A W Hanson

May 1979

APPENDIX B

CAPABILITIES OF THE AVIONIC ENGINEERING CENTER OF OHIO UNIVERSITY

Avionics Engineering Center
Department of Electrical Engineering, Clippinger Research Laboratories
Ohio University, Athens, Ohio 45701

December 4, 1981

Mr. Nick Rasch
c/o Holiday Inn
800 N. Broad St.
Fairborn, OH. 45324

Dear Mr. Rasch:

This letter will outline the capabilities of the Avionics Engineering Center (AEC) of Ohio University with respect to the evaluation of the effects of precipitation static and lightning on airborne avionics equipment.

The Avionics Engineering Center currently maintains in operation a Douglas DC-3 aircraft, N7AP, for flight evaluation of p-static and lightning. This aircraft is maintained IFR-capable with the AEC providing qualified crew. With respect to p-static and lightning, the aircraft is equipped with the following data collection equipment: the aircraft has 12 instrumented Dayton-Granger Omega static wick dischargers installed which can be monitored by a Serial Lab Products remote I/O unit with 16 channel A/D capability. This I/O unit is driven by a Heath H-89 computer that provides the necessary software to provide the data collection function. The Heath H-89 has a built-in floppy-disk mass storage unit which is supplemented by an Analog Digital Products Inc. Byte-Bucket Digital cassette recorder for data collection. Other sensors provided on the aircraft are an EMC-25 Interference Analyzer, Monroe Electric Field Intensity Meter, and a Ryan Model WX7A, StormScope. The aircraft also has an operational weather radar on board. To produce p-static conditions in clear air, the DC-3 is equipped with a biased discharger system which allows the aircraft to be charged electrically in flight.

The current operational costs of the aircraft is $400.00 per hour. Ohio University maintains qualified A&P and AI personnel to provide any assistance in installing and maintaining equipment in the aircraft. The AEC maintains facilities to provide prototype development and analysis to assure successful completion of a task. The AEC has access to the Ohio University IBM-370/158 computer with excellent software support.

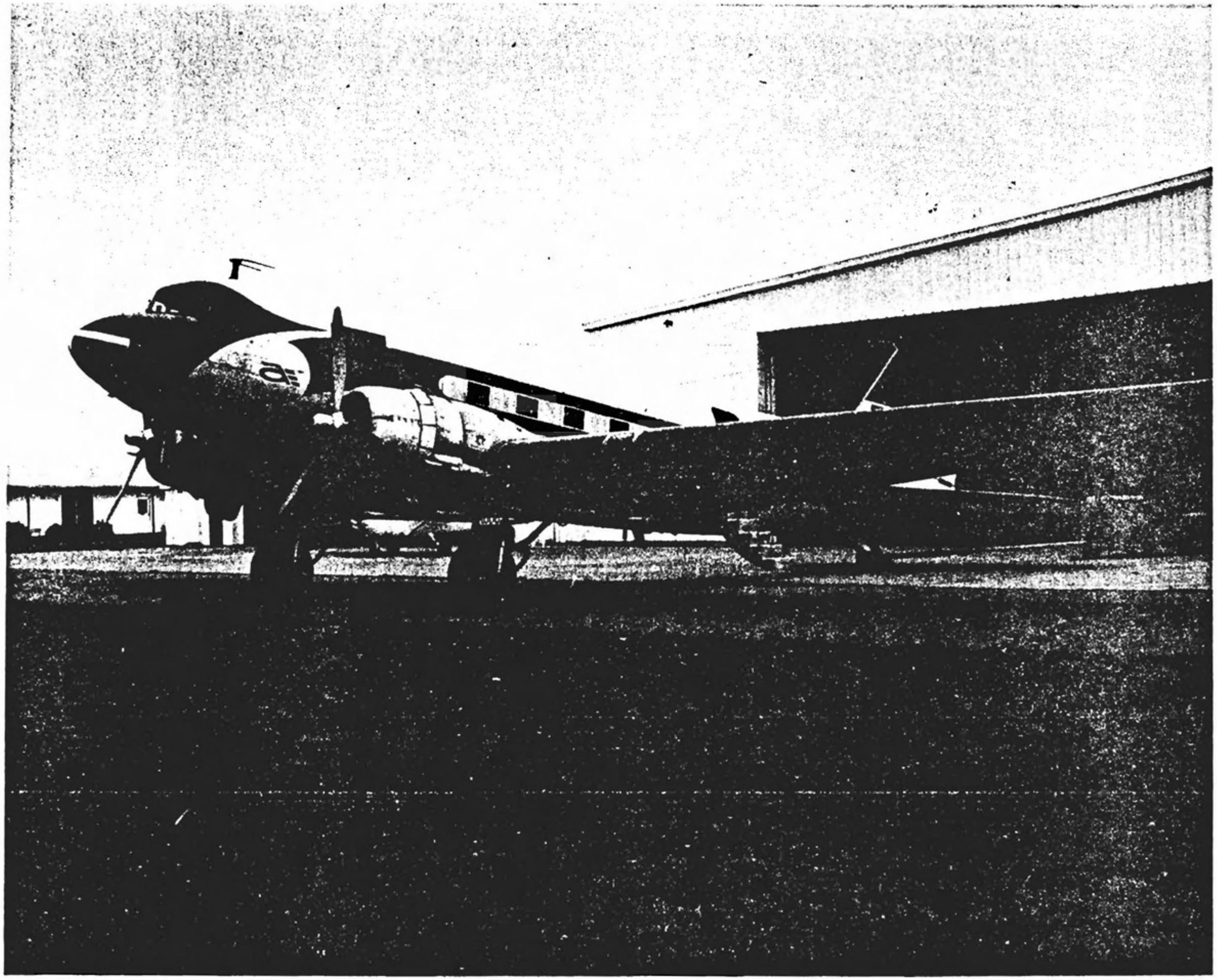
Current programs under way at the AEC involve an FAA contract to evaluate the effects of p-static and lightning on the use of Loran C as a navaid for aircraft. The AEC has sucessfully completed ground and flight tests of the effects of p-static and lightning using two Loran-C receivers in the aircraft. This information will be available in a final report at the completion of the contract period, or through the FAA Technical Officer.

Sincerely,

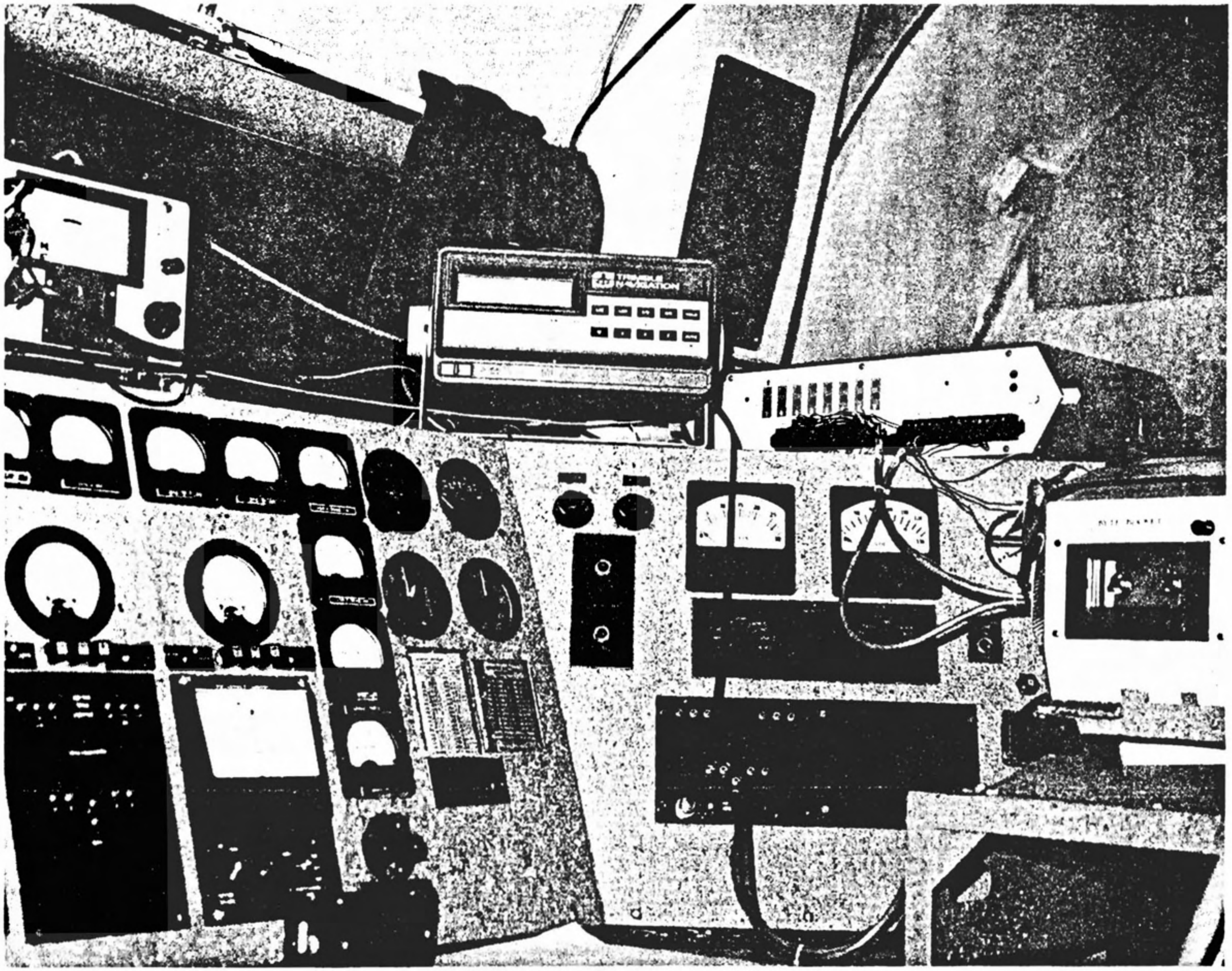
James D. Nickum
Research Engineer
614/594-6873 or FTS 923-1395

JDN:sm

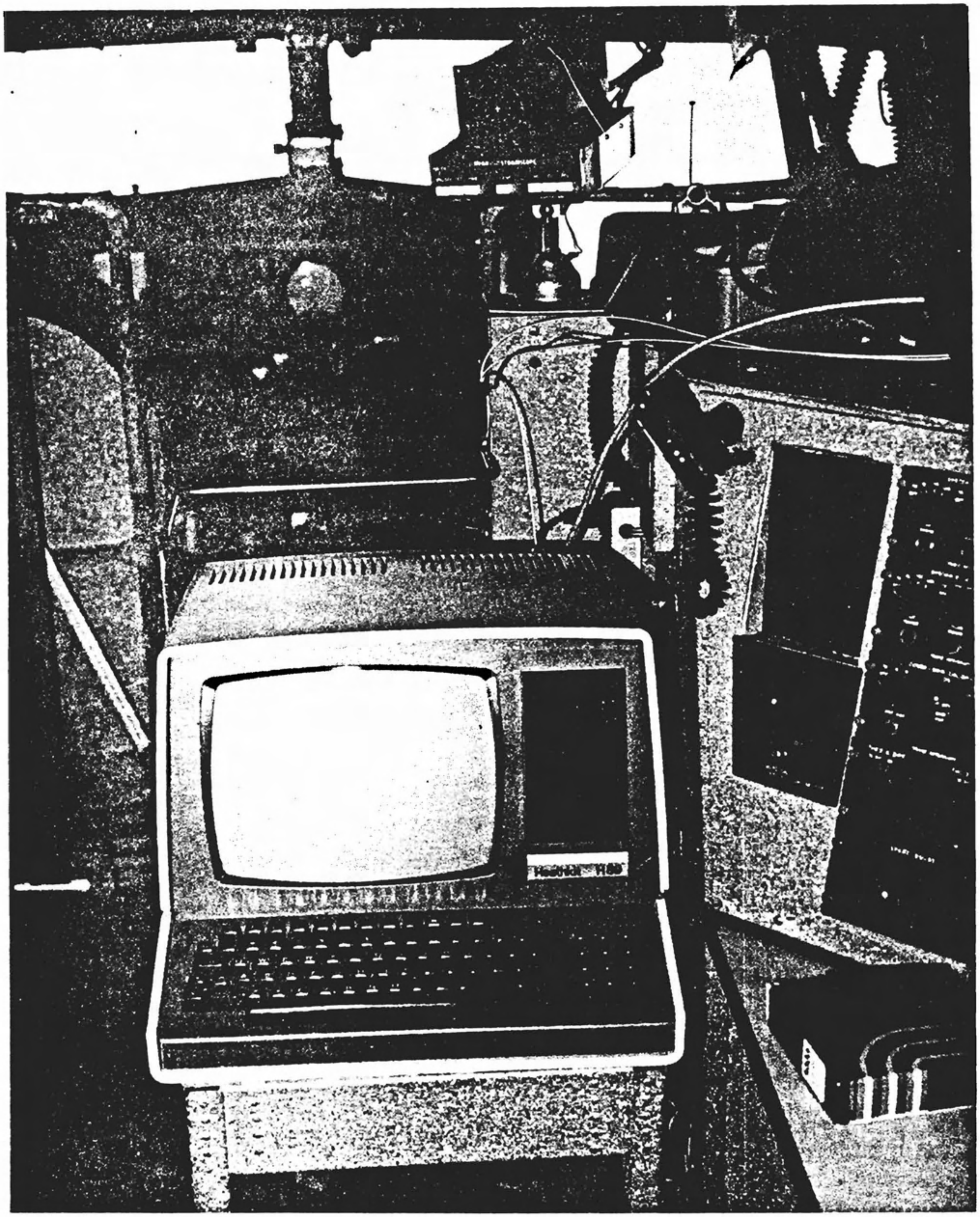
Enclosure



Avionics Engineering Center DC-3, N7AP.



Part of Operator Test Panel Showing, Bottom Left Clockwise: Discharger Monitor Panel, Monroe Field Mill, Trimble Loran Receiver SLP Serial 1/0 Unit, Byte Bucket Digital Cassette Recorder.



Heath H-89 Digital Computer at Operator Test Panel and Ryan's Storm Scope.

APPENDIX C

LIST OF ATTENDEES

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National Interagency Coordinating Group (NICG)

8-9 December 1981

Gary A. DuBro	AFWAL/FIESL	(513) 257-7718
Lawrence C. Walko	AFWAL/FIESL	(513) 2750-7718
Jack Rubin	DAVAA-S	(201) 544-4954
Jack Lippert	AFWAL/FIEA	(513) 255-2916
Eddie J. Preston	AFWL/NTYC	(505) 844-0611
W. David Rust	NOAA/NSSL	FTS: 736-4916 (405) 360-3620
Jack Corbin	ASD/ENACE	AV 785-5078/5986 (513) 255-5078/5986
Felix L. Pitts	NASA/LARC	(804) 827-3681
Albert W. Hall	NASA/LARC	(804) 827-2037
Nick Rasch	FAA/Tech Center	(609) 641-8200 (X1153)
Rudy C. Beavin	AFWAL/FIEA	(513) 255-2395
Wallace C. Buzzard	AFWAL/FIEA	(513) 255-2916
David L. ALbright	AVRADCOM/DRDAV-DM	AV 693-1726 (314) 263-1726
Joel L. Terry, Jr.	App Tech Lab/DAVDL-ATL-ASA	AV 927-2071 (804) 878-2071
John Birken	NAVAIR/AIR-51610/AIR-03PAE	AV 222-3936 (703) 532-3935