NASA Contractor Report 3270

Calibration Tests on Magnetic Tape Lightning Current Detectors

K. E. Crouch

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Calibration Tests on Magnetic Tape Lightning Current Detectors

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Information Office

1980

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CALIBRATION TESTS ON

MAGNETIC TAPE

LIGHTNING CURRENT DETECTORS

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SUMMARY

Development and application tests of a low cost, passive, peak lightning current detector (LCD) found it to provide measurements with accuracies of ±5% to ±10% depending on the readout method employed. The LCD, which was invented at the National Aeronautics and Space Administration, John F. Kennedy Space Center (NASA-KSC), uses magnetic audio recording tape to sense the magnitude of the peak magnetic field around a conductor carrying lightning currents. The test results showed that the length of audio tape erased was linearly related to the peak simulated lightning currents in a round conductor.

Accuracies of ±10% were shown for measurements made using a stopwatch readout technique to determine the amount of tape erased by the lightning current. The stopwatch technique is a simple, low cost means of obtaining LCD readouts and can be used in the field to obtain immediate results. Where more accurate data are desired, the tape is played and the output recorded on a strip chart, oscilloscope, or some other means so that measurements can be made on that recording. Conductor dimensions, tape holder dimensions, and tape formulation must also be considered to obtain a more accurate result. If the shape of the conductor is other than circular (i.e. angle, channel, H-beam) an analysis of the magnetic field is required to use an LCD, especially at low current levels.

INTRODUCTION

Calibration and application techniques development work for the use of LCDs was performed during 1979 under the sponsorship of W. Jafferis, Shuttle Operations Directorate and R.J. Cerrato, Chief, Research and Technology/Technology Utilization Office NASA-KSC.

The report is presented in four sections. The first two sections contain summary, introduction and background information. The third section presents a description of how to make various LCD measurements using the techniques developed during this program. The fourth and final section contains the details of the experimental investigations carried out during the program. Since the investigations were not all closely related, the results of each investigation are discussed separately.

BACKGROUND

To design systems that can survive lightning strokes, a knowledge of the magnitude of those lightning strokes must be known. To quote from Lord Kelvin (1824-1907), "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it;..."(Ref.1) But since lightning strikes occur at statistically governed times and places, direct measurements by ordinary means are not capable of providing enough data to suitably describe the statistical nature of lightning. This has long been recognized along with the need for inexpensive recording devices with which to measure lightning parameters such as the peak current amplitude (Ref. 2).

The first such devices used were magnetic links which were introduced in the early 1930's. These devices are small packages of magnetic steel positioned next to a conductor that carried lightning currents (Ref. 3). The magnetic field around the conductor will magnetize the steel to an extent dependent on the magnitude of the current. Comparing the magnetized link to laboratory exposed links provides a method of determining the peak current.

The data collected using these magnetic links provided a large portion of the statistical base for present estimates of the lightning peak current distributions.

Other, more sophisticated systems have and are presently being installed to gather more data on lightning (Ref. 4).

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1. Richards. J.A., Sears, F.W., Wehr, M.R. and Zemansky, M.W.: Modern University Physics, Addison-Wesley Pub. Co. Inc., 1960 p. 2

2. McEachron, K.V. and Patrick, K.G.: Playing with Lightning, Random House 1940 pp. 98-102

3. Foust, C.M. and Kuehni, H.P.: The Surge-Crest Ammeter, General Electric Review Vol. 35 No. 12 Dec. 1935 pp. 644-648

4. Schneider, H.M. Stillwell, H.R.: Measurement of Lightning Current Waveshapes on Distribution Systems, IEEE-PES Summer Power Meeting Vancouver B.C. Canada July 1979.

This report covers work done to calibrate and develop application techniques for a new, passive, peak lightning current detector (LCD). The LCD developed by NASA-KSC was reported in 1976 (Ref. 5) and patented in 1978 (Ref. 6). The LCD consists of a length of magnetic audio recording tape upon which a reference continuous wave voltage signal has been recorded. When this tape is placed in the magnetic field near a current carrying conductor, that field will change the magnetic domains on the tape.

The magnetic intensity (H) of the field around a conductor is proportional to radial distance (r) and current (i);

$$H = \frac{i}{2\pi r} \quad (1)$$

If the tape is positioned along the radial distance, then the length of tape affected will indicate the current carried by the conductor. The early work has shown that, not only does the principle work, but it provides reasonably accurate data at relatively low initial costs.

An LCD is not field (current) direction sensitive, whereas a magnetic link remains magnetized in the direction of the impressed field. Two successive strokes of opposite polarity will leave a magnetization level on the magnetic link which bears no relationship to either peak. Since there is no way a current can reconstruct the reference signal on the magnetic tape, it will always indicate the highest peak current.

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5. Livermore,S.F.:Development of Lightning Current Detector, NASA TR-1482 1976

6. Livermore, S.F.: Lightning Current Detector, U.S. Patent 4112357, Sept. 1978

APPLICATION CONSIDERATIONS

There are a variety of possible applications where the LCD could provide useful information concerning peak lightning currents in conductors. Data on lightning current magnitudes in telephone cables, radio broadcast towers, power transmission systems, oil well towers, etc., would be very useful in evaluating the lightning protection designs for these systems.

Figure 1 shows a typical mounting for an LCD on a conductor. Figure 2 is a photo of an LCD using a cassette tape installed for calibration tests at Lightning Technologies, Inc. The magnetic tapes are stored in the cassette holder with a portion pulled down inside the tube on the tape carrier. The carrier is positioned so that the flat (width) of the tape is perpendicular to the plane of the conductor. The LCD is shown secured to a conductor by means of a plastic mount and plastic wire ties. Any convenient method of mounting may be used, provided it holds the tube in the desired location and orientation and contains no iron parts that would affect the magnetic fields in the region of the tape.

When an LCD is installed where more than one conductor is present, magnetic fields from the other conductors will affect the results. The effects can be minimized by mounting the LCD so that other conductors are 25 ft. or more away and orienting the LCD so that it points out of or away from the other conductors. Measurements using LCDs with spacings less than 25 ft. between conductors will require sophisticated means of interpreting the data since analysis of the magnetic fields will be necessary in order to interpret the tape recordings.

Magnetic Tape Types

The magnetic tape utilized in an LCD depends somewhat on the use and required accuracy. As discussed later in this report, the calibration factors for different manufacturers' tapes vary by up to 25%. For many applications, other factors (such as the readout method) will limit the overall accuracy of the LCD and any convenient ferric oxide* tape can be used. When a calibration factor averaged from all tapes tested is used, the results should not be in error by more than ±10%.

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* Chrome tapes, which are more resistant to change, would exhibit smaller signal erasures for a given current level and, therefore, were not evaluated for these applications.

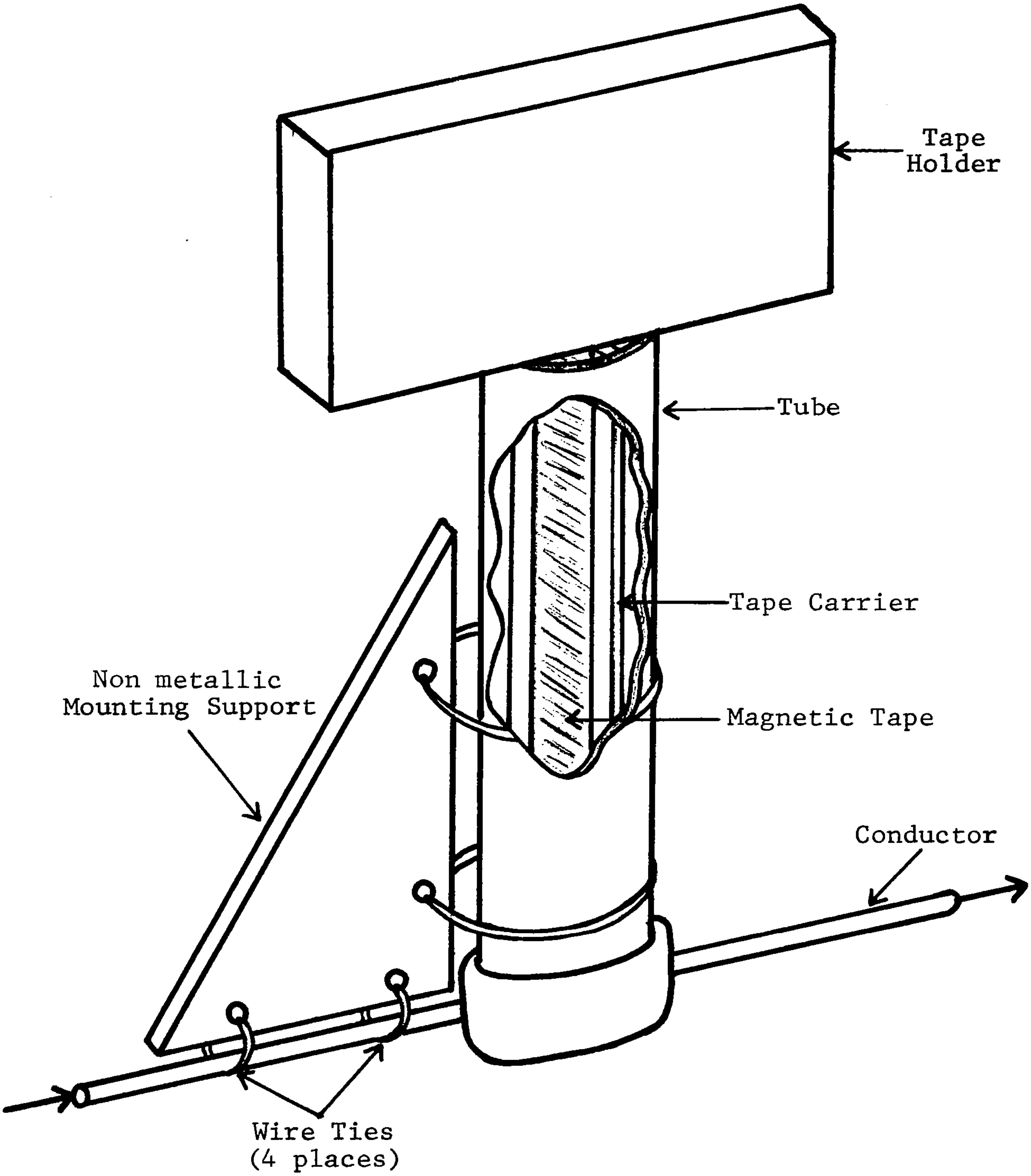

Figure 1 - Typical LCD Mounted on a Conductor

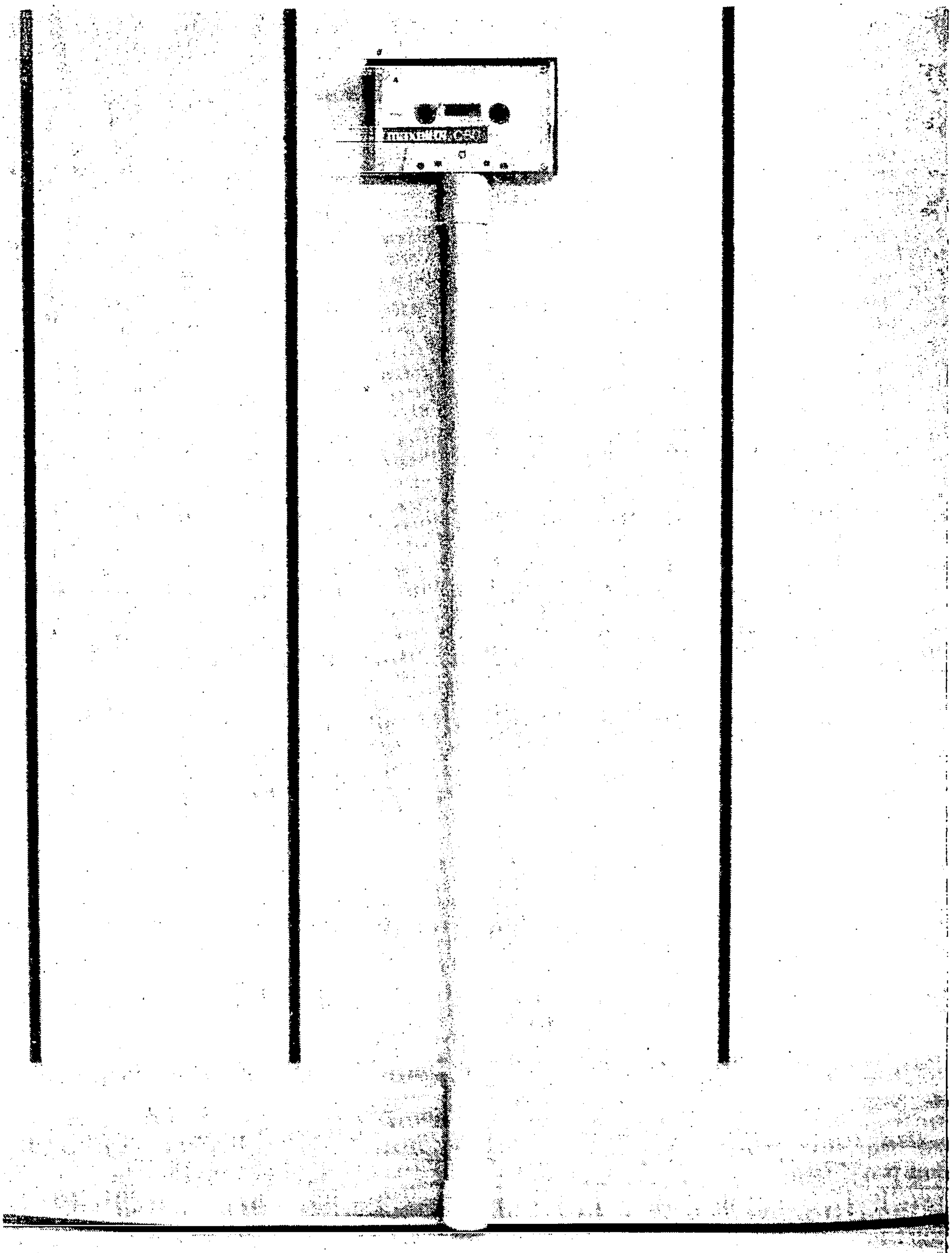

Figure 2 - LCD Installed for Test at Lightning Technologies, Inc.

A more important consideration is the selection of reel-to-reel tapes or cassette tapes. Both give the same technical result, but difference lies in the readout method. The reel magnetic tape is cut, positioned down one side of the tape carrier and back up the other side, and attached at the top. After exposure, it must be removed and spliced to pieces of reference tape of sufficient length to allow it to be played.

A cassette tape will have the cassette mounted in the top of the tape holder with a portion of the tape pulled down into the tube by the tape carrier. After exposure, the tape is wound back into the cassette, and if desired, notes concerning the exposure could be recorded on the tape (date, time, etc.). The cassette can then be advanced and other exposures made so that the entire history of the site can be kept on one cassette. Also, since splices are not needed, the cassette can be played on a battery operated player in the field and the peak current estimates made without going to a laboratory.

Since the reel tapes must be respliced on leader tapes for playback, an external means is commonly used (flashbulb indicator, discussed later, or an observer) to insure that a strike has occurred before going through the effort of reading the tape. Checking a cassette tape by playing it in the field eliminates the need for the external indicator.

If a cassette tape is selected, a quality cassette, such as those manufactured by Maxell (Ref. 7) is suggested, since the cassette shell is an integral part of the tape transport system. The tape to head contact pressure is controlled by the pressure pad which is also part of the cassette shell. Also, a shell fastened together with screws rather than glued is preferred since, in case of damage, the tape can be salvaged or repairs made. Tape length should be 60 minutes total or less to avoid working with the very thin tapes used for long playing cassettes (Ref. 8).

Reference Signal Recording

The LCD technique depends on being able to detect the length of tape upon which a reference signal has been erased. A typical erasure is shown in Figure 3. This sketch illustrates the output of a tape player as it would appear when displayed by an oscilloscope or high frequency strip chart recorder (Visicorder).

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7. Maxell Corp. of America, 60 Oxford Drive, Moonachi, NJ 07074

8. Clyatt, S.P.: Unpublished Data NASA-KSC 1979

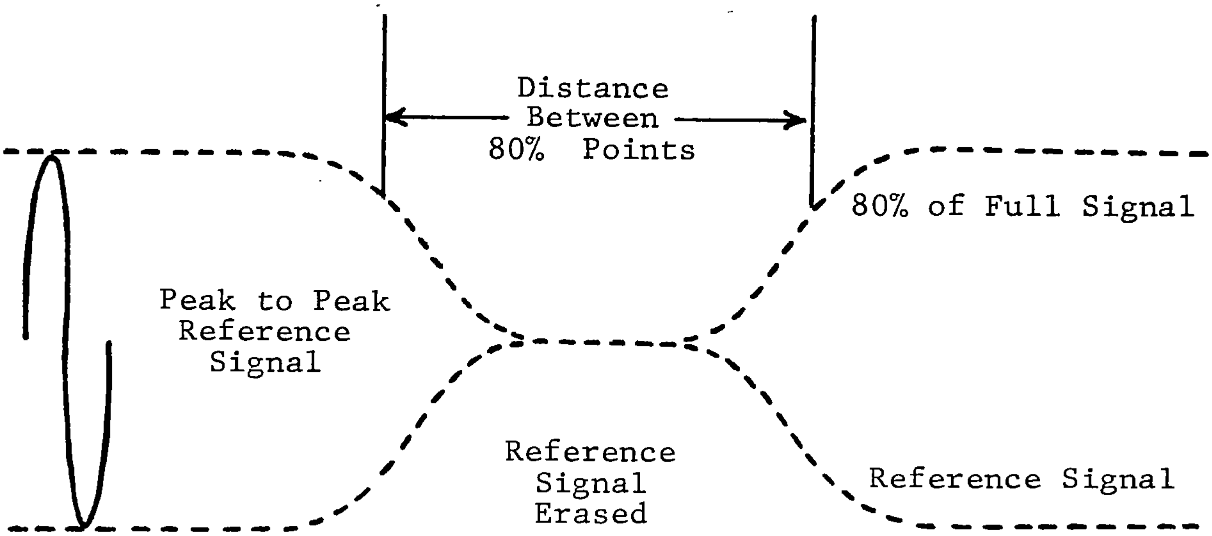


Figure 3 - Typical LCD Erasure Pattern

From Figure 3, it can be seen that the erased portion goes gradually from full reference signal to no signal. The reference signal level must, therefore, be very uniform or consistent to detect where an erasure begins. If for example, the reference were to randomly vary by 20%, then the detection of where an erasure began would be almost impossible. For consistent LCD readings, the reference signal level, when played back, should not vary by more than ±5%.

Theoretically, any reference signal level and frequency can be used. However, as a practical matter, if the level is too low, noise will be a problem, and if it is too high, the recorder/player will saturate and/or limit the output. Therefore, the level should be set at a mid range value, usually specified in the recorder manufacturer's instructions. Most tape recorder/players have the best frequency response in the 100 Hz to 4000 Hz range and so the reference signal frequency selected should fall in this range. For the cassette tests conducted in this report, 400 Hz, which is close to the musical note Middle C (440 Hz), was selected.

Tape Readback Method

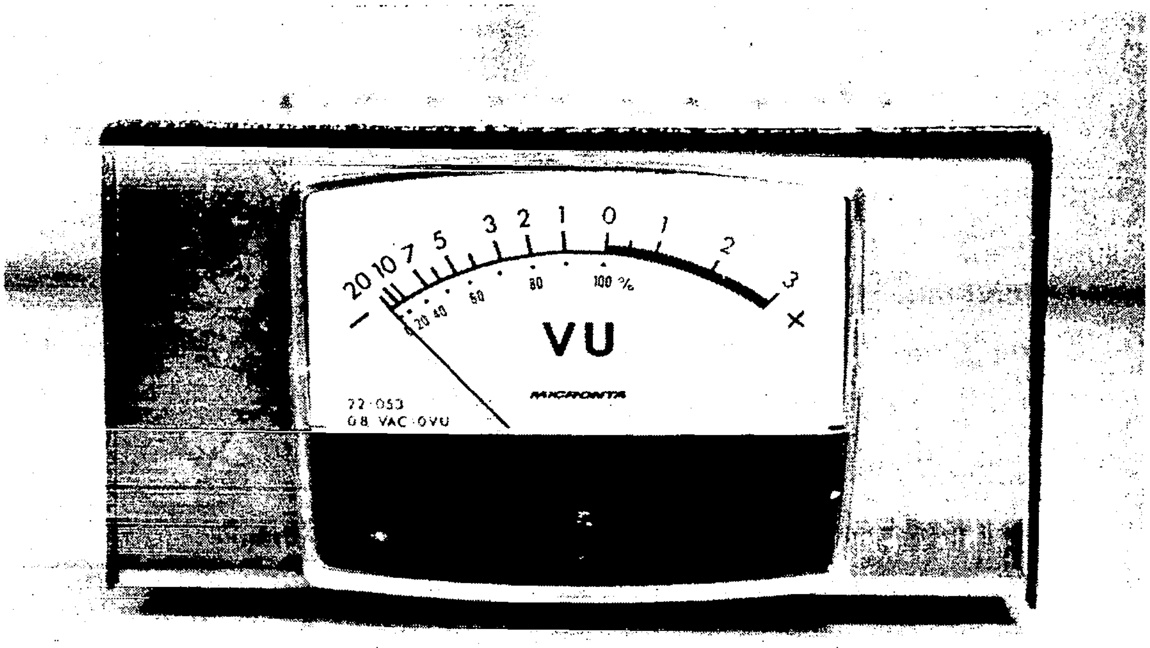
Once a magnetic tape has been exposed to a lightning current magnetic field, a portion of the tape will have been erased. Actually, exposure to the magnetic field magnetizes all the domains on the tape into saturation in the same direction - a DC condition - and the tape player needs a varying magnetic domain pattern - an AC condition - for it to respond. At greater distances and/or lower magnetic intensities, the number of disturbed domains decreases and the original reference signal becomes dominate again.

Measuring the length of tape on which the reference signal is erased requires playing the tape on a player. The speed at which the player operates is quite important and should be known to an accuracy at least greater than the desired measurement error. A length of prerecorded tape can be marked at intervals of 1.5 m and the time between marks measured while the player is operated. A simple marking system consists of placing a small length (0.3 cm) of splicing tape over the oxide on the magnetic tape. Care must be taken to insure that the splicing tape adhesive does not cause the magnetic tapes to stick in the cassette. Timed tapes are also commercially available. Battery operated players especially must be checked for speed quite often as they tend to slow down as the batteries wear out.

A relatively simple method for determining the length of erased tape is to measure the time that the reference signal is absent with a stopwatch. Since the human ear responds to logarithmic changes in sound, a VU meter in parallel with a speaker makes the change visually detectable as well as audible. Such a system is shown pictorially and schemetically in Figure 4.

The volume on the player is adjusted so that the VU meter reads 100% (0 dB) during the reference signal. When the exposed portion of the tape passes, the meter will dip and the time between the 80% points can be measured with a stopwatch. Calibration tests using this method indicate that an accuracy of ±10% is possible when measurements are made using this method.

Low peak currents (less than 7 kA) are hard to measure with this technique because the erasure times (0.1 to 0.5 seconds) approach a person's reaction time, making large errors (100%) quite possible.



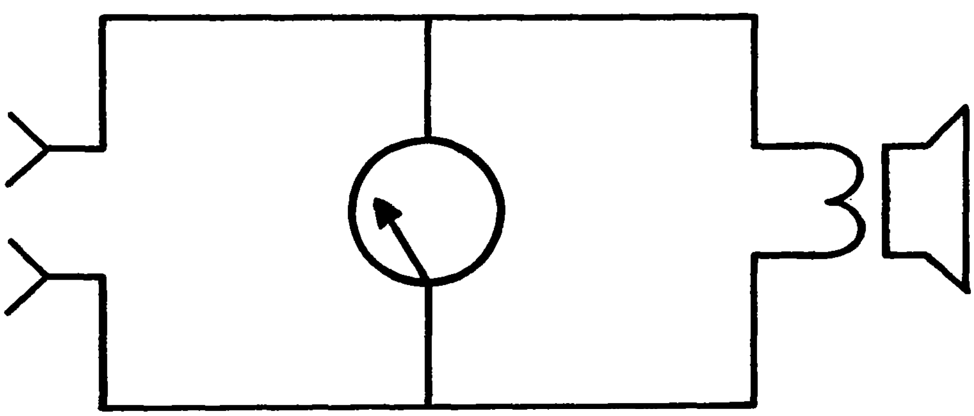


Figure 4 - Magnetic Tape Playback Monitor

More accurate measurements of the erasure time can be made if the output of the tape player is displayed and recorded on an oscilloscope or a strip chart recorder. However, the writing speed of the strip recorder or oscilloscope must be known as accurately as the player speed. The time, or length of tape erased, can then be determined by measurements on the strip chart or oscillogram. Assuming that the player and recorder speeds are known to sufficient accuracy, measurements made with such systems are accurate to within ±5%.

Magnetic Tape Holder Effects

In the discussions thus far, the total length of magnetic tape erased has been measured. This represents the distance from where the erasure starts to the bottom of the LCD and back to where the erasure ends on the back side of the tape carrier. So the tape on the backside of the tape carrier is really in parallel with that on the front side and both are erased simultaneously during exposure. The tape erasure distance is 1/2 of the distance from where the erasure starts to where it stops. Positioning the tape in this manner eliminates the need for determining where the tape reaches the bottom of the LCD. If the tape were only placed on one side of the tape holder, it would have to be spliced at the bottom end and data could be lost during the process.

From equation 1 ($H = i/2\pi r$), it can be seen that for a given current, H is inversely proportional to radial distance, r; but r is measured from the center of the conductor. So the thickness of the holder bottom plate and 1/2 of the diameter of the conductor must be added to 1/2 the length of tape erased in order to compare tapes exposed in different holders and/or on different diameter conductors.

The length of erased tape measured also includes the thickness of the tape carrier. If the tape carrier was infinitely thin, the magnetic tape would fold directly back on itself and no extra tape would be involved, but since it is not, extra tape is required. Even though these dimensions will be small in a well designed holder, they can cause errors at low current levels because the length of the erased tape is short. The effects of the tape holder can be designed out if the tape carrier thickness is made twice the end cap thickness.

Other, less obvious errors can be introduced at low levels if the magnetic tape is not centered over the conductor. These errors will generally be small but questions can be eliminated if guides are provided on the tape carrier and the LCD to insure that the tape is centered over the conductor.

Magnetic Tape Calibration Factors

For many users, peak current accuracies of 5% to 10% will be sufficient and they should use ferric oxide cassette tapes and stopwatch readouts due to the simple procedures involved. It would still be advisable to measure the tape player speed since many inexpensive players, and especially battery operated players will vary more than ± 10% from the standard 4.76 centimeters per second (1 7/8 in/s). Also, currents of less than 5 kA cannot be measured accurately by this method and the conductor should not exceed 1.3 cm (1/2 in) diameter.

When the stopwatch times are measured between 80% of refence signal points and the above conditions are met, the magnetic tape calibration factor is:

4.3 kA/s

If the player is operated at speeds other than standard, the factor must be adjusted accordingly.

For those investigators desiring a more precise measurement, the erasure should be measured by recording the output of the player on an oscilloscope or a strip chart recorder. Again, player and recorder speeds must be known to accuracies better than the desired results. Also, attention must be given to holder and conductor dimensions. The tape formulation also begins to play a part in the readout.

Since the holder and conductor dimensions as well as player and recorder speeds will have to be considered in the measurements, the calibration factors are listed as a function of erased tape length for various measurement points (50%, 80% and 90%) and manufacturers. The calibration factors are:

	50%	80%	90%
Reel Tapes - Group 1*	2.51 kA/cm	1.95 kA/cm	1.75 kA/cm
Reel Tapes - Group 2*			1.40 kA/cm
Cassette - Group 1*	2.53 kA/cm	1.88 kA/cm	
Cassette - Group 2*	2.33 kA/cm	1.78 kA/cm	

The total length of tape erased is determined by multiplying the measurement (strip chart or oscillogram) by the appropriate player and recorder speeds. This length must then be divided by two to account for the tape being folded. Then the

* Group 1 tapes manufactured by Ampex & Maxell; Group 2 tapes manufactured by Scotch and BASF.

distance from the bottom of the tape to the center of the conductor (holder bottom cap thickness + 1/2 conductor diameter) minus 1/2 of the tape carrier thickness, must be added to the length. When multiplied by the appropriate above calibration factor, the peak current measured is then determined.

EXPERIMENTAL INVESTIGATION

The primary emphasis of the effort was to verify calibration factors for LCDs and to develop utilization data to aid ultimate users. To facilitate widespread usage, the costs and complexity of the LCD system must be kept to a minimum. This objective was factored into each decision concerning methods and equipment utilized in the effort so that the resultant LCD system remains a simple, cost effective method of measuring peak lightning currents.

The following sections of the report cover the experimental phases of the effort and are arranged according to the experimental and chronological order.

Calibration of Reel-to-Reel Tapes

The length of ferric oxide, audio recording tape erased by the magnetic field around a conductor could be related to several factors. These factors include peak current, wave shape (unipolar versus oscillatory), level of the prerecorded reference signal, and the ferric oxide tape formulation (controlled by the tape manufacturer).

Tests were conducted to determine the effect of each of these factors on the length of tape erased for a given peak current applied.

Tapes Tested

Ferric oxide, audio recording tapes, 0.64 cm (1/4 in) wide, intended for reel-to-reel recording system were exposed to simulated lightning current magnetic fields. The tapes were:

Ampex Grand Master	Ampex Corporation, Redwood City, CA 94063
Scotch	Minnesota Mining & Manufacturing, St. Paul, MN 55119 Federal Stock No. 5835-00-124-9995
BASF	A tape of German manufacture contributed by Professor M. Darvenezia of University of Florida, Gainesville, FL 32601

The results of these evaluations in no way reflect on the quality or ability of the tapes to perform their intended functions. In fact, the suitability of any piece of equipment discussed in this report to perform the special functions evaluated here in no way reflects on that equipment's ability to carry out its intended function.

Reference Signal Recording Procedures

Before tests were conducted on the magnetic tapes, each had a continuous sine wave, reference signal recorded on the tape. The tapes were prerecorded by NASA-KSC personnel and Prof. M. Darvenezia. The recording procedures used by NASA-KSC are given in Appendix A.

To evaluate the effects of reference signal level, one type of tape, the Ampex Grand Master, had signal levels (voltages) corresponding to 300%, 150%, 100%, 89%, 50% and 30% of an alignment tape level recorded on the tape. Sufficient lengths of tape containing each level were recorded to allow several exposures. The procedures for recording these levels is also covered in Appendix A.

Tape Exposure and Readback Procedures

The prerecorded tapes were cut in 120 cm lengths, attached to tape carriers and inserted into holding tubes for exposure as shown in Figure 5. These tubes were then positioned over a conductor through which were passed simulated lightning currents. Figure 6 shows a tape holding tube mounted above a 6" diameter pipe during tests conducted at General Electric Company High Voltage Laboratory (GE HVL), Pittsfield, Mass. The wires in the foreground are part of the calibration fixture returns.

After exposure to the simulated lightning current, each tape was identified and all tapes were spliced back together.

The length of tape with the reference signal erased was measured by playing the tapes on a player and observing the output on a strip chart recorder. The recorder output was rectified and filtered by a low pass filter before being applied to the strip chart recorder. The equipment used, which was supplied by NASA-KSC, was Ampex 1160 tape recorder/player and a Sanborn 322 Amplifier/Recorder.

The rectifier-filter consisted of a diode feeding a 0.1 μF capacitor in parallel with a 470 kΩ resistor. The output of this filter was designed to follow the envelope of the 700 Hz reference signal as it was erased by the lightning current magnetic fields.

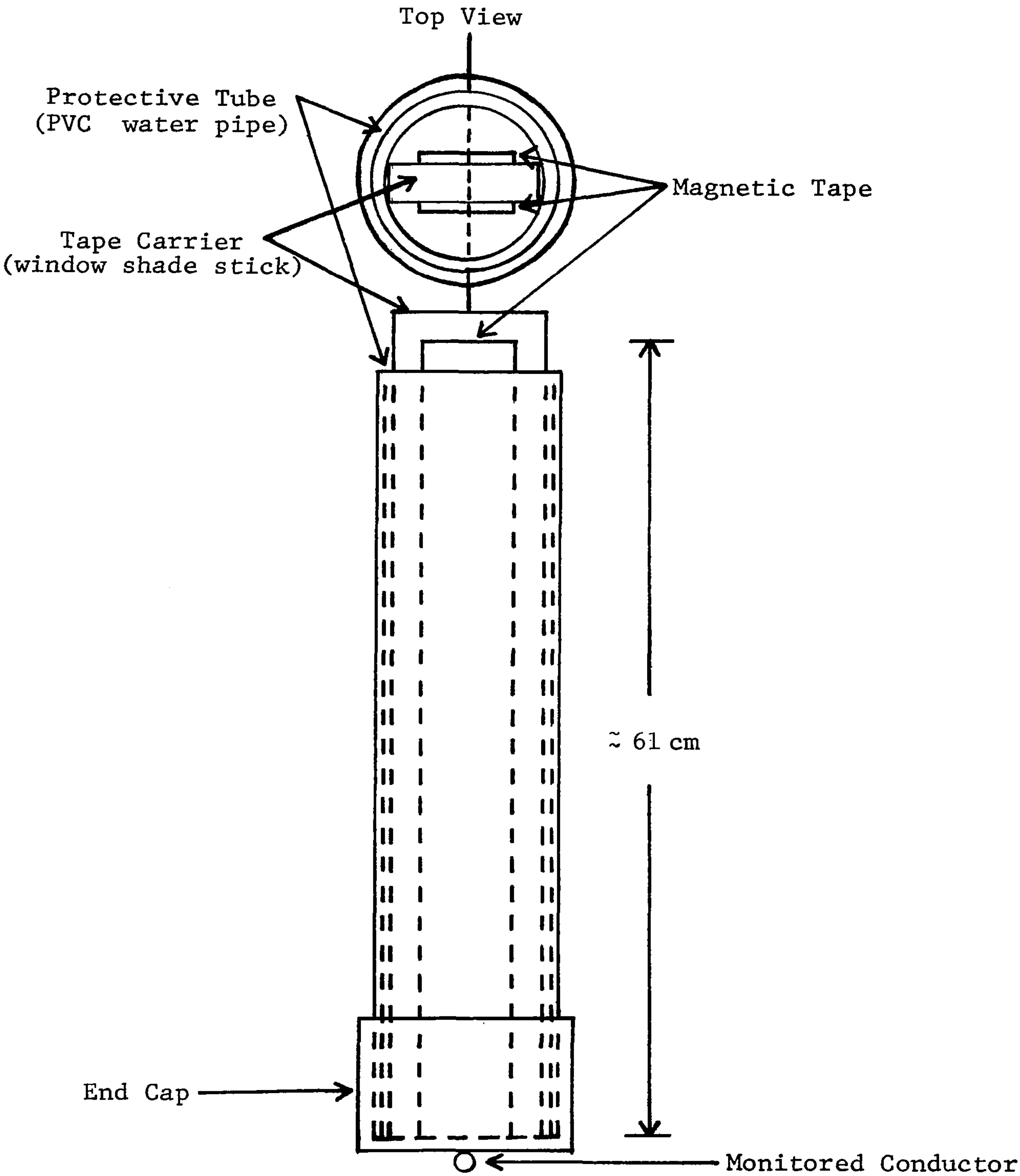


Figure 5 - Magnetic Tape Holder Tubes

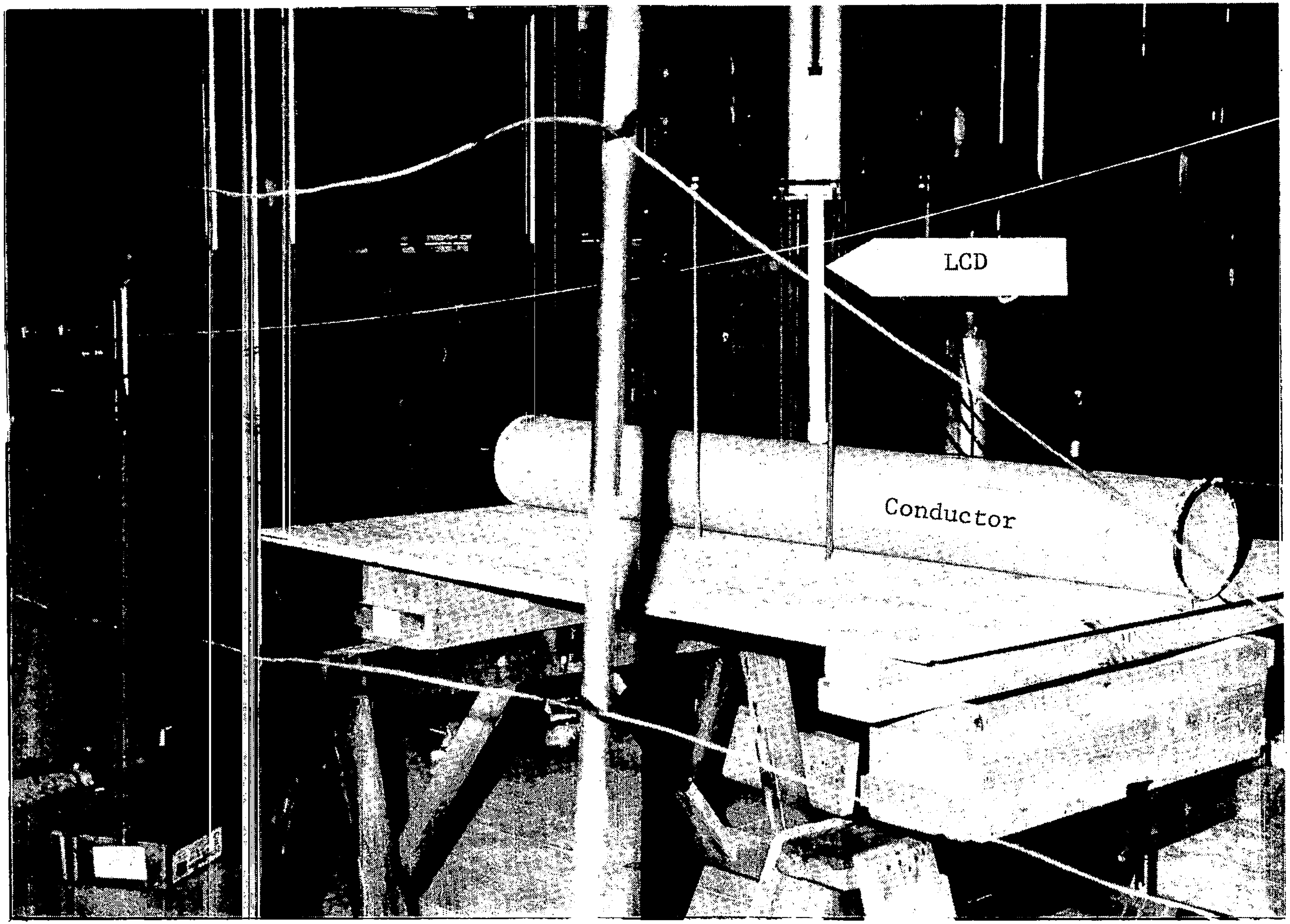
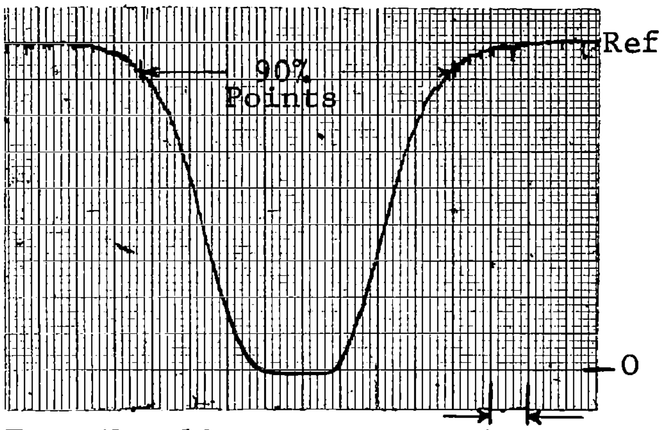


Figure 6 - Typical Exposure Test 6" Dia. Pipe and LCD

The Ampex tape recorder was operated at 19.6 cm/s (7 1/2 in/s) and the Sanborn recorder was run at 20 mm/s. A typical Sanborn recorder display is shown in Figure 7. The erasure length was arbitrarily defined as the distance between the 90% of full signal points. Any percentage of signal can be selected, and in the cassette work, discussed later, 80% and 50% points were used. Low values, such as 10%, are not practical since for low currents, the 10% point may not be reached and hence will be undefined.

Tape Erased



Test No. 10 4.8 cm

Scotch Tape
300% Recording Level
19.8 cm Erasure
26 kA Oscillatory Current

Figure 7 - Typical Sanborn Strip Chart Recording of an Exposed Magnetic Tape

The length of tape erased can be determined by knowing the tape player speed and the strip chart recorder speed. For the present tests, the distance in mm between the 90% points was divided by 20 (mm/s) and multiplied by 7 1/2 (in/s) and 2.54 (cm/in) to obtain the length of magnetic tape involved. This length must be divided by two to get the radial erasure distance. One-half of conductor diameter and the holder dimensions must also be factored into the measurement.

Calibration Test Fixture Considerations

To accurately measure the erasure effects of simulated lightning current magnetic fields on the magnetic tape, a calibration fixture must be constructed that will produce a uniform magnetic field around the conductor. The magnetic intensity around an infinitely long conductor at a distance r is given by:

$$H = \frac{i}{2\pi r} \tag{2}$$

where,

H = magnetic intensity (amps per meter)

i = current in the conductor (amps)

r = radial distance from the center of the conductor to the point of interest (in meters)

However, in a test circuit, the simulated lightning current will be carried by a conductor which is not infinite in length. The error due to the length of this conductor can be calculated using Figure 8. For values of x equal $+\infty$ and $-\infty$ respectively, values of theta (θ) will be 0 and π. The equation:

$$H = -\frac{i}{2\pi r}\int_{\theta_1}^{\theta_2} \sin\theta \, d\theta \tag{3}$$

when evaluated at these values yields equation (2).

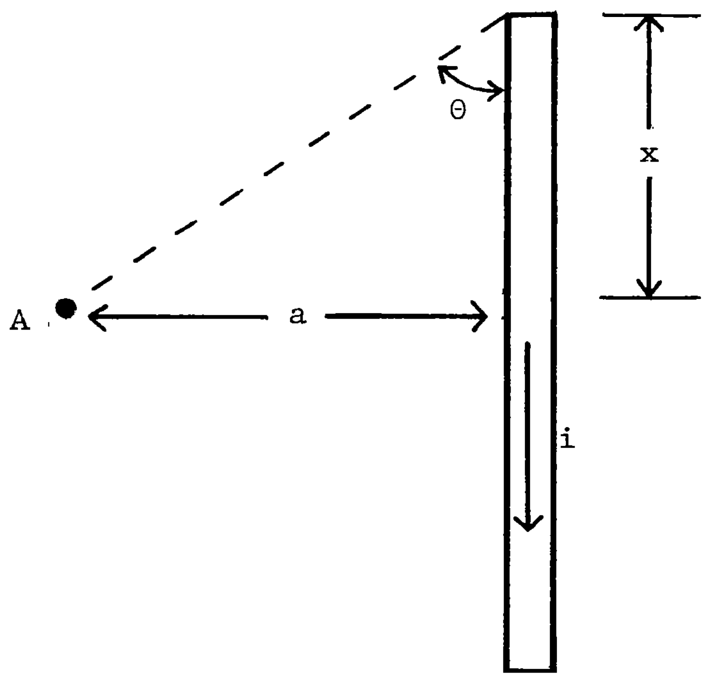


Figure 8 - Magnetic Intensity Errors Due to the Finite Length of a Conductor

Evaluating equation (3) at the integration limits gives:

$$H = -\frac{i}{4\pi r}\left[-\cos(\theta_2) + \cos(\theta_1)\right] \qquad (4)$$

It can be seen that substitutions 0 and π for θ_2 and θ_1 makes the term in the brackets become -2. As values of x in Figure 8 become shorter than infinity, the value of the term in the brackets will begin to decrease. If the value of x is shortened until the term in the brackets becomes 1.9 or 1.8, the error in the computed value of H at the point "A" will be 5% and 10% respectively. These numbers correspond to angles of 18 and 26 degrees respectively. Preliminary calibration data on LCD's indicated that approximately 5 mm of tape is erased for each kA of lightning current. Therefore, at 10 kA, approximately 5 cm of tape will be erased and at 100 kA, approximately 50 cm will be erased. To maintain an error in H of 5% or less, the value of x must then be 1.52 meters or greater. This means that the length of conductor near the magnetic tape will have to be 3.4 meters or more.

If a simple, square current loop is used for calibration, the return conductors will be perpendicular to the measuring conductor, as shown in Figure 9 and will not influence the magnetic fields present at the tape because they will produce equal and opposite magnetic fields. The conductors going to

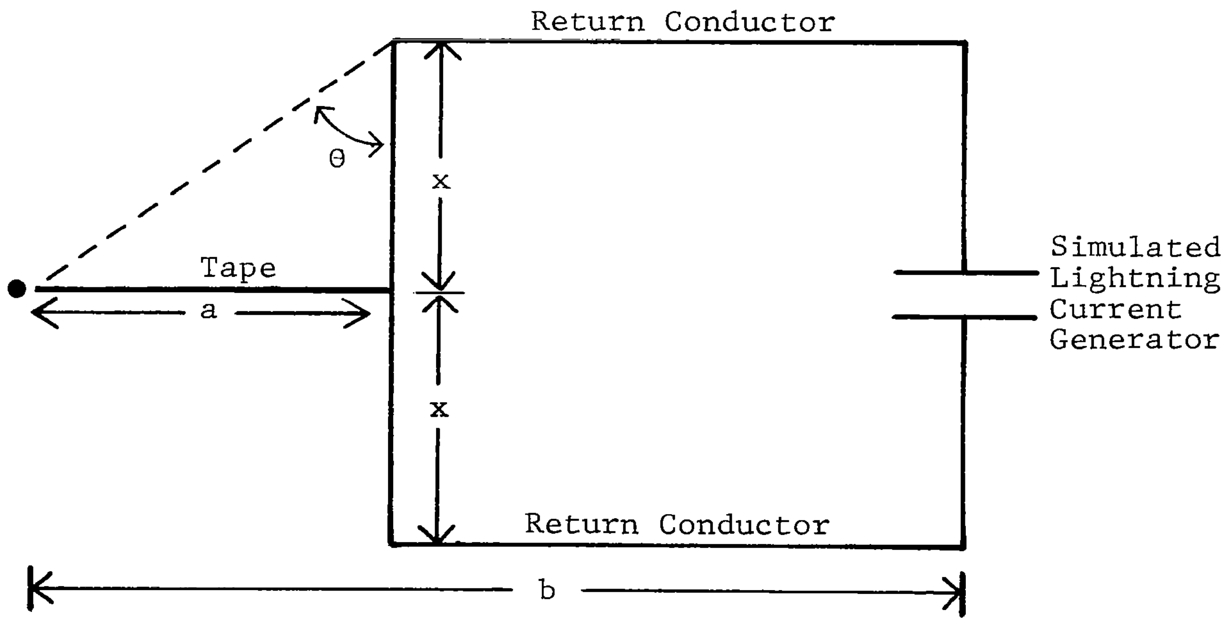


Figure 9 - Magnetic Intensity Errors Due to Return Conductor Proximity

the capacitor bank, which are parallel to the conductor under measurement will affect the magnetic field at the tape. If this influence is to be less than 5%, then the distance back, b, must be approximately 20 times the length of the erasure, a. For a simulated lightning current of 100 kA, the distance from the capacitor bank to the tape must be about 10 meters. The self-inductance of a loop of wire 3 m x 10 m will be between 15 and 20 microhenries. This much inductance will severely limit the amount of simulated lightning current that can be used to produce oscillatory or critically damped waves for calibration purposes in most test laboratories.

Consequently, the test arrangement shown in Figure 10 was chosen as a practical arrangement that offers a relatively uniform magnetic field. The test conductor length is 5 meters which is longer than the required 3 meters derived from Figure 8. The symmetrical return configuration cancels the effects of the return conductors at the center where the test tapes are positioned.

Simulated Lightning Currents

The simulated lightning currents used for calibrating the various magnetic tapes were generated by the RLC circuits shown in Figure 11. Two sets of tests, one on the reel tapes and one on the cassette tapes were performed. The reel tape tests were conducted at the GE HVL and the cassette tape tests were conducted at Lightning Technologies, Inc. high current laboratory. Generator parameters are given on Figure 11. Typical applied current oscillograms are shown in Figures 12 and 13. The GE HVL high current test generator was charged to a peak voltage of 130 kV and the Lightning Technologies, Inc. facility was charged to a 50 kV peak. Consequently, higher test currents were obtained at G.E.

All simulated lightning currents were measured directly using a pulse current transformer. The pulse current transformer is rated for a 250 kA, has an IT product of approximately 64 A·s and a frequency response of 1 Hz to 400 MHz. It uses a special ferrite core and has a secondary winding of 100 turns. The secondary current is measured by inserting a very low inductance coaxial resistor of 0.01 ± 0.1% ohms in series with the secondary winding. The voltage across the low inductance resistor is carried in a double shielded coaxial cable and displayed on a high speed Tektronix oscilloscope. The peak currents reported here were taken from photographs of the oscilloscope traces. The scope time base and vertical preamplifiers were calibrated prior to tests using the oscilloscopes internal reference voltage and a crystal controlled pulse generator.

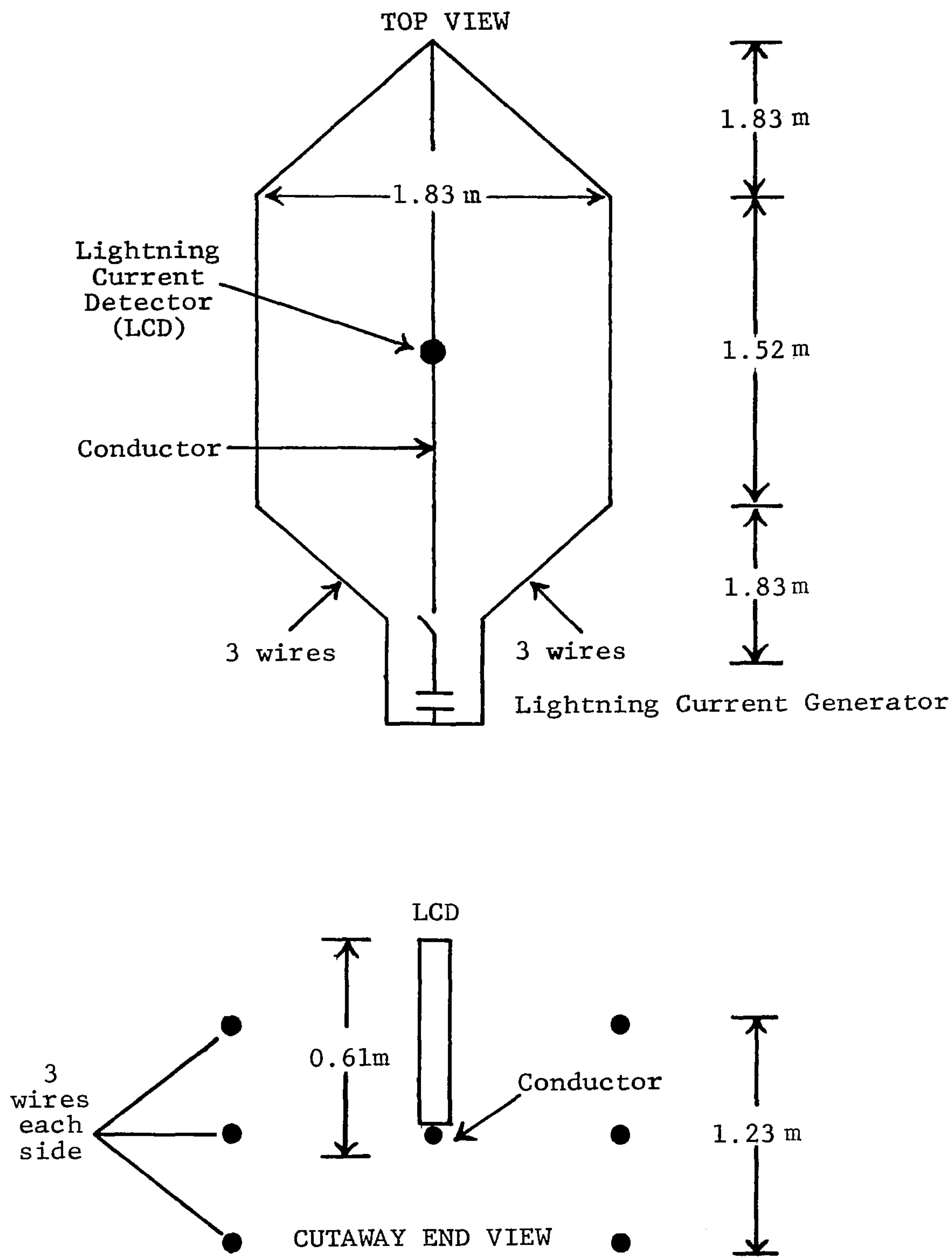
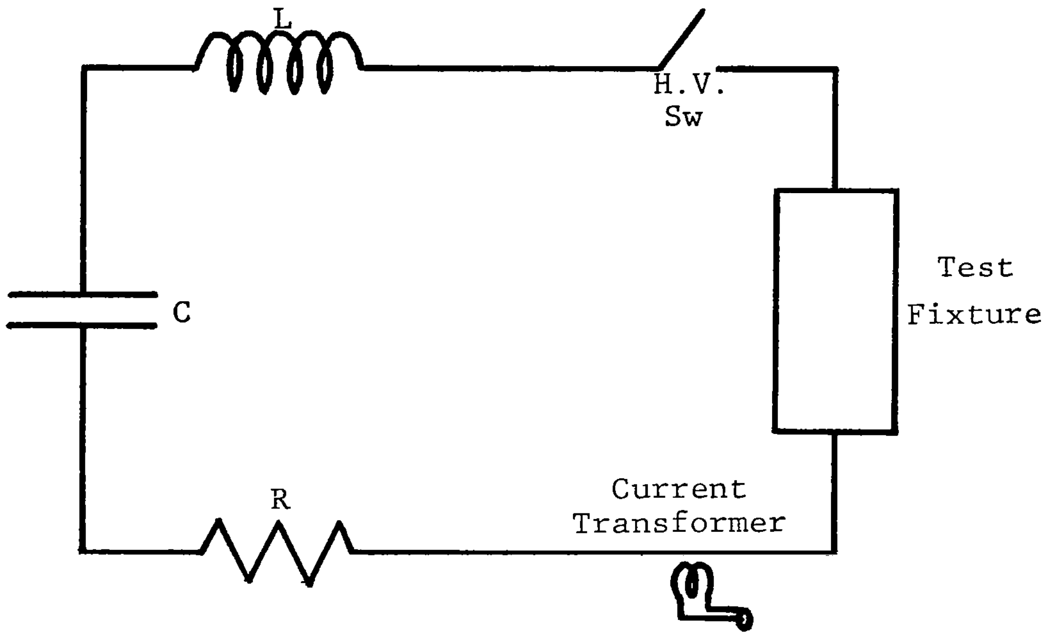


Figure 10 - Calibration Test Fixture



General Electric High Voltage Laboratory

For Oscillatory Waves:

C = 6 μF at 150 kV

L = 8 μH

R = 73 mΩ

For Unipolar Waves:

C = 6 μF at 150 kV

L = 8 μH

R = 2.31Ω

Lightning Technologies, Inc. High Current Laboratory

For Oscillatory Waves:

C = 20 μF at 50 kV

L = 11 μH

R = 113 mΩ

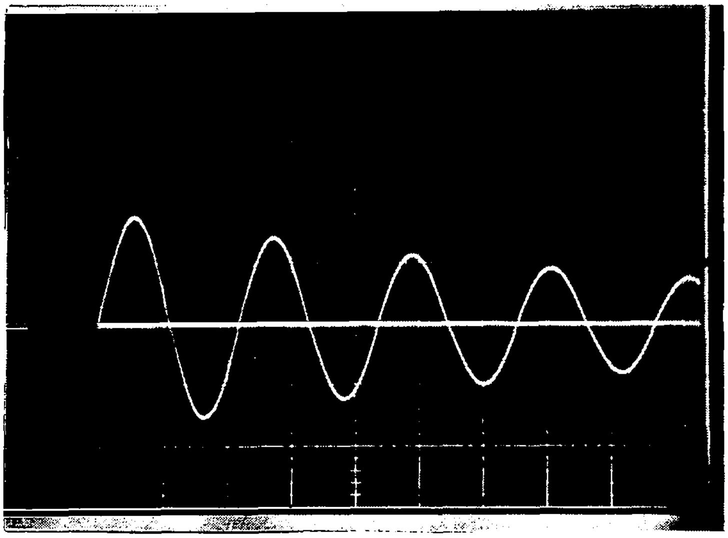
For Unipolar Waves:

C = 20 μF at 50 kV

L = 11 μH

R = 1.48Ω

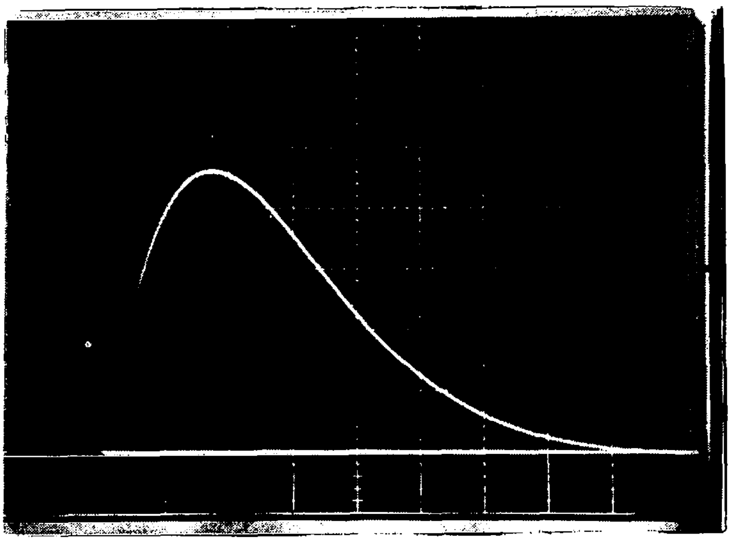
Figure 11 - Simulated Lightning Current Generator Schematic



Test #7

Oscillatory Current
Horizontal 20 μs/div.
Vertical 50 kA/div.

88 kA Peak

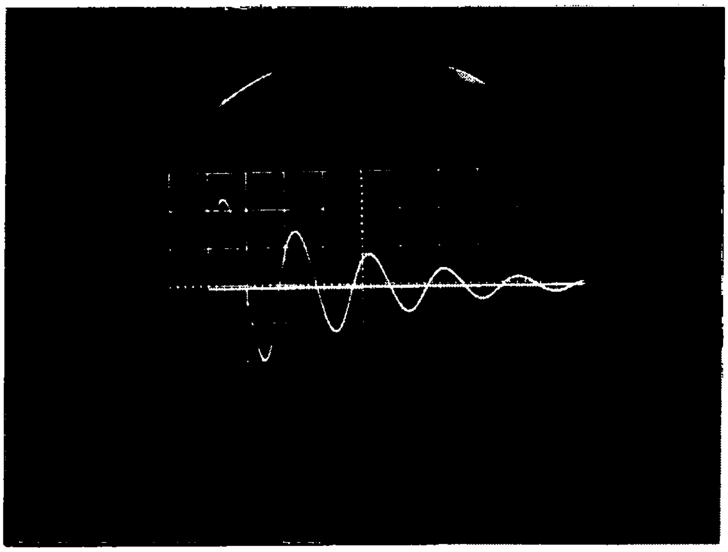


Test #17

Unipolar Current
Horizontal 5 μs/div.
Vertical 5 kA/div.

48 kA Peak

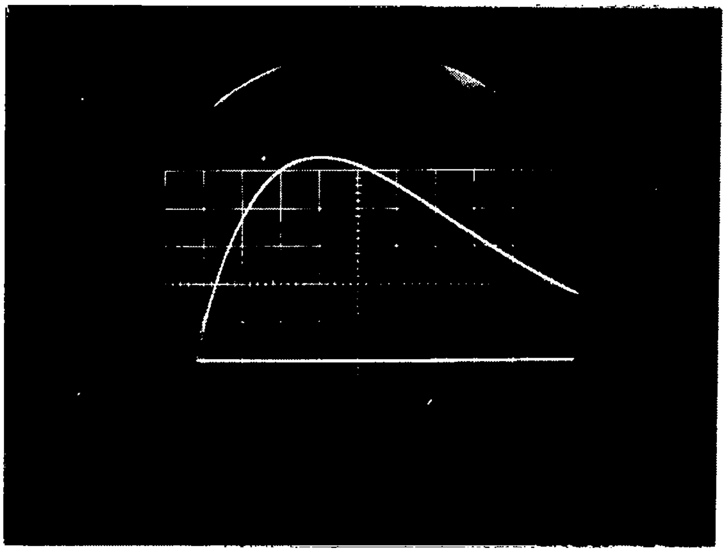
Figure 12 - Typical Applied Simulated Lightning Current Waves
General Electric High Voltage Laboratory



Test #84

Oscillatory Current
Horizontal 50 μs/div.
Vertical 20 kA/div.

48 kA Peak



Test #102

Unipolar Current
Horizontal 5 s/div.
Vertical 10.0 kA/div.

5.4 kA Peak

Figure 13 - Typical Applied Simulated Lightning Current Waves at Lightning Technologies, Inc.

Test Configurations and Current Levels

To establish the relationship between length of tape affected and peak current applied, tests were applied to various types (as discussed previously) at different peak currents and waveshapes.

The reel tapes were tested using oscillatory (22.9 kHz) and unipolar (5 x 18 μs) test currents with peak magnitudes of approximately 1, 5, 10, 15, 25, 50, and 75 kA. Calibration tests were conducted using the LCD described previously.

Test Results - Reel Tape Calibrations

The first seven tests verified that the dimensions of the test fixture were sufficient to provide an acceptably uniform magnetic field. With test current levels which were higher than those used for calibration (>80 kA), the return conductors were positioned approximately one foot closer to the center line. The tests resulted in tape erasure changes of less than 5% indicating that larger fixture dimensions were not necessary.

Tests 8 through 16 were conducted with oscillatory (22.9 kHz) simulated lightning currents passed through a 0.635 cm diameter conductor. In most tests, more than one tape was exposed.

The test data for tape signal erasures between 50%, 80% and 90% of full reference signal levels are given for Ampex tapes while only the 90% points are given for the Scotch and BASF tapes. The data presented has not been adjusted to account for holder dimensions or conductor diameter. To obtain the total radial distance to the conductor center, each must be increased by 0.5 cm which is the dimensional constant for this test setup.

During Tests 8, 9 and 17, tapes with the different reference signal levels recorded were exposed. The results, given in Table 1, show that the length of tape erased is not a function of the recording level used.

The erasure lengths measured are not always consistent because all tapes were read at the same strip chart recorder gain setting, making the lower percentage level tapes somewhat harder to read accurately. Most of the tests were conducted using the tapes which had been recorded at the 300% reference signal level.

TABLE 1

Summary of Reference Signal Recording Level Tests

Ampex Grand Master Tape - Measurements between 90% of reference signal. Erasure given in centimeters(cm) for various percentage recording levels.

Test No.	30%	50%	80%	100%	150%	300%
8	40.1	35.1	43.1	44.1	43.1	45.2
9	31.5	32.2	30.2	29.5	31.8	29.2
17	NR*	16.8-23.9	24.8	26.0	24.0	24.8

* NR - Not Readable

A summary of the reel tape calibration test data is given in Table 2.

Plots of peak simulated lightning current versus length of tape erased are shown in Figures 14 through 22. The data shown on each graph is taken from Table 1 but the lines were drawn by performing a linear regression analysis of the data points. A Texas Instruments Programmable 59 electronic calculator was used to perform a least squares analysis. The T.I. program not only calculates the slope and y-axis intercept co-efficients, but will calculate an x (or y) value estimate for any given y (or x). This feature was used to calculate the x-axis intercept (y = o) and the x value at I = 50 kA. These values were used to draw the lines on each plot. The equation of the line for each graph is also given on the figure.

The graphs of Figures 14 through 22 show that the relationship between the length of tape erased and the peak current is linear and that with one exception, all of the data points for disturbance exceeding 3 cm fall within 10% of the line. Uncertainties due to finite measurement resolution at distances of less than 3 cm are responsible for most of the data point scatter in this area. As an example, 0.5 cm was the minimum measurement increment, so ±8% error. At a 1 cm value, the error is ±25%.

The data point at 10.5 kA on Figures 14 through 17 is not even near the line. These data points were all from Test No. 12 and since none of the rest of the data deviates this far from the line, the test itself is suspect. Quite possibly, the tape carrier turned inside the holder during this test. Earlier tests have shown that if the tape width is not parallel to the magnetic lines of force, the amount of tape erased is greatly reduced (Ref. 9). The data from test No. 12 was not used in the linear regression analysis.

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9. Livermore, S: Op. Cit.

TABLE 2

Length of Reel Tape Erased Versus Applied Peak Test Currents

Test No.	Peak Current kA	Ampex 50% cm	Ampex 80% cm	Ampex 90% cm	Scotch 90% cm	BASF 90% cm
	Oscillatory Test Currents (22.9 kHz)					
8	74	31.0	40.0	45.2		41.9
9	50	21.4	27.4	29.2		29.2
10	26	11.4	14.5	15.5	19.8	
11	15	5.7	7.7	8.9	11.4	
12	10.5	1.5	2.1	2.3	3.3	
13	5.2	1.2	1.5	1.9	2.9	
14	1.3	0	0	0	0	
15	3.3	0.9	1.2	1.4	2.1	
16	2.2	0	0.4	0.7	1.3	
	Unipolar Test Currents (5 x 18 μs)					
17 A	48	16.4	22.6	24.8		31.4
17 B	25.5				17.0	15.2
18	16				10.7	9.8
19	9.5				6.1	5.2
20	5.2				3.0	3.1
21	3.2				1.0	0
22	2.2				0.8	0.3
23	1.4				0	0
25	42.5	15.7	21.4	23.4		
26	26.5	8.5	11.4	12.2	14.7	
27	16	5.2	7.1	7.9	9.9	
28	9.5	3.3	4.5	4.8	5.8	
29	5.2	1.5	2.4	2.5	3.3	
30	3.1	0	1.0	1.0	1.5	
31	2.2	0	0	0	0	
32	1.4	0	0	0	0	
33	44	15.2	20.0	21.8	28.7	
34	26	9.3	12.9	13.7	16.8	
35	26	9.5	13.5	14.2	17.0	

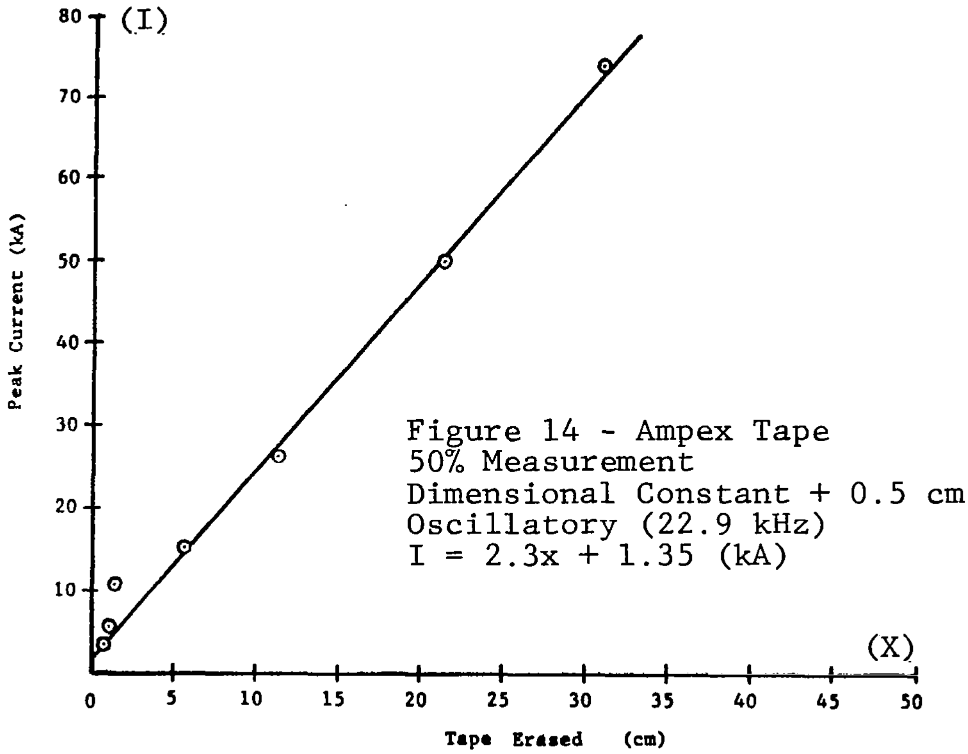


Figure 14 - Ampex Tape
50% Measurement
Dimensional Constant + 0.5 cm
Oscillatory (22.9 kHz)
I = 2.3x + 1.35 (kA)

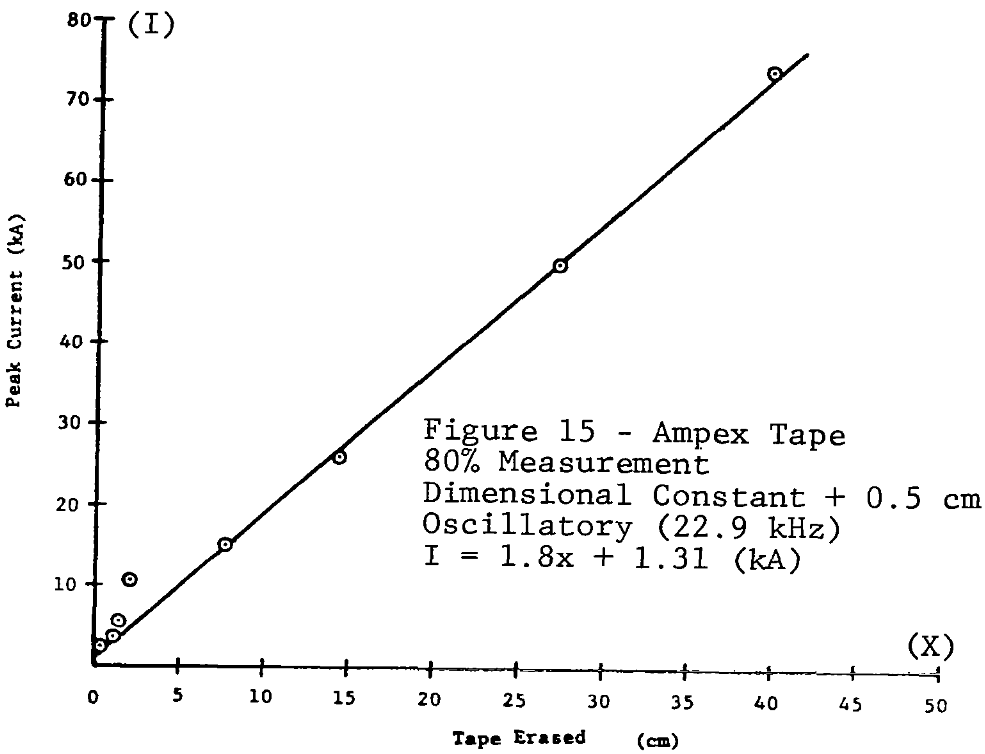
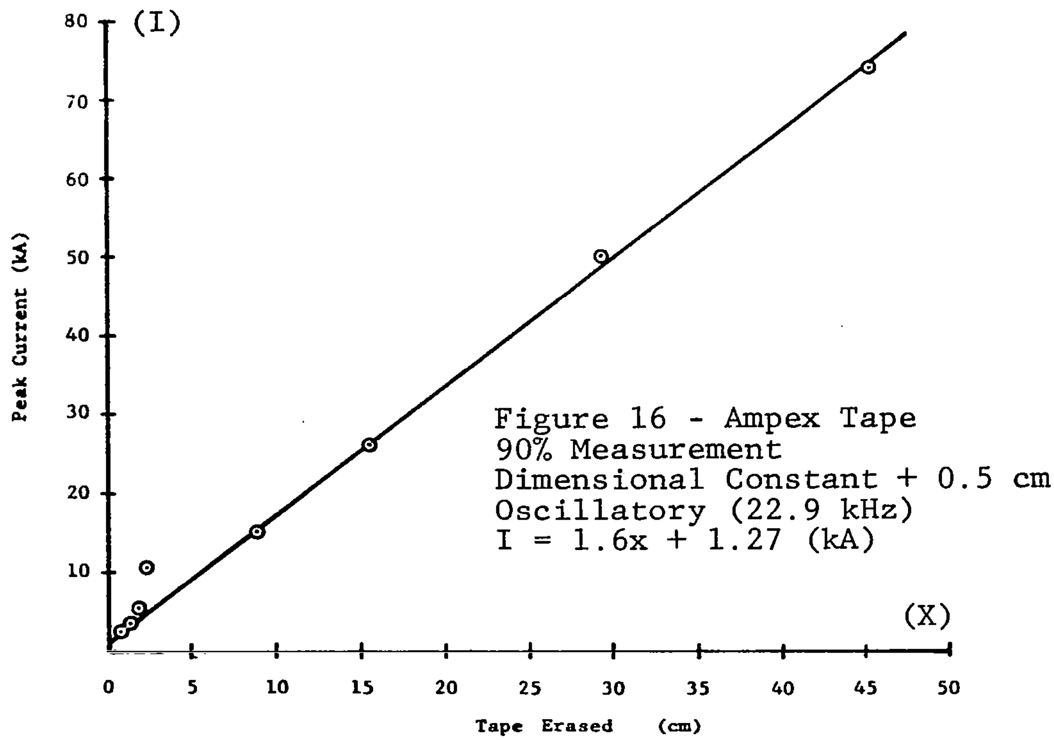
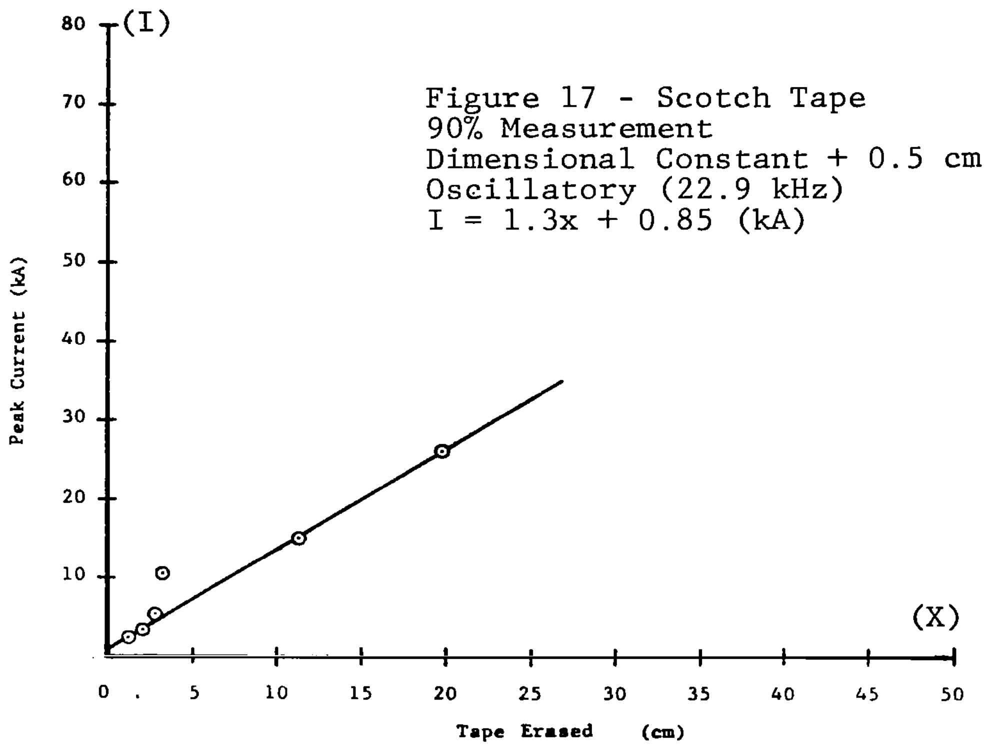


Figure 15 - Ampex Tape
80% Measurement
Dimensional Constant + 0.5 cm
Oscillatory (22.9 kHz)
I = 1.8x + 1.31 (kA)


(I)
80
70
60
50
40
30
20
10
Peak Current (kA)
Figure 16 - Ampex Tape
90% Measurement
Dimensional Constant + 0.5 cm
Oscillatory (22.9 kHz)
I = 1.6x + 1.27 (kA)
(X)
0
5
10
15
20
25
30
35
40
45
50
Tape Erased (cm)


(I)
80
70
60
50
40
30
20
10
Peak Current (kA)
Figure 17 - Scotch Tape
90% Measurement
Dimensional Constant + 0.5 cm
Oscillatory (22.9 kHz)
I = 1.3x + 0.85 (kA)
(X)
0
5
10
15
20
25
30
35
40
45
50
Tape Erased (cm)

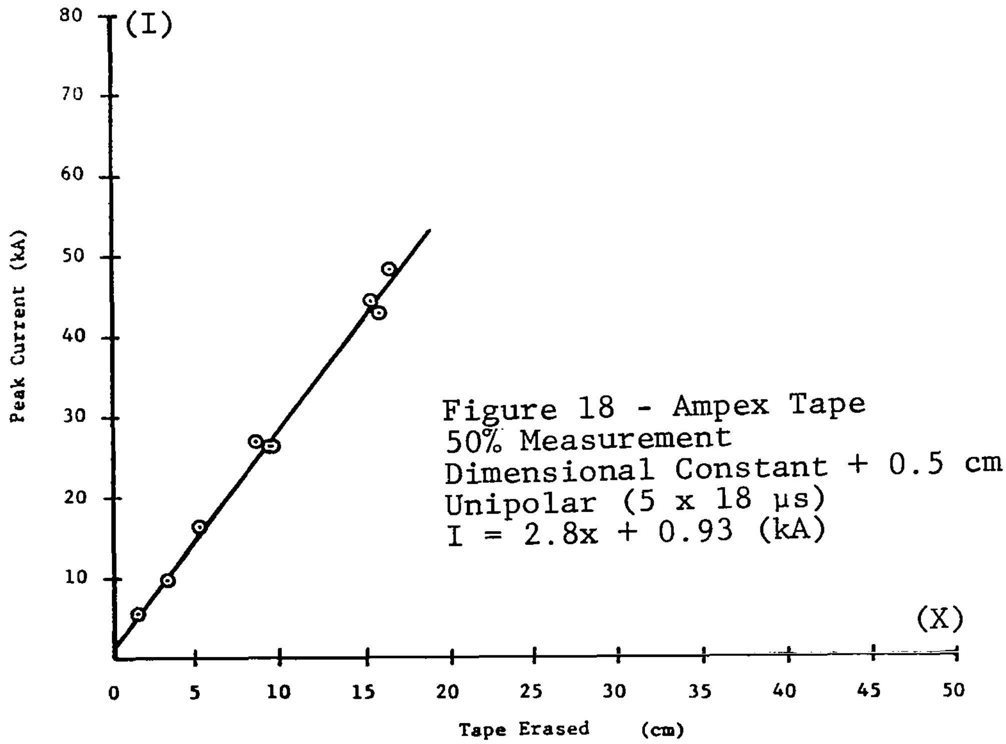


Figure 18 - Ampex Tape
50% Measurement
Dimensional Constant + 0.5 cm
Unipolar (5 x 18 μs)
$I = 2.8x + 0.93$ (kA)

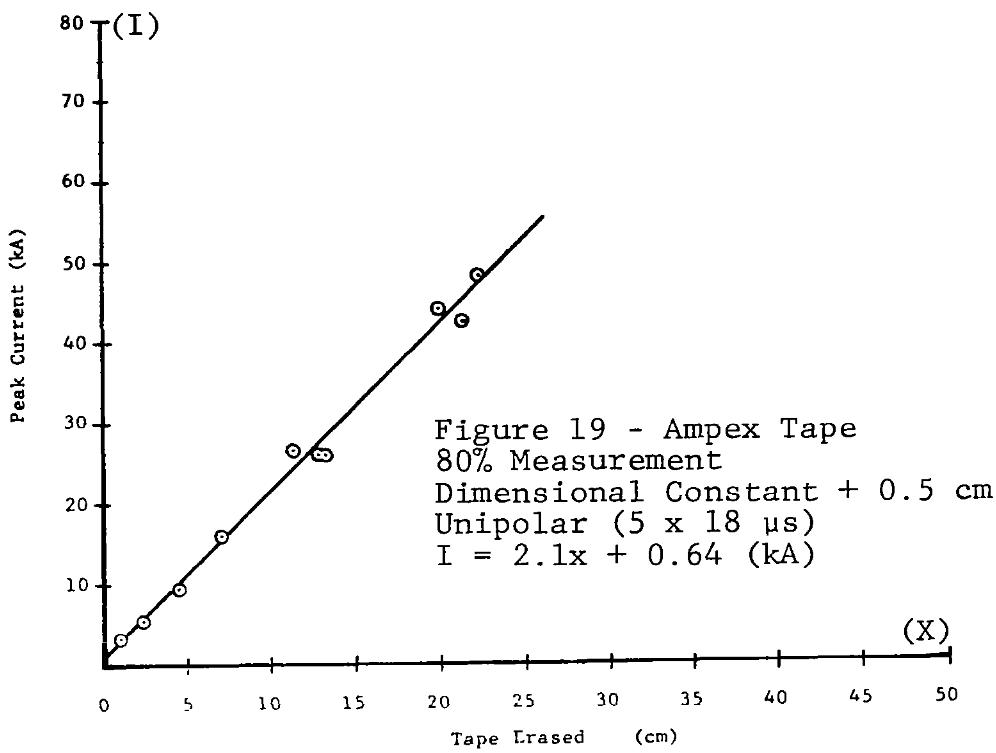
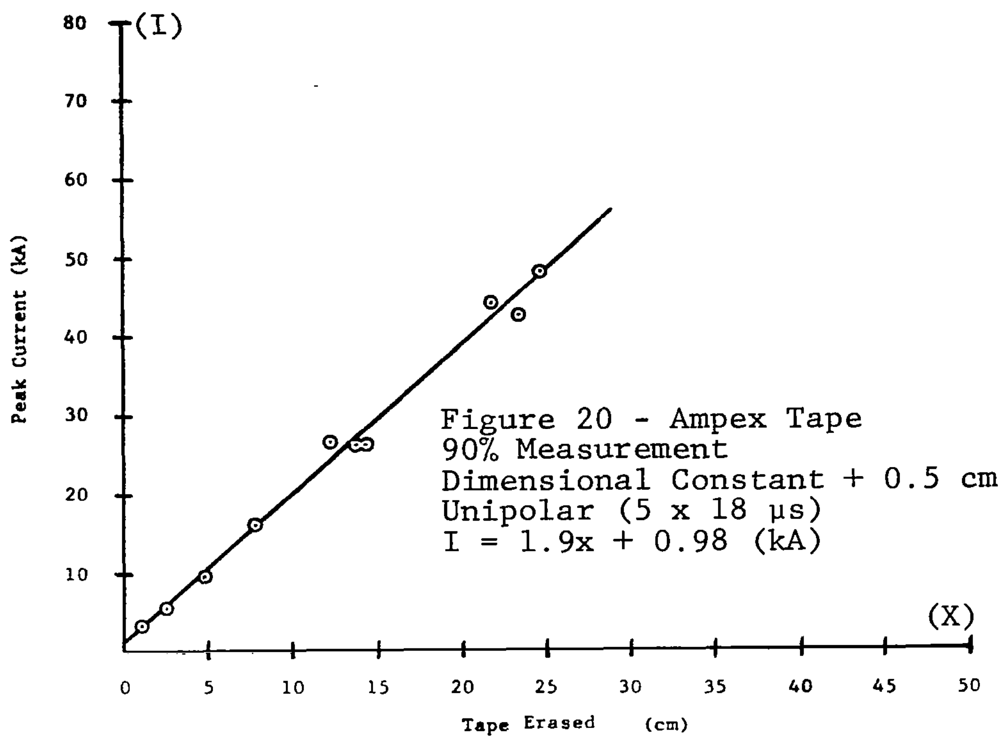
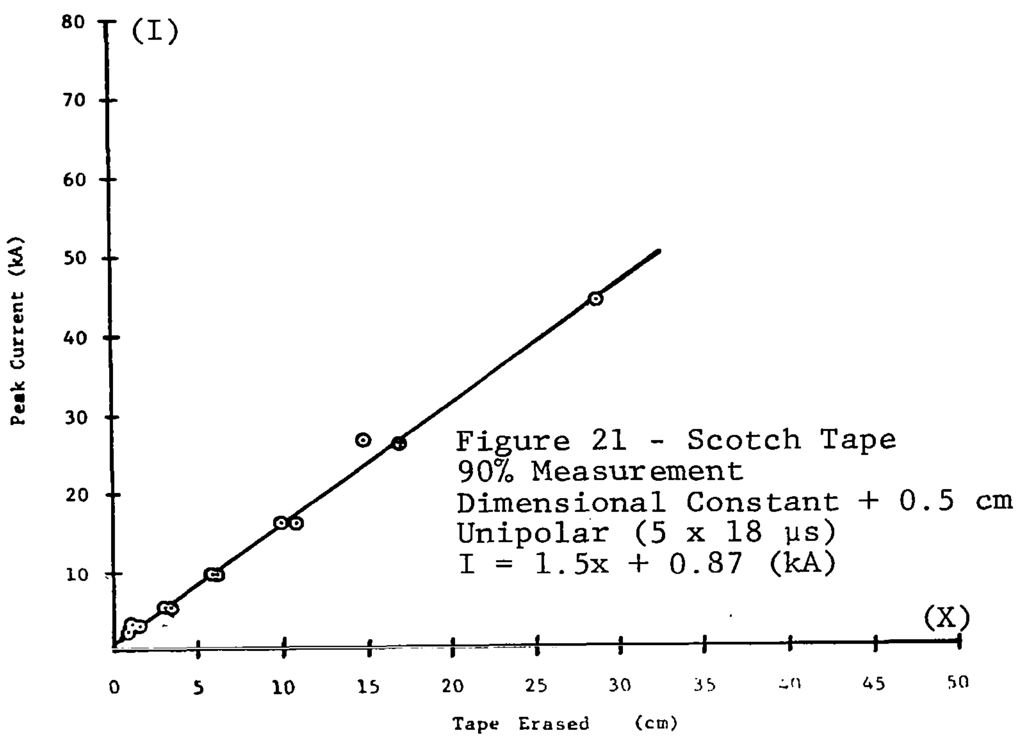


Figure 19 - Ampex Tape
80% Measurement
Dimensional Constant + 0.5 cm
Unipolar (5 x 18 μs)
$I = 2.1x + 0.64$ (kA)



(I)
80
70
60
50
40
30
20
10
Peak Current (kA)
(X)
0
5
10
15
20
25
30
35
40
45
50
Tape Erased (cm)
Figure 20 - Ampex Tape
90% Measurement
Dimensional Constant + 0.5 cm
Unipolar (5 x 18 μs)
I = 1.9x + 0.98 (kA)



(I)
80
70
60
50
40
30
20
10
Peak Current (kA)
(X)
0
5
10
15
20
25
30
35
45
50
Tape Erased (cm)
Figure 21 - Scotch Tape
90% Measurement
Dimensional Constant + 0.5 cm
Unipolar (5 x 18 μs)
I = 1.5x + 0.87 (kA)

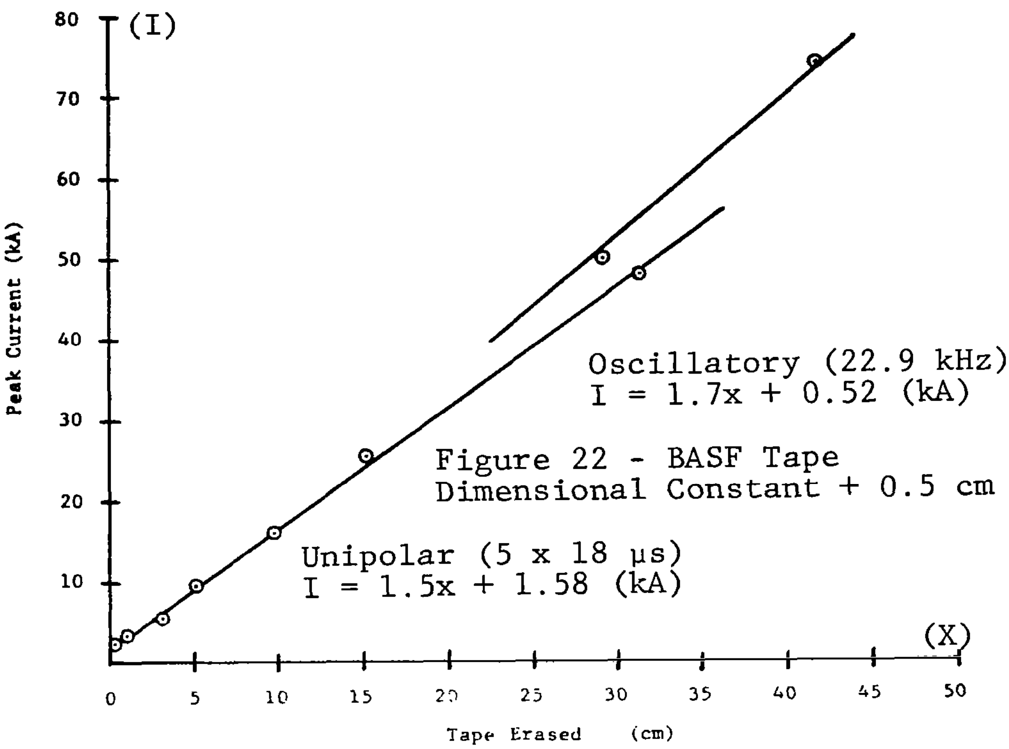


Figure 22 - BASF Tape Dimensional Constant + 0.5 cm

Table 3 compares the calibration factors for the various tapes as well as their respective x-axis intercepts (zero current). Since the data has not been adjusted for dimensions of holder and conductor, the x-axis intercept should be 0.5 cm. The intercepts listed, calculated by the analysis program, come close to this value.

Two tapes, Ampex and Scotch, show a difference of about 27% with more Scotch tape being erased for a given peak current than Ampex. This difference holds for both unipolar and oscillatory currents. Table 3 also indicates that oscillatory currents erase 16% to 20% more tape than unipolar currents. If this difference is significant and it appears to be, then unipolar calibrations must be used since lightning currents are always unidirectional. A time dependency has been postulated. That is, the longer the field is applied, the more erasure occurs. For these tests, the pulse widths applied (time between 50% points) are about the same with the unipolar being the longer of the two. The repeated half cycles of the oscillatory wave should have no affect since repeated unipolar waves (discussed below) had no affect. The possibility of a polarity effect due to the presence of both positive and negative fields seems remote since the tapes were inserted randomly. If one magnetic field direction was preferred, it would have been positive for some tests and negative for others.

TABLE 3

Calibration Factors Reel Tapes
Values given are linear regression calculated values

Tape Type and Measurement Points	Calibration Factor (slope) (kA/cm)	x-Axis Intercept (cm)
Oscillatory Simulated Lightning Currents (22.9 kHz)		
Ampex 50%	2.31	-0.6
Ampex 80%	1.80	-0.7
Ampex 90%	1.62	-0.8
Scotch 90%	1.26	-0.7
Unipolar Simulated Lightning Currents (5 x 18 μs)		
Ampex 50%	2.78	-0.3
Ampex 80%	2.10	-0.3
Ampex 90%	1.88	-0.5
Scotch 90%	1.51	-0.6
BASF 90%	1.58	-1.1

The reference signal level of the BASF tape varied randomly during playback (about 10%) and made the 90% measurement points hard to judge. Consequently, the data contains more uncertainty than either the Ampex or Scotch data. The BASF tape does appear to behave more like the Scotch tapes than the Ampex. Its calculated x-axis crossing misses the 0.5 cm point by more than either of the other tapes which is probably caused by the reading uncertainties. On Figure 22, line equations are given for both unipolar and oscillatory test waves. The oscillatory case is derived from the 2 data points and a -0.5 cm x-axis crossing assumption. It can be assigned no more than a 50% confidence of accuracy. The unipolar data is at least 3 times better (based on 6 points instead of 2) but no better than 15%. The Ampex and Scotch calibration factors are based on much better defined reference levels, and more data which makes ± 5% accuracy estimates reasonable.

Tests 34 and 35 were carried out to determine if repeated simulated lightning currents would have any affect on the amount of tape erased. Test 34 was exposed to 1 unipolar current while the tape in test 35 was exposed to 5 simulated curents. The results show that the erasures were within 3% of each other, which is within the reading errors. Thus the results can be considered to be identical.

Conclusions

Plots of the calibration data show that a linear relationship exists between the peak current and the amount of tape erased.

A 25% difference in calibration factors between tape types was found and 16% difference between oscillatory and unipolar currents was noted.

Repeated applications of the same peak current had no effect on the amount of tape erased.

Calibration of Cassette Tapes

As discussed earlier, the reel tapes present some handling difficulties. It appears that using cassette tapes will overcome many of these problems, but before they can be used, calibrations have to be performed to determine which cassette tape types are best and which calibration factors should be used. This section of the report covers the tests and evaluations carried out on cassette tapes, recorders and playback systems. These tests were performed subsequent to those made on the reel tapes. Where possible, data obtained on the reel tapes were used as a basis of comparison.

Reference Signal Recording Procedure

Two cassette recording evaluations were carried out prior to recording the reference signal on the cassette tapes. First, several cassette tape recorders were compared to determine what recorder should be used to record the reference signal. Second, the various tapes were compared to determine which tapes would be exposed to the simulated lightning currents.

It must be noted that the evaluations carried out here assess the ability of a tape or a piece of equipment to perform a special function and in no way should be construed to reflect on the ability of that tape or piece of equipment to perform its intended function.

Cassette Recorder Evaluations

Four cassette recorders were compared to determine which would record the most consistent signal on a given tape. The recorders evaluated ranged from an inexpensive single track, consumer type recorder to a highly sophisticated stereo recorder. (Price range approximately \$30.00 to \$300.00). The evaluated recorders were: a hand held battery operated Unisef Model TU- 502 (Japanese), General Electric portable Model 3-5105C, Realistic portable Model CTR-30B, and a Realistic Model SCT-16.

An audio signal generator was adjusted to provide a 550 Hz 150 $\pm$ 1 mV AC signal. This signal was then connected to the microphone or auxiliary input of each recorder. The record level controls on the stereo recorder were adjusted to obtain a reading of 0 dB (100%) on the recorder internal VU meters. One minute recordings were made with each recorder on a Scotch Highlander cassette.

Evaluations of the different recordings were made by listening to the playback and observing the voltage level on a VU meter which was connected in parallel with an 8Ω speaker. (See Figure 4). All playback was done on the G.E. recorder because its auxiliary output was capable of driving the 8Ω speaker. The volume control was adjusted to obtain an average reading of 0 dB (0.8 VAC) on the VU meter. Deviations in the output from the tape were recorded in % dip or overshoot. The results of the evaluation are given in Table 4.

TABLE 4

Cassette Recorder Evaluation Results

Recorder	Peak Deviations	Remarks
SCT-16 Stereo	± 2%	Consistent Level
General Electric	+ 5, -8%	Mostly 2% - 3%
Realistic	± 5%	± 3% Average
Unisef	+ 10, -20%	± 7% Average

The most consistent level of signal was recorded by the SCT-16 recorder. Discussions with audio recording specialists revealed that, for the recording consistency desired in this application, the two most important considerations in the recording system are tape to head pressure and tape speed variations. The SCT-16 recorder has a dual capstran drive which gives good control for both of these features. The SCT-16 recorder was used for recording all further cassette test evaluations.

It was noted during the evaluation that playback is much less critical than recording as to what equipment can be used. Once a consistent signal has been recorded on a tape, all four recorders gave essentially the same playback.

Cassette Tape Selection

Seven cassette tapes were compared on their ability to consistently reproduce the recorded reference voltage signal. The cassette tapes evaluated were:

FUJI FX-1	FUJI Photo Film USA, Inc., New York, NY 10001
Maxell UDXLI	Maxell Corp. of America, Moonachie, NJ 07074
Maxell UD	" "
Maxell LN	" "
Scotch Highlander	Minn. Mining and Man. Co., St. Paul, MN 55119
Realistic Supertape Gold	Radio Shack, Fort Worth, TX 76102
Realistic LN	" "

Ampex I 670 Cassettes were contributed by KSC and did not arrive in time to included in this evaluation.

A two-minute recording was made on each of the seven tapes using the stereo recorder. The audio signal generator was set at 400 ± 5% Hz, 150 ± 1 mV. Playback was again on the G.E. portable with observation on the VU meter. The results of this evaluation are given in Table 5.

TABLE 5

Cassette Tape Selection Results

Cassette Tape	Peak Deviations	Remarks
FUJI FX-1	± 3%	Slow +1%, -1% variation
Maxell UDXLI	0, +2%	Consistent
Maxell UD	0, +2%	-5%, +3% at start
Maxell LN	0, +2%	-3%, +5% at start
Scotch Highlander	-3, +1%	-10% at start
Realistic Supertape	± 7%	-20%, +8%, -15% peaks
Realistic LN	± 5%	Same

All the tapes had more variations near the beginning than later on. Maxell UD, LN and Scotch tapes were selected for further testing along with Ampex tapes supplied by NASA-KSC.

Recording Procedure

Both sides of each cassette were recorded in stereo using the SCT-16 stereo recorder. A 400 ± 5% Hz, 150 ± 2 mV signal was supplied to both left and right stereo channels and the record level controls were adjusted to give 0 dB readings on the internal VU meters.

Tape Exposure and Readback Procedures

The cassette tapes were exposed to the simulated lightning currents in the same type of holding tubes used for the reel tapes. The dimensions of the holders and the conductor diameter were different resulting in a holder dimensional constant of 0.5 cm for the Ampex and Scotch tapes, and 0.2 cm for the Maxell tapes.

The cassette tapes were not cut, but pulled out and attached to the tape carrier with adhesive tape. The cassette holder was supported externally above the holder tube. The use of adhesive tapes on the magnetic tapes was found to be quite unsatisfactory. In some cases, the adhesive tape adhered so tightly that the magnetic tapes broke while attempting to remove the adhesive tape. In other cases, part of the adhesive would remain on the magnetic tape and cause fouling problems during playback. Plastic clips to hold the tape to the carrier would have been much better.

After one length had been exposed, it was wound into the cassette and a new length was pulled out for the next test.

After all the cassette tapes had been exposed, they were played back on the G.E. recorder, VU meter speaker system and the time between the 80% points and the 50% points measured using a hand operated stopwatch. The tapes were recorded in stereo with identical signals on both tracks, and on both sides. When the tapes were played back, a single track (mono) player was used, so the output was the sum of both the left and right tracks at once. Readings were also taken on both sides of the tape and averaged, so the data represents 2 erasure measurements.

In addition to the stopwatch measurements, tape signal erasures were also measured using an oscilloscope. The tape player was started at a point just preceding the erasure on the tape and its output was recorded photographically on the oscilloscope. Typical oscillograms of the output are shown in Figure 23. Measurements of the times between the 80% and 50% points were made on the oscillograms.

Calibration Test Fixture

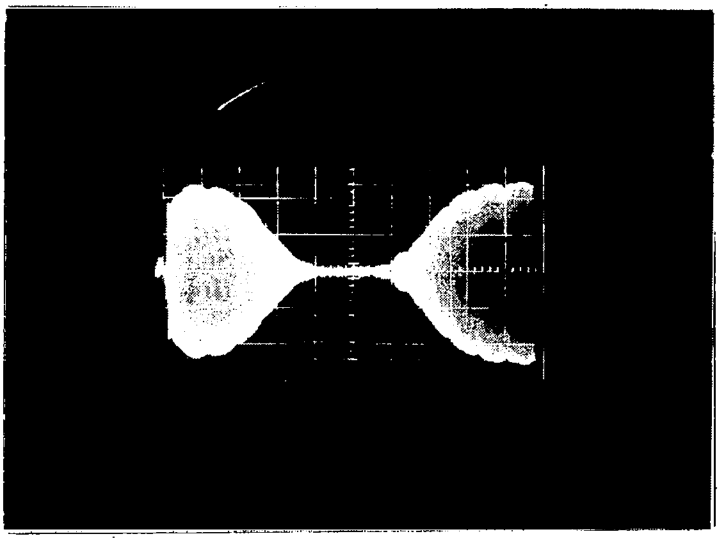
The calibration test fixture used was essentially the same as described for reel tape calibration. That test fixture had been erected at the GE HVL while the present fixture was constructed at Lightning Technologies, Inc. high current laboratory.

Simulated Lightning Currents

Simulated lightning currents were generated using the circuits and parameters given for the reel tape calibrations.

Test Configuration and Current Levels

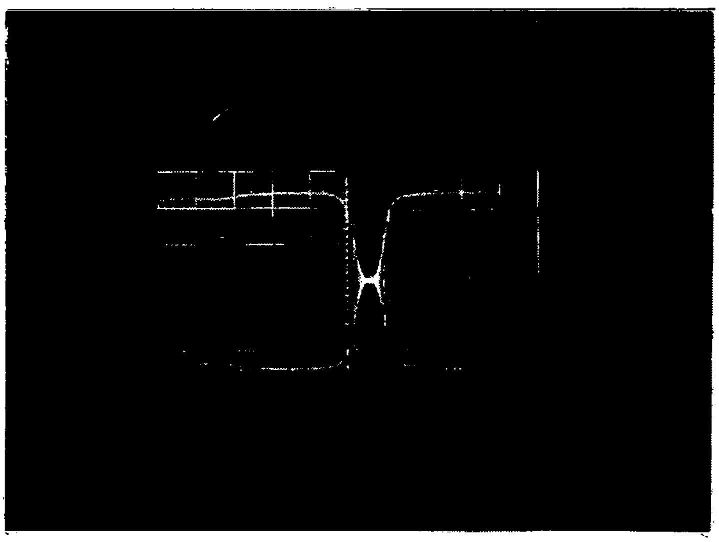
Cassette tapes were exposed to the magnetic fields of oscillatory (10.7 kHz) and unipolar (12 x 43 μs) simulated lightning current pulses with peak amplitudes of 2, 5, 10,



Test #84

Scotch Tape
Sweep 2.0 s/div.
Vertical 0.5 v/div.

48 kA Peak



Test #98

Maxell LN
Sweep 0.5 s/div.
Vertical 0.5 V/div.

2.9 kA Peak

Figure 23 - Typical Cassette Erasure Oscillograms

15, 25, and 50 kA. Calibration tests were conducted using the LCD described previously and an insulated #14 wire (0.27 cm diameter).

Test Results

Measurements of the length of cassette tape erased for the different applied simulated lightning current are given in Table 6. All data given are total erasures in seconds as measured during playback. It was intended that two exposures be made at each peak current applied. However, due to instrumentation difficulties (forgetting to reset the scope or replace film, etc.) some test currents were not measured. Since the same generator charge voltage was used and the tape erasure data are the same, it can be assumed that the same peak currents were applied. Therefore, all data were reported.

A study of Table 6 shows that very little difference exists between the two Maxell tapes and the Ampex tape. However, the Scotch tape appears to be different, with more erasure for a given current. This follows the trend seen in the reel tape data discussed previously.

Table 7 summarizes Table 6 by combining the Maxell and Ampex data and the data for each current level. Since the values listed in Table 7 do not all represent the same number of measurements, they must be given different weights in the analysis. All data points in Table 6 represent the same number of measurements (2), so the number of values taken from Table 6 to obtain the value listed in Table 7 is given in parenthesis.

A comparison of the stopwatch data and the oscillogram data in Table 7 shows that the latter is about 5% lower. This difference is greatest at the longest times and decreases as the currents get smaller. The reason is not clear but it could be related to the VU meter damping. When the rate of change of signal is fast, the meter will lag the actual signal. If the rate of change is decreasing, then at some point the meter will catch up with the signal and may overshoot to a leading position and oscillate somewhat. On some readings, this phenomena was occurring at the measurement points (50% to 80%) and made the actual points somewhat indeterminate. Consequently, it is thought that the oscillogram data is more reliable than the stopwatch data. When the two are averaged together to get a final tabulation, which is shown in Table 8, the two corresponding values are treated equally even though one, the stopwatch, may have represented more measurements than the other.

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TABLE 6

Cassette Tape Erasure Times

Total Times as Measured by Stopwatch and on Oscillograms in Seconds

(Stopwatch data represents average of forward and reverse channels)

Test No.	Peak Current kA	Ampex Stopwatch		Maxell UD Stopwatch		Maxell LN Stopwatch		Maxell LN Oscillogram		Scotch Stopwatch		Scotch Oscillogram	
		50%	80%	50%	80%	50%	80%	50%	80%	50%	80%	50%	80%
OSCILLATORY TEST CURRENTS (10.7 kHz)													
83		8.4	10.8	8.5	11.0	8.4	11.2	7.9	10.1	9.1	12.1	8.7	11.5
84	48.0	8.4	10.8	8.6	11.0	8.4	10.8	7.9	10.1	9.2	12.2	8.5	10.9
85		8.9	11.0	8.6	10.9	8.5	11.2	7.9	10.3	9.3	12.4	8.7	10.7
86	49.0	8.6	11.2	8.6	10.9	8.6	11.0	8.1	10.5	9.2	12.0	8.7	11.1
87	25.5	4.6	6.1	4.6	5.6	4.6	6.0	4.5	5.7	4.9	6.5	4.6	6.0
88		4.2	5.6	4.6	5.8	4.5	5.9	4.5	5.5	4.6	6.2	4.6	6.3
89	26.0	4.5	6.0	4.6	5.8	4.3	5.8	4.1	5.3	4.8	6.6	4.7	6.2
90	15.0	2.6	3.4	2.8	3.4	2.6	3.5	2.5	3.3	2.7	3.8	2.6	3.6
91	15.1	2.6	3.6	2.6	3.4	2.6	3.4	2.2	3.1	2.8	3.8	2.6	3.5
92	10.8	1.8	2.2	1.8	2.4	1.9	2.4	1.8	2.3	1.9	2.6	1.8	2.5
93	10.8	1.7	2.2	1.8	2.4	1.8	2.4	1.7	2.3	1.9	2.6	1.8	2.5
94	5.4	0.7	0.9	0.8	1.2	0.8	1.1	0.86	1.1	0.8	1.1	0.78	1.16
95	5.6	0.8	1.0	0.9	1.0	0.9	1.1	0.91	1.16	0.8	1.2	0.81	1.19
96	3.6	0.4	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.4	0.6	0.46	0.71
97	2.8	0.3	0.4	0.4	0.5	0.4	0.4	0.4	0.5	0.3	0.4	0.23	0.5
98	2.9	0.4	0.4	0.4	0.5	0.4	0.6	0.4	0.6	0.4	0.5	0.3	0.5

TABLE 6 (con'd)

Cassette Tape Erasure Times

Total Times as Measured by Stopwatch and on Oscillograms in Seconds

(Stopwatch data represents average of forward and reverse channels)

Test No.	Peak Current kA	Ampex Stopwatch		Maxell UD Stopwatch		Maxell LN Stopwatch		Maxell LN Oscillogram		Scotch Stopwatch		Scotch Oscillogram	
		50%	80%	50%	80%	50%	80%	50%	80%	50%	80%	50%	80%
UNIPOLAR TEST CURRENTS (12 x 43 μsec)													
102	5.4	0.6	0.9	0.8	0.9	0.7	1.0	0.7	1.1	0.6	1.0	0.66	1.04
103	9.9	1.2	1.9	1.4	1.9	1.4	1.9	1.4	1.9	1.5	2.2	1.4	2.0
104	14.2	2.2	3.2	2.3	3.0	2.2	3.0	2.2	2.9	2.2	3.4	2.1	3.1
105	23.0	3.6	4.8	3.8	4.8	3.6	5.0	3.2	4.9	3.6	5.2	3.2	4.9

TABLE 7

Summary of Cassette Calibration Data

Maxell and Ampex Combined and Compared to Scotch

Total Tape Disturbance Time Between 50% and 80% Levels Shown in Seconds

Peak Current kA	50% Level Amp. & Max. Stp.	50% Level Amp. & Max. Osc.	50% Level Scotch Stp.	50% Level Scotch Osc.	80% Level Amp. & Max. Stp.	80% Level Amp. & Max. Osc.	80% Level Scotch Stp.	80% Level Scotch Osc.
Oscillatory Test Currents (10.7 kHz)								
48.5	8.5 (12)	8.0 (4)	9.2 (4)	8.6 (4)	11.0 (12)	10.3 (9)	12.2 (4)	11.0 (4)
25.8	4.5 (9)	4.4 (3)	4.8 (3)	4.6 (3)	5.8 (9)	5.5 (3)	6.4 (3)	6.2 (3)
15.0	2.6 (6)	2.4 (2)	2.8 (2)	2.6 (2)	3.5 (6)	3.2 (2)	3.8 (2)	3.6 (2)
10.8	1.8 (6)	1.8 (2)	1.9 (2)	1.8 (2)	2.3 (6)	2.3 (2)	2.6 (2)	2.5 (2)
5.5	0.8 (6)	0.9 (2)	0.8 (2)	0.8 (2)	1.1 (6)	1.1 (2)	1.2 (2)	1.2 (2)
3.6	0.5 (3)	0.6 (1)	0.4 (1)	0.5 (1)	0.6 (3)	0.7 (1)	0.6 (1)	0.7 (1)
2.8	0.4 (6)	0.4 (2)	0.4 (2)	0.4 (2)	0.5 (6)	0.6 (2)	0.5 (2)	0.5 (2)
Unipolar Test Currents (12 x 43 μsec)								
23.0	3.7 (3)	3.2 (1)	3.6 (1)	3.2 (1)	4.9 (3)	4.9 (1)	5.2 (1)	4.9 (1)
14.2	2.2 (3)	2.2 (1)	2.2 (1)	2.1 (1)	3.1 (3)	2.9 (1)	3.4 (1)	3.1 (1)
9.9	1.3 (3)	1.4 (1)	1.5 (1)	1.4 (1)	1.9 (3)	1.9 (1)	2.2 (1)	2.0 (1)
5.4	0.7 (3)	0.7 (1)	0.6 (1)	0.7 (1)	0.9 (3)	1.1 (1)	1.0 (1)	1.0 (1)

Stp. - Stopwatch Measurements
Osc. - Oscillogram Measurements
Max. - Maxell Tape
Amp. - Ampex Tape
( ) - Number of Points from Table 6 Represented by the Listed Value

TABLE 8

Final Summary of Cassette Calibration Data

Stopwatch and Oscillogram Data Combined

Peak Current kA	50% Level Amp. & sec.	50% Level Max. cm.	50% Level Scotch sec.	50% Level Scotch cm.	80% Level Amp. & sec.	80% Level Max. cm.	80% Level Scotch sec.	80% Level Scotch cm.
Oscillatory Test Currents (10.7 kHz)								
48.5	8.3	19.8 (4)	8.9	21.2 (4)	10.6	25.2 (4)	11.6	27.6 (4)
25.8	4.5	10.7 (3)	4.7	11.2 (3)	5.7	13.6 (3)	6.3	15.0 (3)
15.0	2.5	6.0 (2)	2.7	6.4 (2)	3.4	8.1 (2)	3.7	8.8 (2)
10.8	1.8	4.3 (2)	1.9	4.5 (2)	2.3	5.5 (2)	2.6	6.2 (2)
5.5	0.8	1.9 (2)	0.8	1.9 (2)	1.1	2.6 (2)	1.1	2.9 (2)
3.6	0.6	1.4 (1)	0.4	1.0 (1)	0.6	1.4 (1)	0.6	1.4 (1)
2.8	0.4	1.0 (2)	0.4	1.0 (2)	0.5	1.2 (2)	0.5	1.2 (2)
Unipolar Test Currents (12 x 43 μsec)								
23.0	3.5	8.3 (1)	3.4	8.1 (1)	4.9	11.7 (1)	5.0	11.9 (1)
14.2	2.2	5.2 (1)	2.2	5.2 (1)	3.0	7.1 (1)	3.3	7.9 (1)
9.9	1.4	3.3 (1)	1.4	3.3 (1)	1.9	4.5 (1)	2.1	5.0 (1)
5.4	0.7	1.7 (1)	0.6	1.4 (1)	1.0	2.4 (1)	1.0	2.4 (1)

Amp. - Ampex Tape   Max. - Maxell Tape   ( ) Relative weighting factors

Now, each column of data represents an equal data population, but there still remains a difference row to row. For example, the 48.5 kA measurements represent 4 times as many measurements as the 3.6 kA measurements. These relative weighting factors must be kept in mind when lines are drawn through the plotted data since more consideration must be given to the "heaviest" points. This was done in the computer calculation by entering the data point the number of times shown in Table 8.

Figures 24 through 31 show plots of the data in Table 8. The data plotted is taken from the table and as in the reel tape plots given earlier, the lines are plotted from computed linear regression analysis estimates. The data points show that a linear relationship exists between peak current and length of tape erased.

Table 9 lists the calibration factors for the different tape types as well as an x-axis intercept for each. Again as in the previous reel tape tests, oscillatory currents erased more than unipolar currents except for the 80% Ampex-Maxell measurement where both were the same. This time the difference is smaller (10% versus 16%).

TABLE 9

Calibration Factors for Cassette Tapes

Values Given are Linear Regression Calculated Values

Tape Type and Measurement Point		Calibration Factor (slope) kA/cm	x-Axis Intercept cm
Oscillatory Simulated Lightning Currents (10.7 kHz)			
A - M	50%	2.42	-0.2
A - M	80%	1.90	-0.2
Scotch	50%	2.24	-0.4
Scotch	80%	1.74	-0.2
Unipolar Simulated Lightning Currents (12 x 43 μs)			
A - M	50%	2.64	-0.3
A - M	80%	1.87	-0.6
Scotch	50%	2.62	-0.5
Scotch	80%	1.83	-0.4

A - M = Ampex & Maxell Tapes

Comparing the reel and cassette tape data, the cassette tapes are erased less than the reel tapes for oscillatory (4.8% to 5.5%) and more (5% to 12%) for unipolar waves. In making these comparisons, it must be recognized that different amounts of data are represented, implying different confidence levels for each set of data. There were ~9 oscillatory data points for the reel tapes versus 64 data points for the cassette tapes. The unipolar reel tape data is based on ~12 points while the cassette data represents only 4 points. Basically, this means that the cassette unipolar data can show larger differences with other data bases and still not be significantly different because its uncertainty is greater.

It is interesting to note that the cassette oscillatory data is closer to the unipolar reel tape data (10% to 15%) than the reel oscillatory tape data (16% to 20%).

A possible explanation of the difference between unipolar and oscillatory erasures may be related to the state of magnetization left on the tape. When a tape is erased by a unipolar wave, all domains on the tape are magnetized in the same direction. When the tape is erased by an oscillatory current, the same thing happens during the first half cycle. During the second half cycle, the magnetic field intensity is lower and of an opposite polarity. If the tape domains are completely bilateral, all but a short length of tape domains will be magnetized in the reverse direction. However, if the domains are not bilateral, some could be magnetized at even lower magnetic intensity during the second half cycle in the reverse direction. If this process is possible, then more erasure of the tape will be caused by an oscillatory current wave, than by a unipolar wave and the amount of extra erasure will be related to the percent of undershoot or reversal. The tests performed at G.E. (reel tapes) used an oscillatory wave with an 89% reversal. That is, each succeeding half cycle was 89% of the proceeding one. The cassette tapes were tested at Lightning Technologies, Inc. and that test current had a 77% reversal. Since the cassette oscillatory tapes were erased less than the reel tapes, the pattern does fit the above scenerio - but of course, does not prove it.

All of this leads to the conclusion that, based on the data, there does appear to be a difference between oscillatory and unipolar erasures and the amount of difference appears to depend on the percent reversal in the test current. Since lightning is unipolar, for accurate measurements (±5%) calibrations based on unipolar test currents probably should be used. The present data base is too small at this point to draw such conclusions as fact and more tests should be made to verify these assumptions.

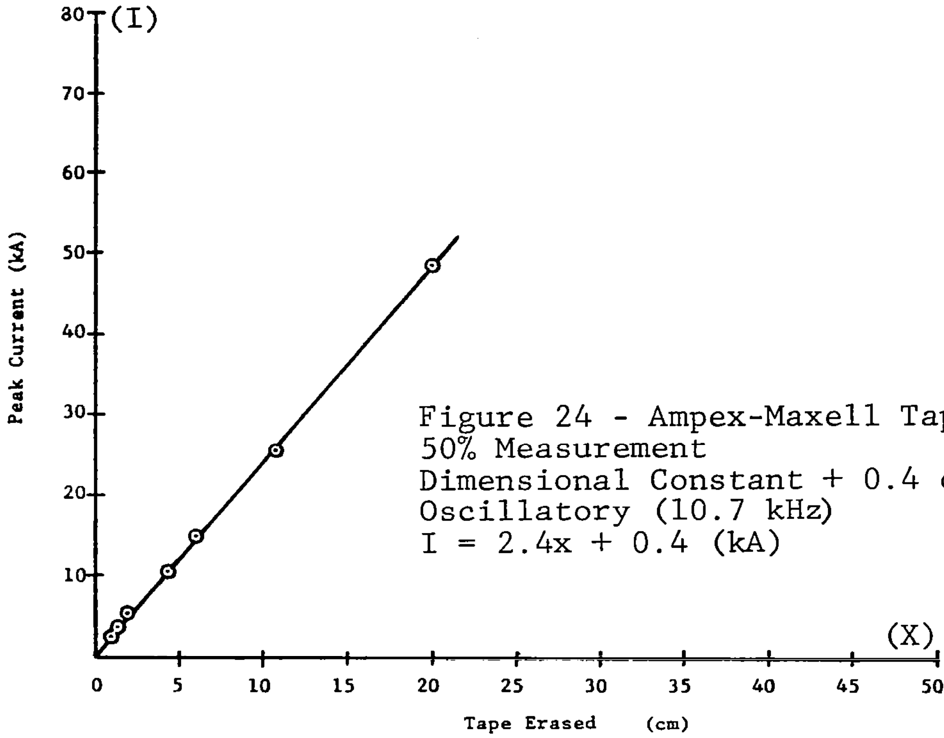


Figure 24 - Ampex-Maxell Tapes
50% Measurement
Dimensional Constant + 0.4 cm
Oscillatory (10.7 kHz)
$I = 2.4x + 0.4$ (kA)

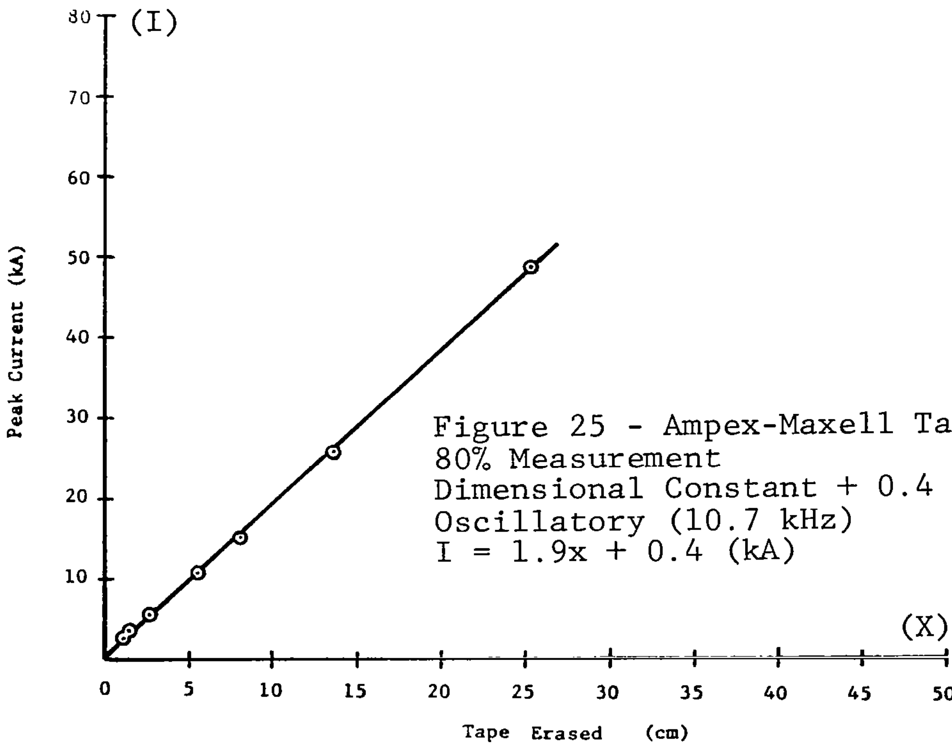


Figure 25 - Ampex-Maxell Tapes
80% Measurement
Dimensional Constant + 0.4 cm
Oscillatory (10.7 kHz)
$I = 1.9x + 0.4$ (kA)

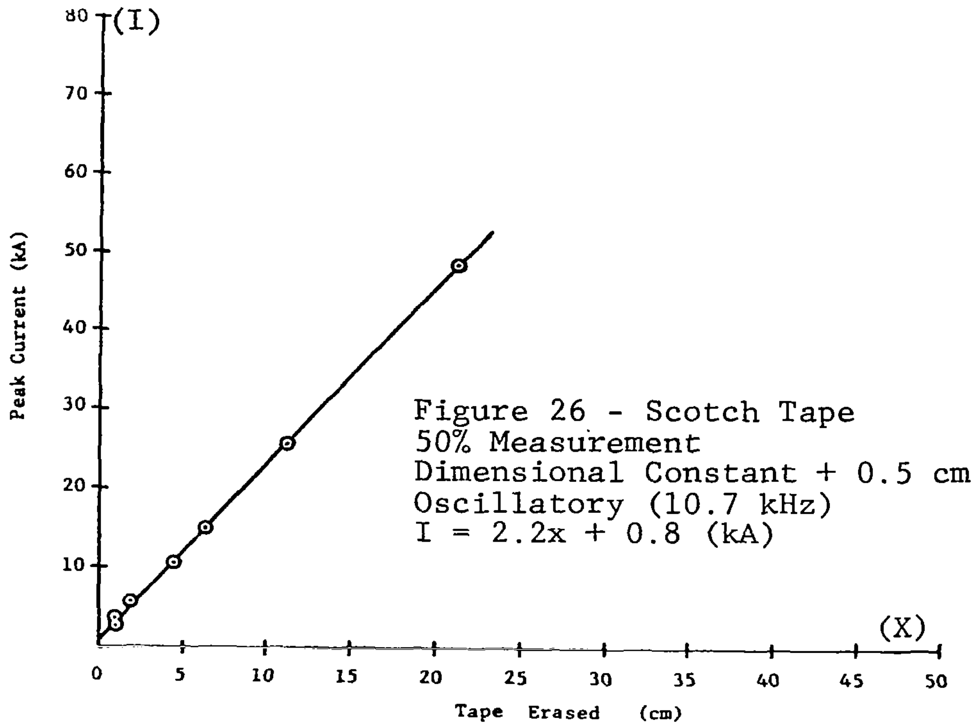


Figure 26 - Scotch Tape
50% Measurement
Dimensional Constant + 0.5 cm
Oscillatory (10.7 kHz)
I = 2.2x + 0.8 (kA)

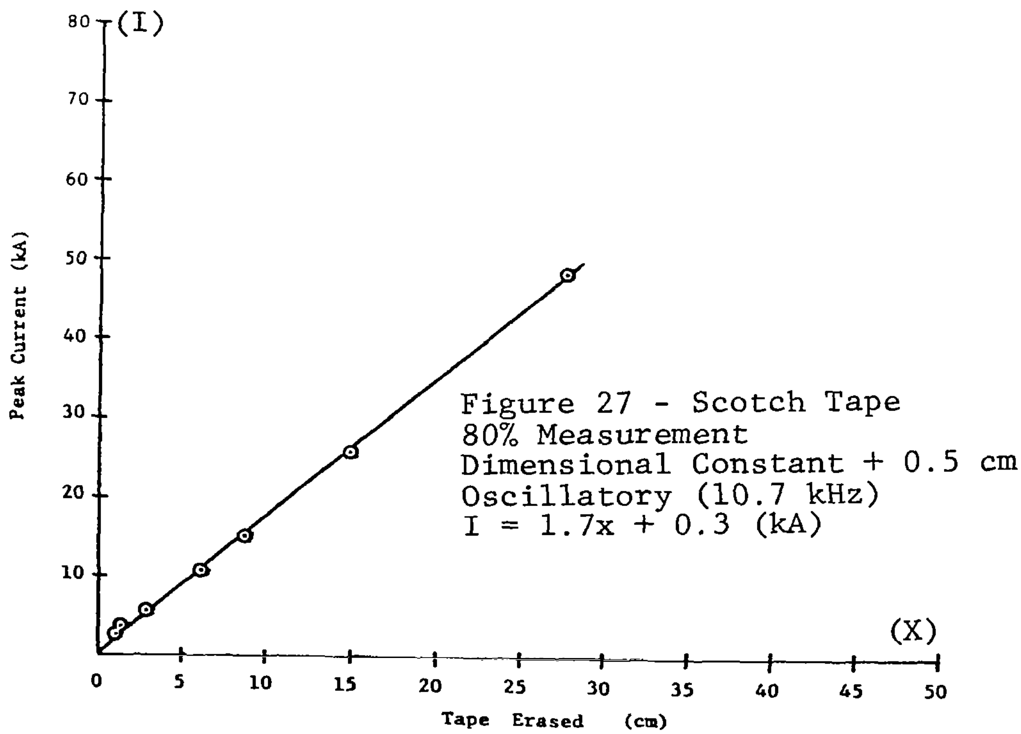


Figure 27 - Scotch Tape
80% Measurement
Dimensional Constant + 0.5 cm
Oscillatory (10.7 kHz)
I = 1.7x + 0.3 (kA)

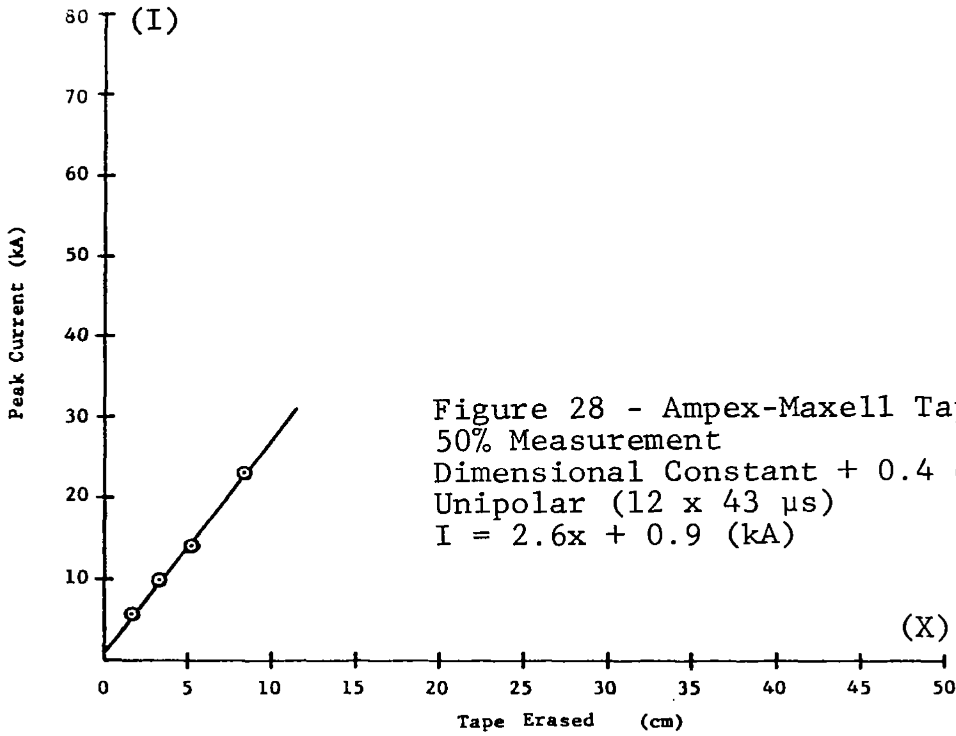


Figure 28 - Ampex-Maxell Tapes
50% Measurement
Dimensional Constant + 0.4 cm
Unipolar (12 x 43 μs)
I = 2.6x + 0.9 (kA)

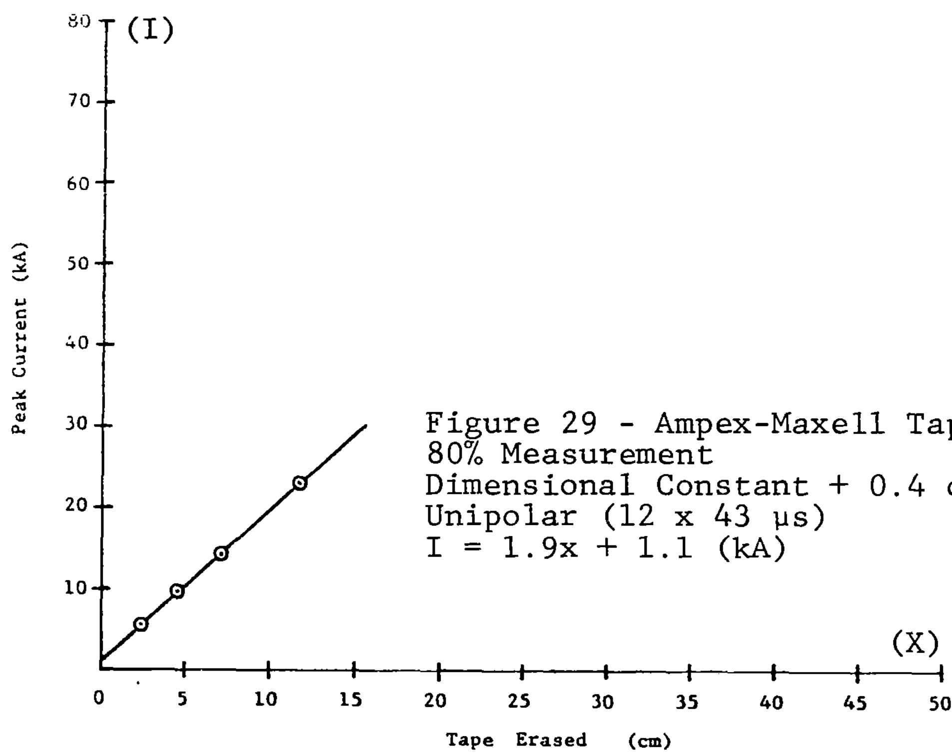
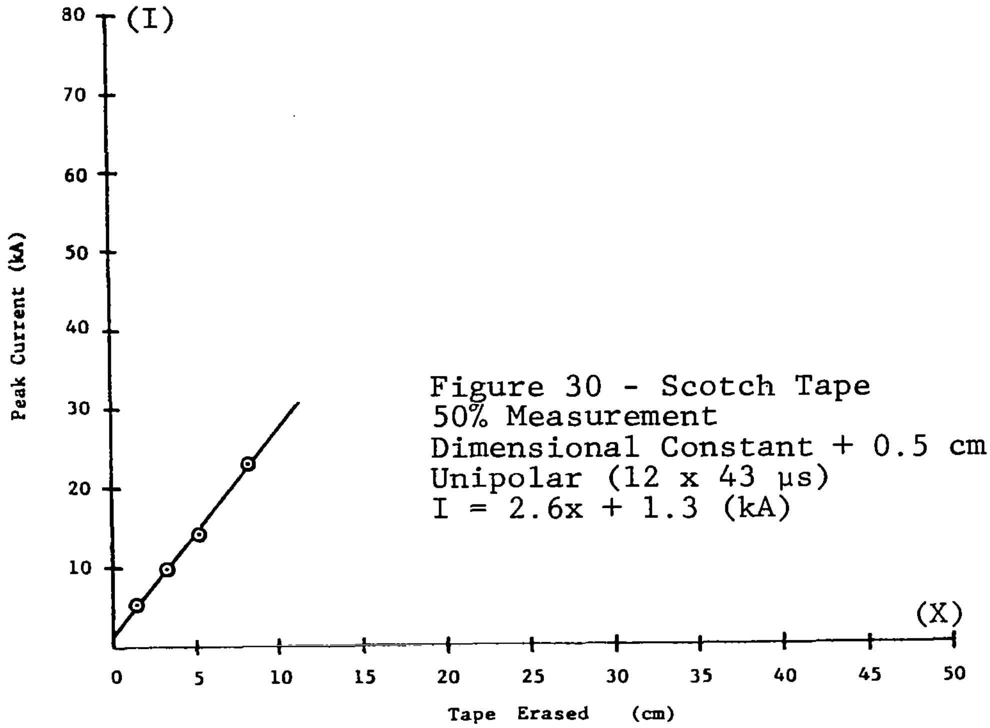
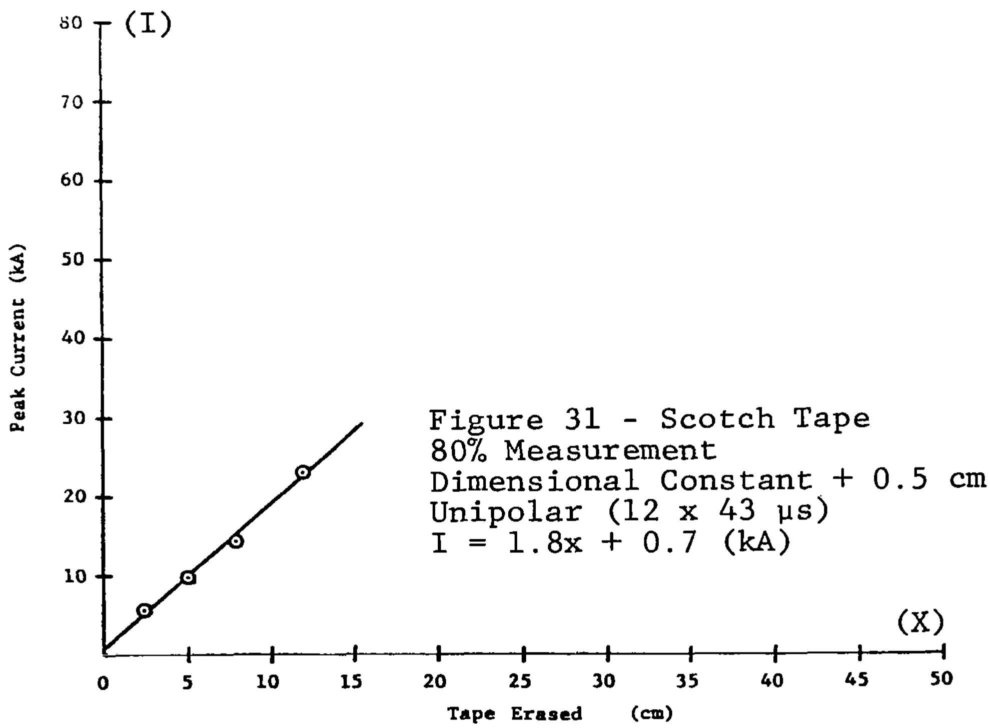


Figure 29 - Ampex-Maxell Tapes
80% Measurement
Dimensional Constant + 0.4 cm
Unipolar (12 x 43 μs)
I = 1.9x + 1.1 (kA)


80
70
60
50
40
30
20
10
(I)
Peak Current (kA)
Figure 30 - Scotch Tape
50% Measurement
Dimensional Constant + 0.5 cm
Unipolar (12 x 43 μs)
I = 2.6x + 1.3 (kA)
(X)
0
5
10
15
20
25
30
35
40
45
50
Tape Erased (cm)


80
70
60
50
40
30
20
10
(I)
Peak Current (kA)
Figure 31 - Scotch Tape
80% Measurement
Dimensional Constant + 0.5 cm
Unipolar (12 x 43 μs)
I = 1.8x + 0.7 (kA)
(X)
0
5
10
15
20
25
30
35
40
45
50
Tape Erased (cm)

As before, more Scotch tape was erased than Ampex-Maxell but the differences were smaller (8% oscillatory and 1% to 2% unipolar) than for reel tapes (29% oscillatory and 25% unipolar). The averaging of Ampex and Maxell tapes may have affected the data somewhat but in no way can that account for the entire difference.

During tests 102 through 105, four lengths of Ampex Grand Master reel tapes were exposed. The results of reading these tapes is given in Table 10 and plotted in Figure 32.

TABLE 10

Ampex Reel Tapes Exposed During the Cassette Calibrations

Test No.	Current kA	90% Erasure cm
Unipolar Simulated Lightning Current (12 x 43 μs)		
102	5.4	2.9
103	9.9	5.6
104	14.2	8.6
105	23.0	14.0

Linear Regression Calculated Calibration Factor

Ampex 90% 1.58 kA/cm

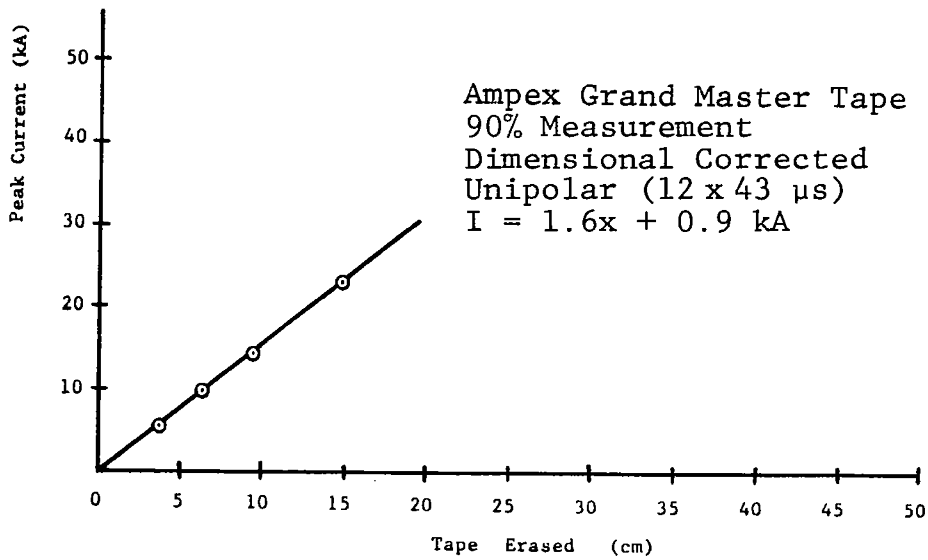


Figure 32

This calibration factor is about 16% lower than that obtained earlier in Table 3. If the difference is real, it would imply that the longer wave (12 x 43 μs) used here erased more reference signal than the shorter wave used earlier. Other comparisons between the data in Table 9 and corresponding values in Table 3 show that the longer times do seem to erase more signal for the unipolar tests (5 and 10% lower), the opposite shows up for the oscillatory data (5% higher). So, although the question cannot be completely resolved without performing more tests, the contrary discrepancies appear to indicate that no exposure time dependence probably exists in the amount of tape erased.

The magnetic intensity required to erase a tape can be calculated. Using Tests 84 and 95, Maxell LN tapes as examples, erasure measurements were made and are shown in Table 11.

TABLE 11

Determination of Erasure Magnetic Intensity

Test No.	84	95
90% Erasure Length	29 cm	3.2 cm
10% - 90% Erasure Length	19 cm	2.1 cm
Dimensional Constant	0.2 cm	0.2 cm
Calculated Magnetic Intensity (H)		
at 10% ref. length	75 kA/m	69 kA/m
at 10% ref. length	26 kA/m	26 kA/m

To erase 10% of the reference signal requires 26 kA/m (327 Oersteds). To remove 90% of the signal requires ~72 kA/m (904 Oersteds). The Maxell tape has a magnetic coercivity (H_c) of 345 Oersteds. H_c corresponds to the magnetic intensity required to reduce to zero the residual flux density that remains in a ferromagnetic material which was forced into magnetic saturation. It appears to take about 3 times this magnetic intensity to completely erase the reference signal.

Conclusions

Cassette tape signal erasure plots show that a linear relationship exists between peak current and length of tape on which the reference signal was erased.

As in the reel tape tests, more Scotch tape was erased than Ampex or Maxell for a given peak current; however, the difference between them was less (8%) than observed earlier (25%). Oscillatory test currents do appear to erase more of the magnetic tape than a unipolar wave of the same peak current and this effect appears to be related to the amount of reversal in the current wave. Higher reversals may erase more tape than lower reversals but the exact dependence would require further tests to establish. Until such tests have been conducted and the dependence established, magnetic tape calibrations should be carried out using only unipolar test currents.

Tape Orientation Evaluations

Earlier testing (Ref.10) revealed that when the plane of the tape was perpendicular to the magnetic lines of force, the amount of signal erasure was greatly reduced. In an LCD, the tape is held so that the length of the tape is perpendicular to the conductor and the plane or width of the tape is parallel to the magnetic lines of force around the conductor. Tests were conducted to determine what, if any, effect resulted from having the plane of the tape and its direction parallel to the magnetic lines of force.

Figure 32 illustrates the different configurations with respect to the magnetic lines of force. Figure 32 (a) represents the normal position of the magnetic tapes in the holder while (b) represents the incorrect method of mounting. Figure 32 (c) represents the tests made to evaluate the effects of having the length and the plane of the magnetic tape parallel with the magnetic lines of force. Figures 33, 34 and 35 show the test configuration at the GE HVL for subjecting magnetic tapes to this parallel exposure. In addition to the circular exposure, an angle, as shown in Figure 35, was also tested since it is partially parallel to the plane of the magnetic flux. The dimensions of this test fixture are given in Figure 36.

The tape orientation tests were performed at the GE HVL at the same time as the reel tape calibration tests. All test and readback procedures used during those tests apply to the present tests.

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10. Livermore Op. Cit.

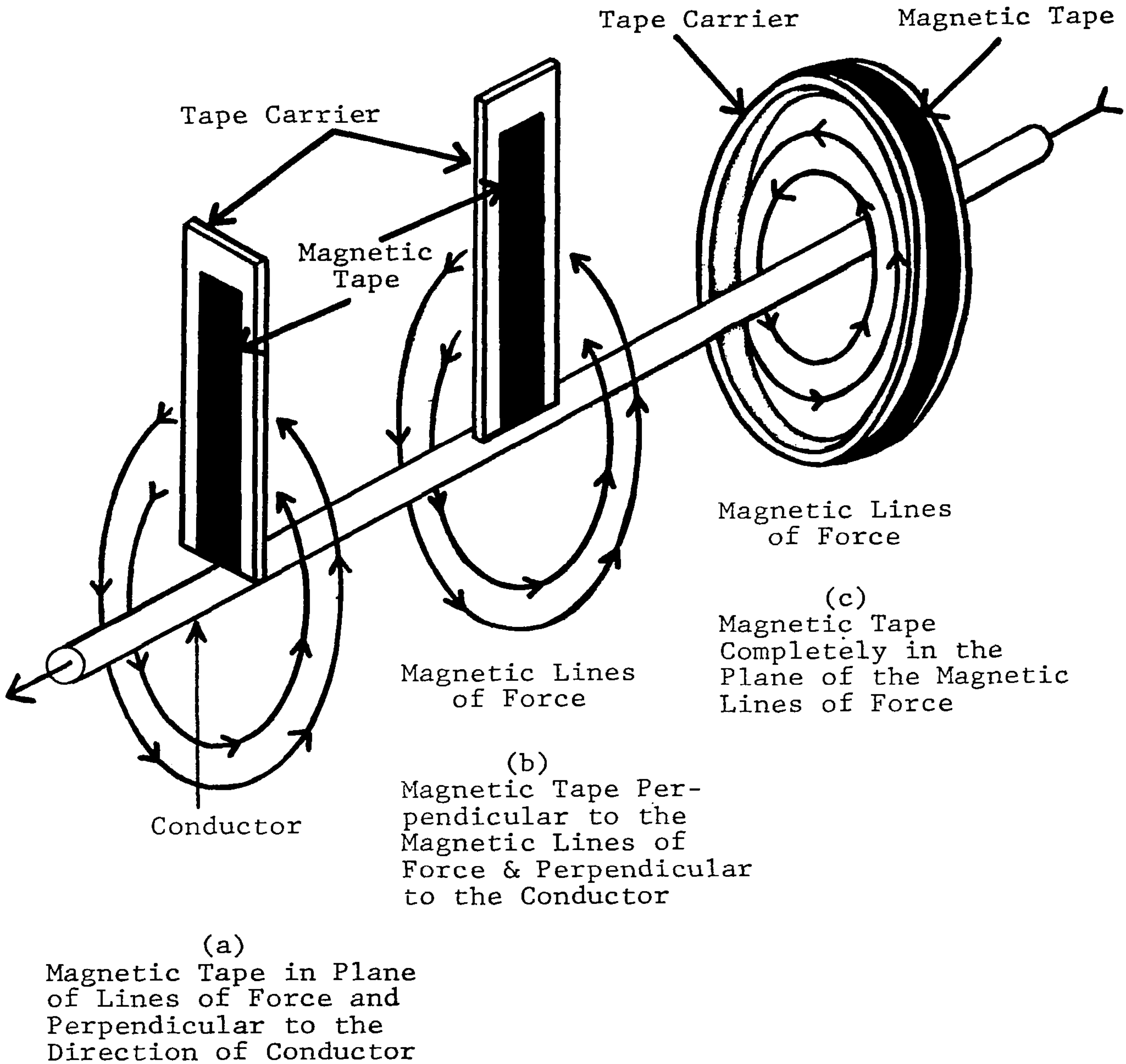


Figure 32 - Magnetic Tape Relationship to the Impressed Magnetic Lines of Force

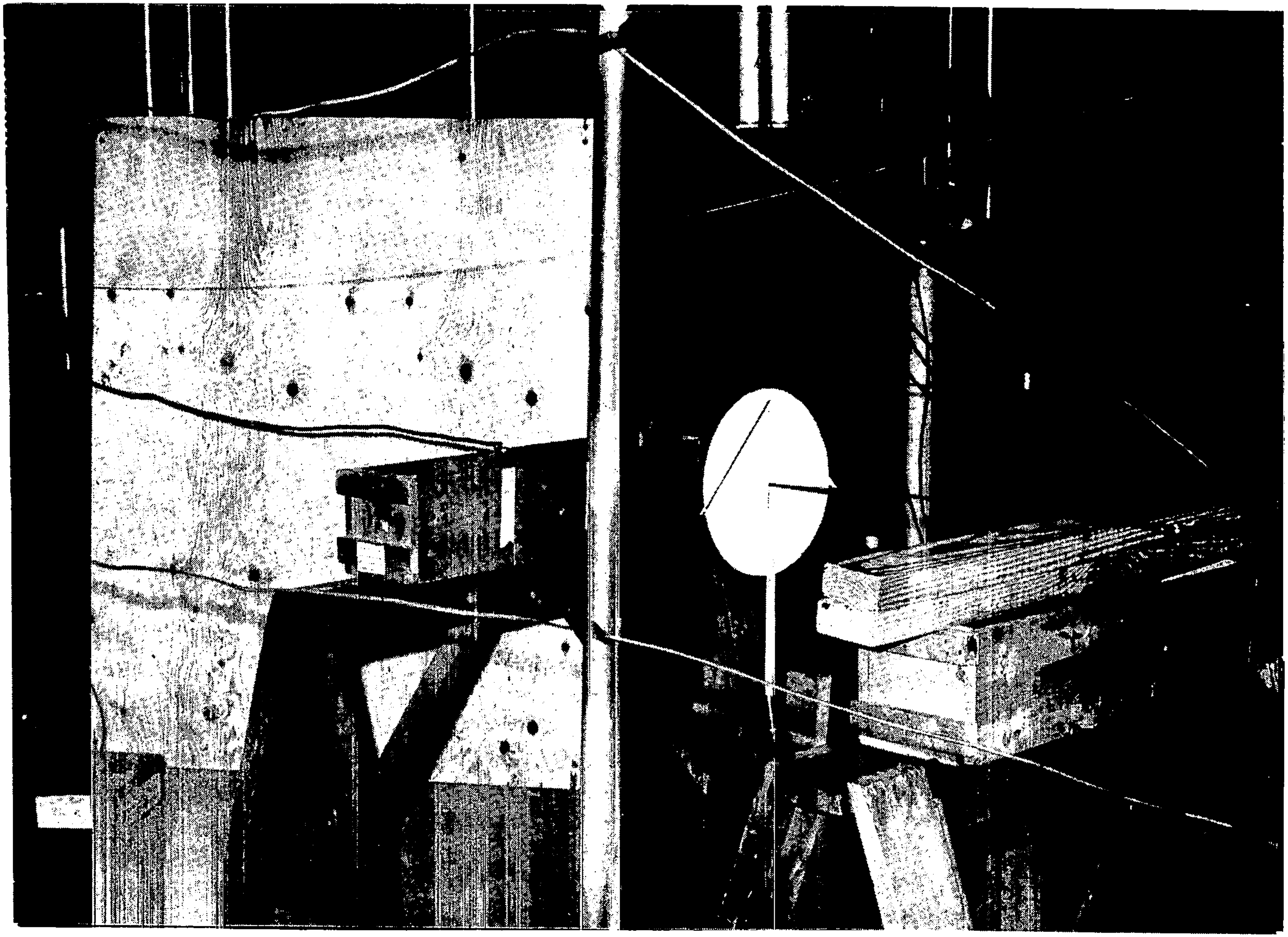


Figure 33 - Parallel Magnetic Field Exposure Test at GE HVL

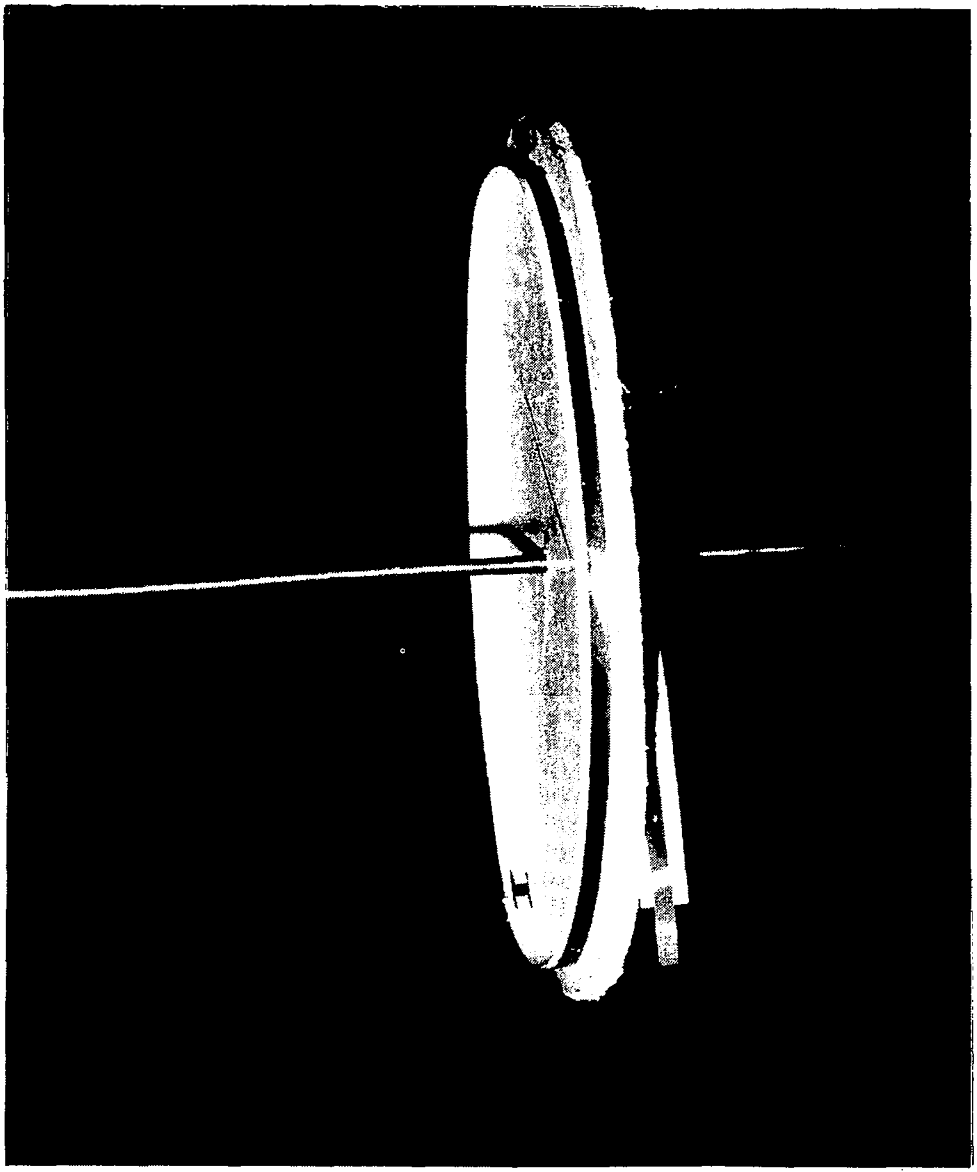


Figure 34- Circular Part of Parallel Field Tape Fixture

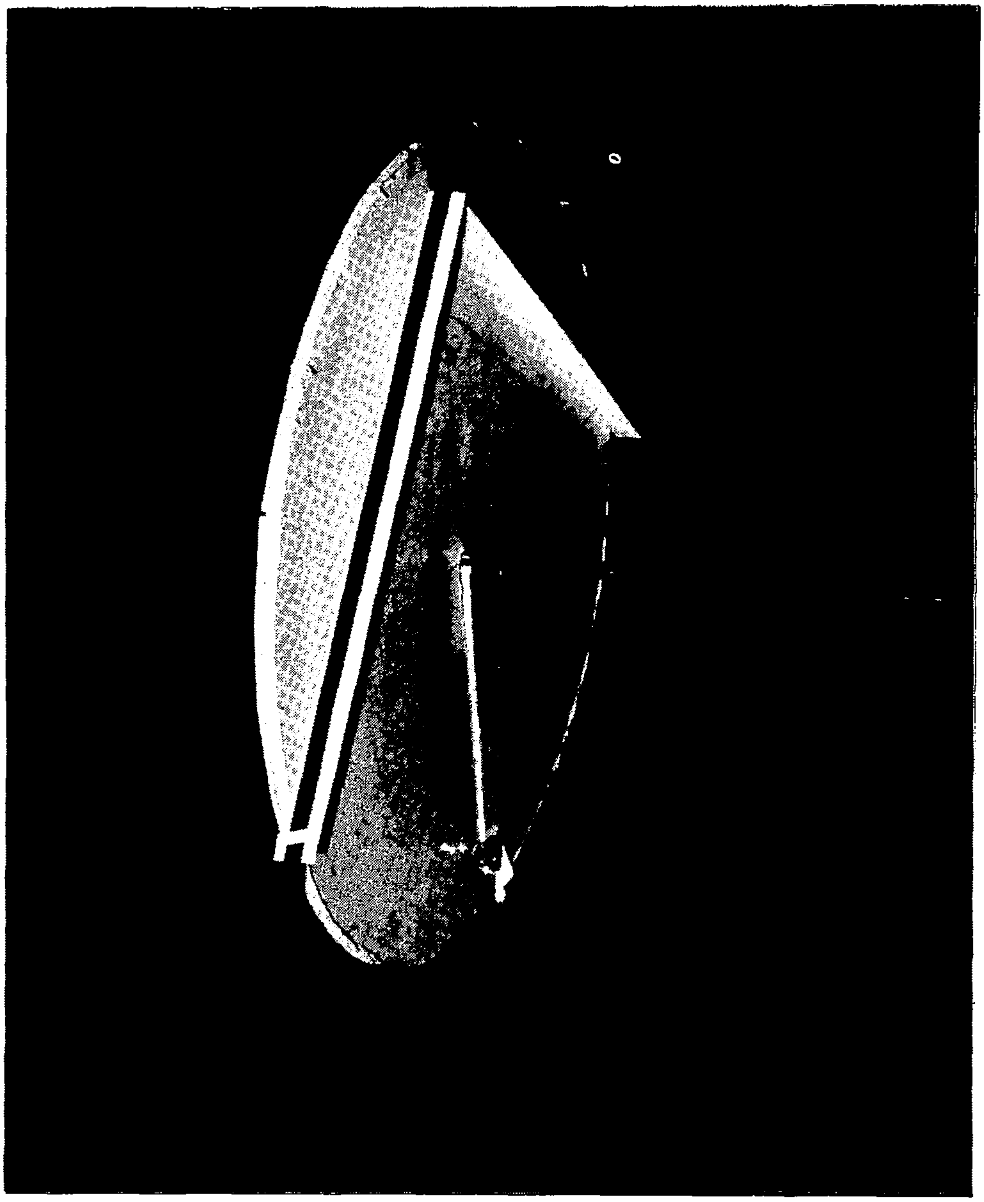


Figure 35 - Angular Part of Parallel Field Tape Fixture

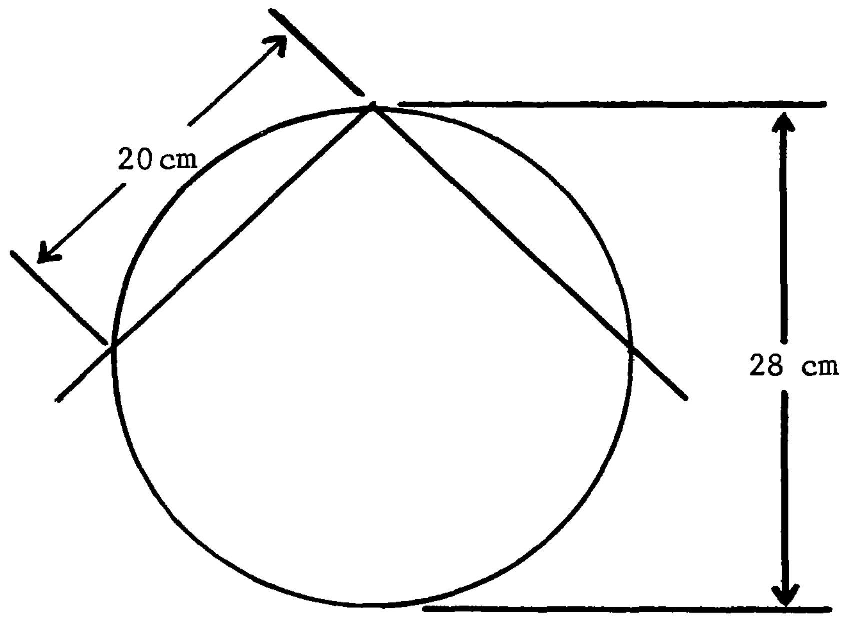
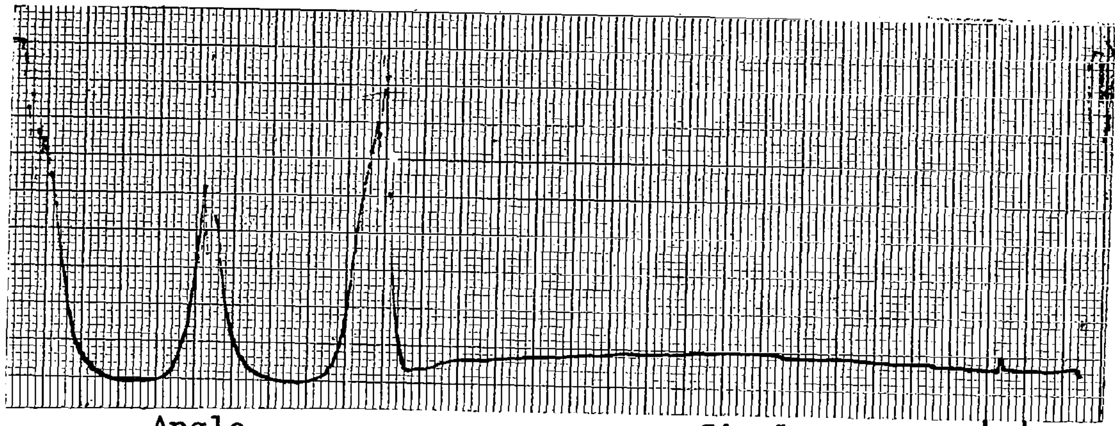


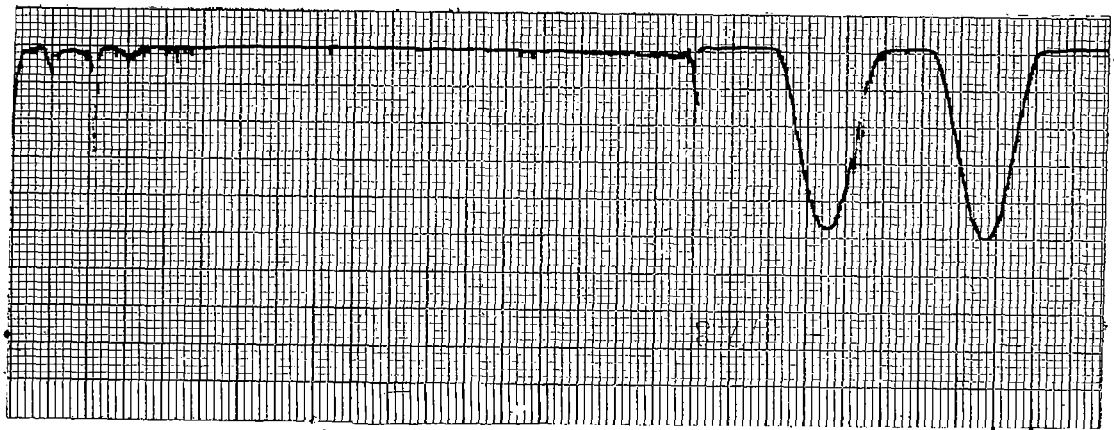
Figure 36 - Dimensions of the Tape Orientation Test Fixture

The tape orientation samples were exposed during Tests 24 through 38. Tests 24 and 25, conducted at 43 kA, caused a complete erasure of the tapes. Tests 28 through 32 were conducted at peak currents of less than 19 kA and no erasure at all resulted. Tests 26, 27, 36, 37 and 38 which were conducted at current levels of 26, 16, 16, 17.5 and 14 kA respectively, and resulted in partial erasures of the tapes. During Tests 37 and 38, Scotch tapes were also exposed. Because of the nature of the results, especially the angle data, it is very hard to express the data in descriptive numbers. Therefore, Figures 37, 38 and 39 show the strip chart data for each of these tests.

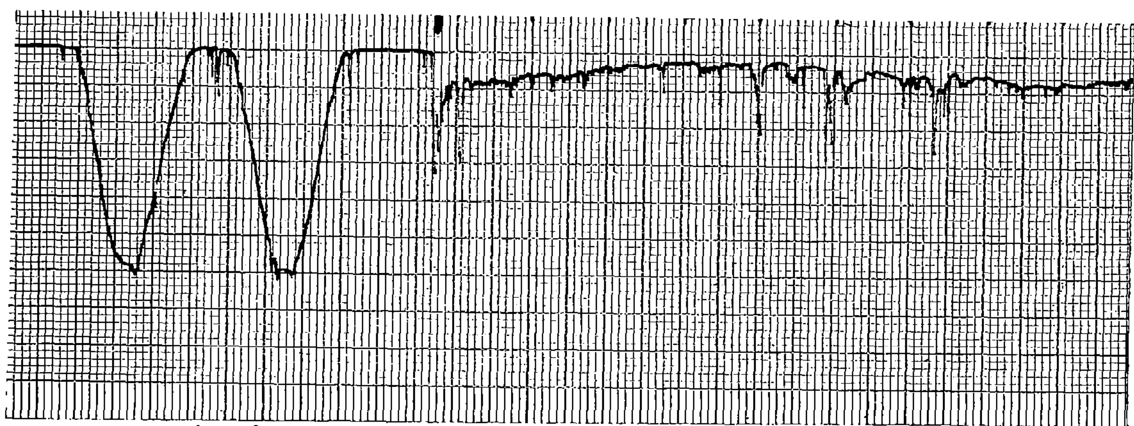
The circle shown in Figure 37, Test 26, had a 90% erasure (10% of reference signal remaining) at 26 kA. The same current level, 26 kA, will produce a 14 cm erasure (10% erased, 90% remaining) on an LCD; and the circle is 14 cm from the center of the conductor. This indicates that this tape orientation results in more erasure than in an LCD orientation. Tests 27 and 36, conducted at 16 kA, produced 5% to 10% erasures (90% reference signal remaining) of the circles and average maximum erasures of 60% in the angle tapes.



Test No. 26

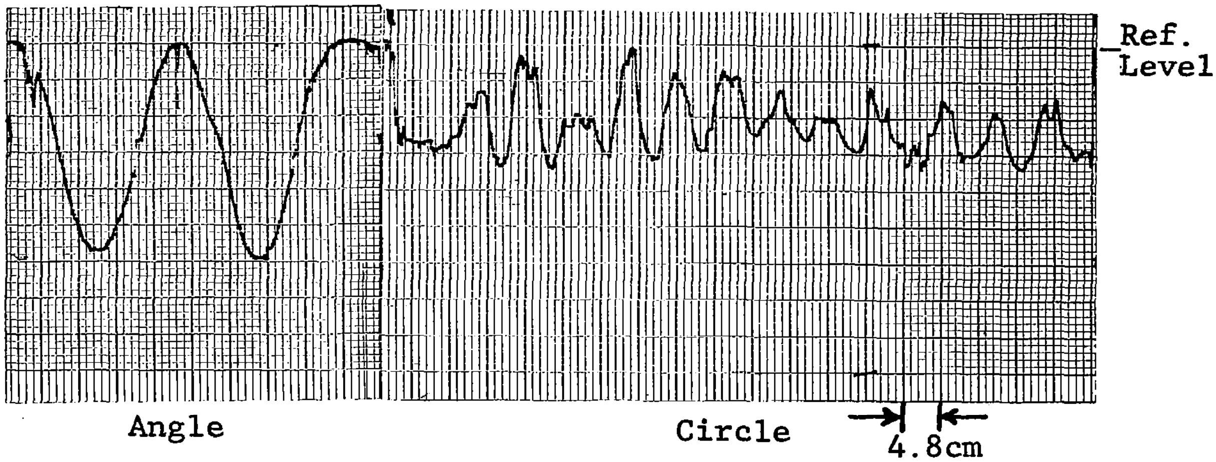


Test No. 27

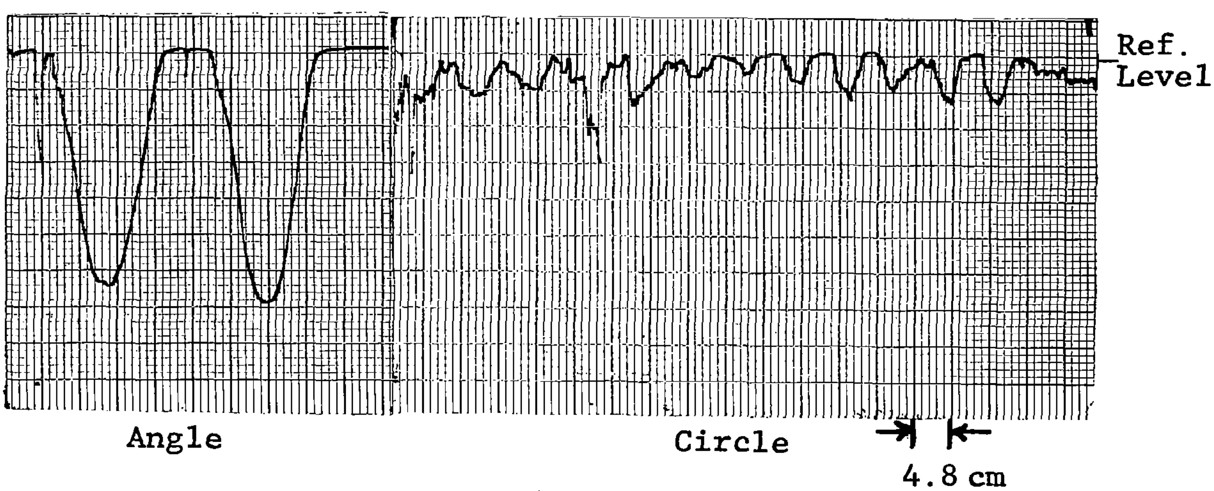


Test No. 36
Ampex Tape

Figure 37 - Tape Orientation Test Results



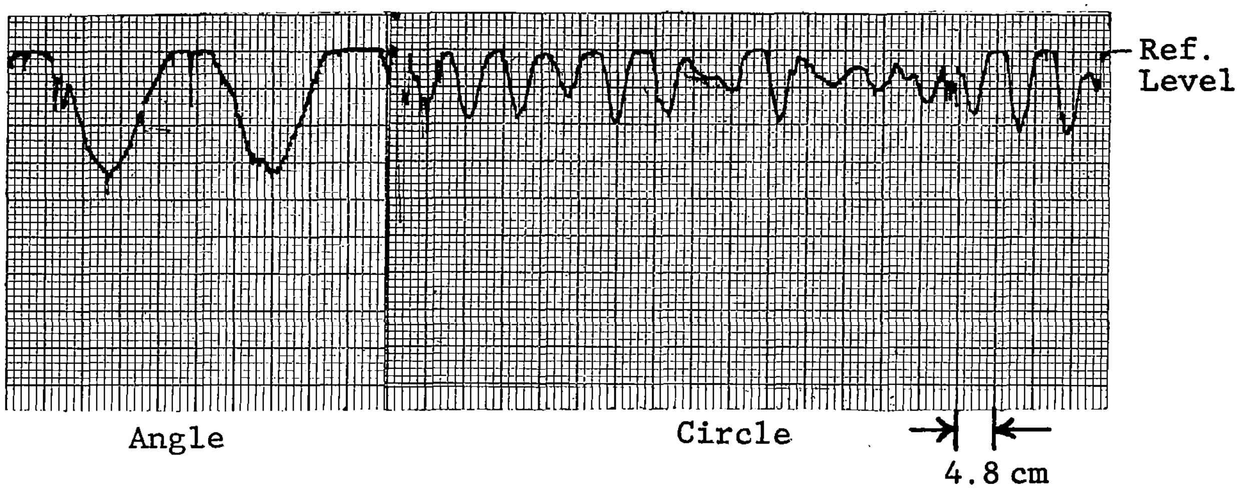
Scotch Tape



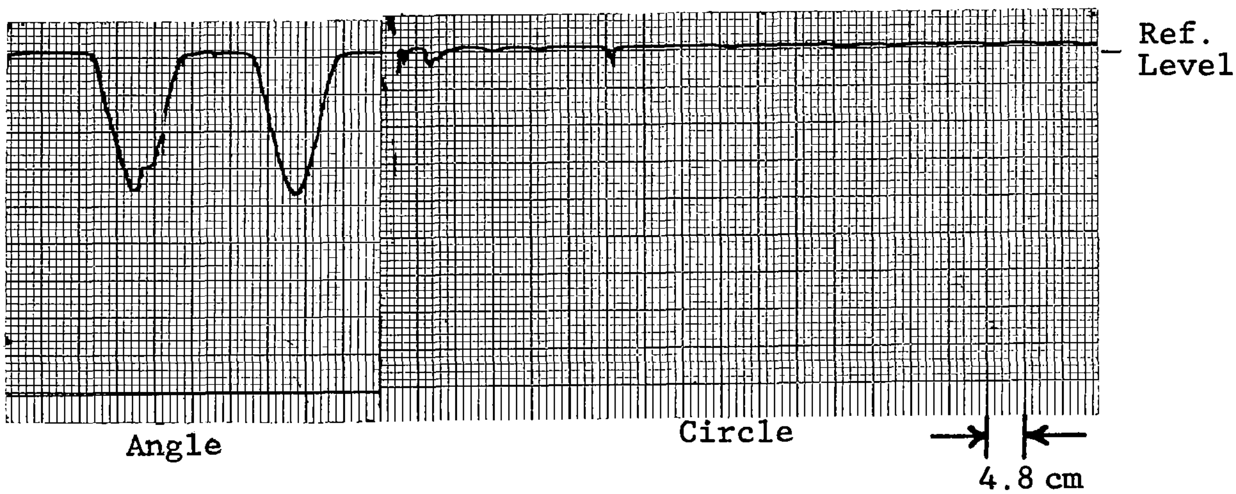
Ampex Tape

Test No. 37

Figure 38 - Tape Orientation Test Results.



Scotch Tape



Ampex Tape

Test No. 38

Figure 39 - Tape Orientation Test Results.

This current level of 16 kA will erase 10% of the signal (90% remaining) at a distance of 8.5 cm, 20% of the signal (80% remaining), at 7.6 cm and 50% of the signal (50% remaining) at 5.8 cm. Here the circle was 14 cm from the conductor and the closest point of the angle was 10 cm. Therefore, it appears that in both cases, circles and angles, more erasure resulted when tapes were oriented completely in the place of the magnetic field. As in other tests, Figures 38 and 39 show that more signal was erased on Scotch tape than Ampex tape at the same peak current levels.

There are instances where using magnetic tapes as current detectors in this orientation is desirable. Information about currents in structures where LCDs cannot be mounted, aircraft nose booms, internal pipes in towers, can be obtained by wrapping a tape around that structure. The tape would then act as a threshold detector. Depending on the size of the structure, the erasure of the tape would indicate that a certain peak current had been exceeded. For example, on a 28 cm diameter tube, currents of 16 kA will erase 10% of the signal, 26 kA will erase 90% of the signal. So reading the tape will indicate the peak current was less than 16 kA, 16-26 kA or greater than 26 kA.

To make use of magnetic tapes as current detectors in these types of applications and orientations, calibrations of the tape for each particular application will probably be required. A general calibration for circular shapes is possible and may be useful but many structures of interest will not be circular. And in many non-circular structures, an aircraft wing for example, as the current peaks increase more and more of the tape will be erased. Therefore, one tape around the wing could be used to measure a fairly wide range of currents passing through the wing.

Conductor Structural Shape Tests

Many times, measurements of lightning current magnitudes will be necessary in conductors which are not cylindrical in shape. At distances which are large (10 times) compared to the dimensions of the conductor, the magnetic field around the conductor will approach that of a cylindrical conductor. At distances closer to the conductor, the magnetic field lines will be greatly influenced by the shape of the conductor.

Tests were conducted using various structural shapes to determine how the shapes, and the sizes of those shapes, affected the length of magnetic tape signal erased.

Test Procedures

The tests were performed using magnetic Scotch reel tapes, and were run concurrent with the reel tape calibration tests. All procedures used there apply here also.

All tests were conducted in the LCD holder described in Figure 5. The 13 structural shapes tested and their standard dimensions in inches are shown in Figure 40. Figures 41, 42 and 42 show three of these shapes in the test fixture at the GE HVL.

Test Results

Test 40 through 61 were conducted at 10 kA, Tests 62 to 77 were conducted at 26 kA. These levels were chosen as representive of current levels that may exist in structural members. Most lightning strokes (50%) have peak currents of 20 kA or less while less than 1% exceed 200 kA (Ref.11). In large structures containing many members, each member may not carry more than 10% of the incident stroke, making even the 10 kA level high.

The results of the tests are shown in Table 13. From the calibration test results, 10 kA and 26.5 kA, unipolar currents should erase 6.6 cm and 17.6 cm (90% measurements) of tape signal respectively. Tests made on the 1 inch and 2 inch shapes and all pipes result in tape signal erasures that are close to the 6.6 cm and 17.6 cm values (± 1 cm) in most cases. However, Test No. 64 appears completely out of line and may have been exposed with the tape plane perpendicular to the magnetic lines of force.

The magnetic fields in the vicinity of the larger (6") structural shapes are distorted to the point that meaningful conclusions based on the tape erasure distances are not possible without some knowledge of the fields. For example, the tape strip charts for Tests 70 and 73 are shown in Figure 44. Because the LCD extended into the structural shape, the end closest to the conductor was not erased. A plot of the magnetic field (constant intensity contours) around the shape would show that the field intensity does not change linearly with radial distance. The magnetic field intensity contours

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11. Cianos, N.; Pierce, E.T.: A Ground Lightning Environment for Engineering Usage, Technical Report 1, prepared by the Standard Research Institute for the McDonnell Douglas Astronautics Co., Huntington Beach, CA August 1972 p. 65

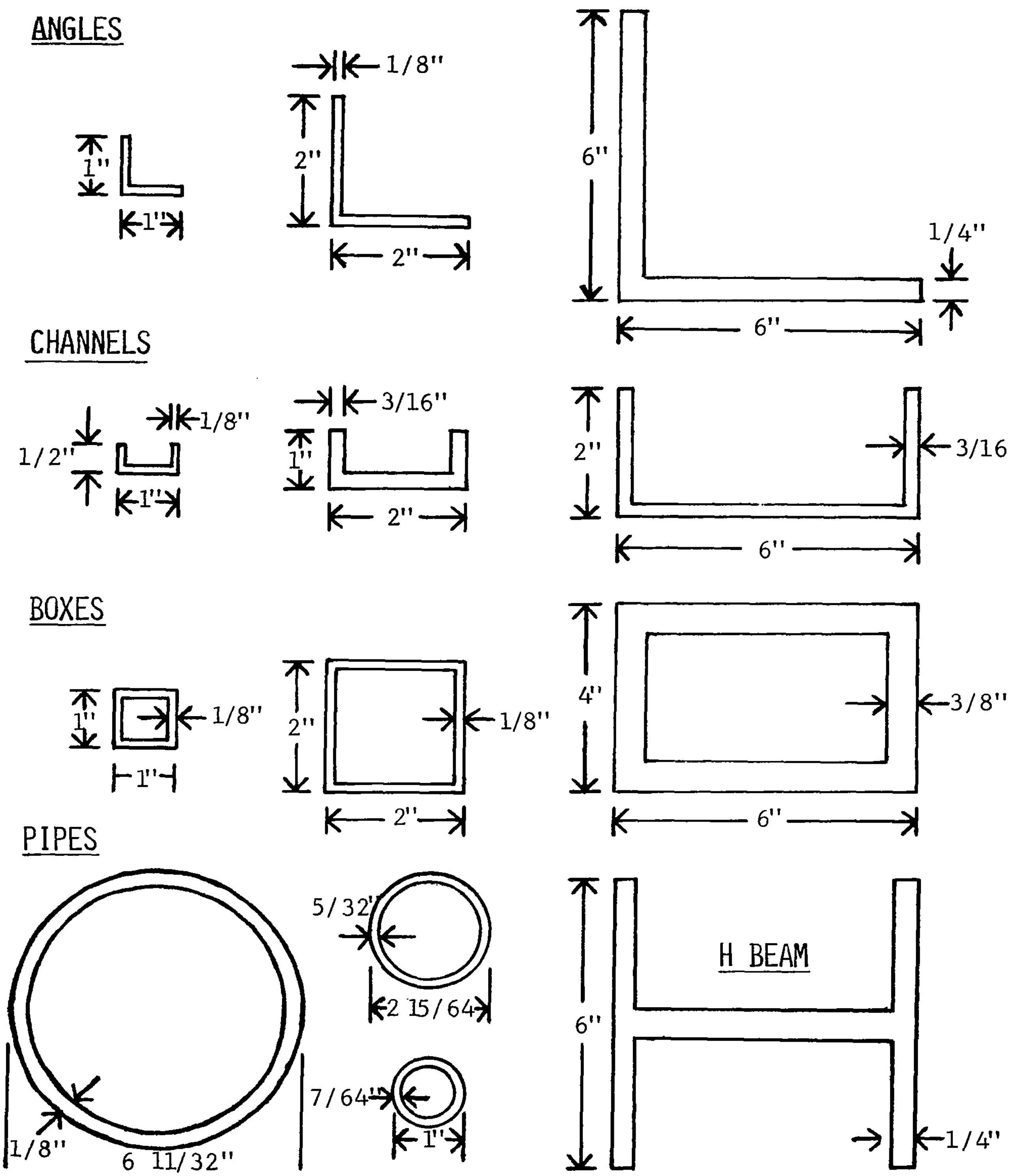

Figure 40 - Various Steel Structural Shapes
Structural Steel Shapes Tested.

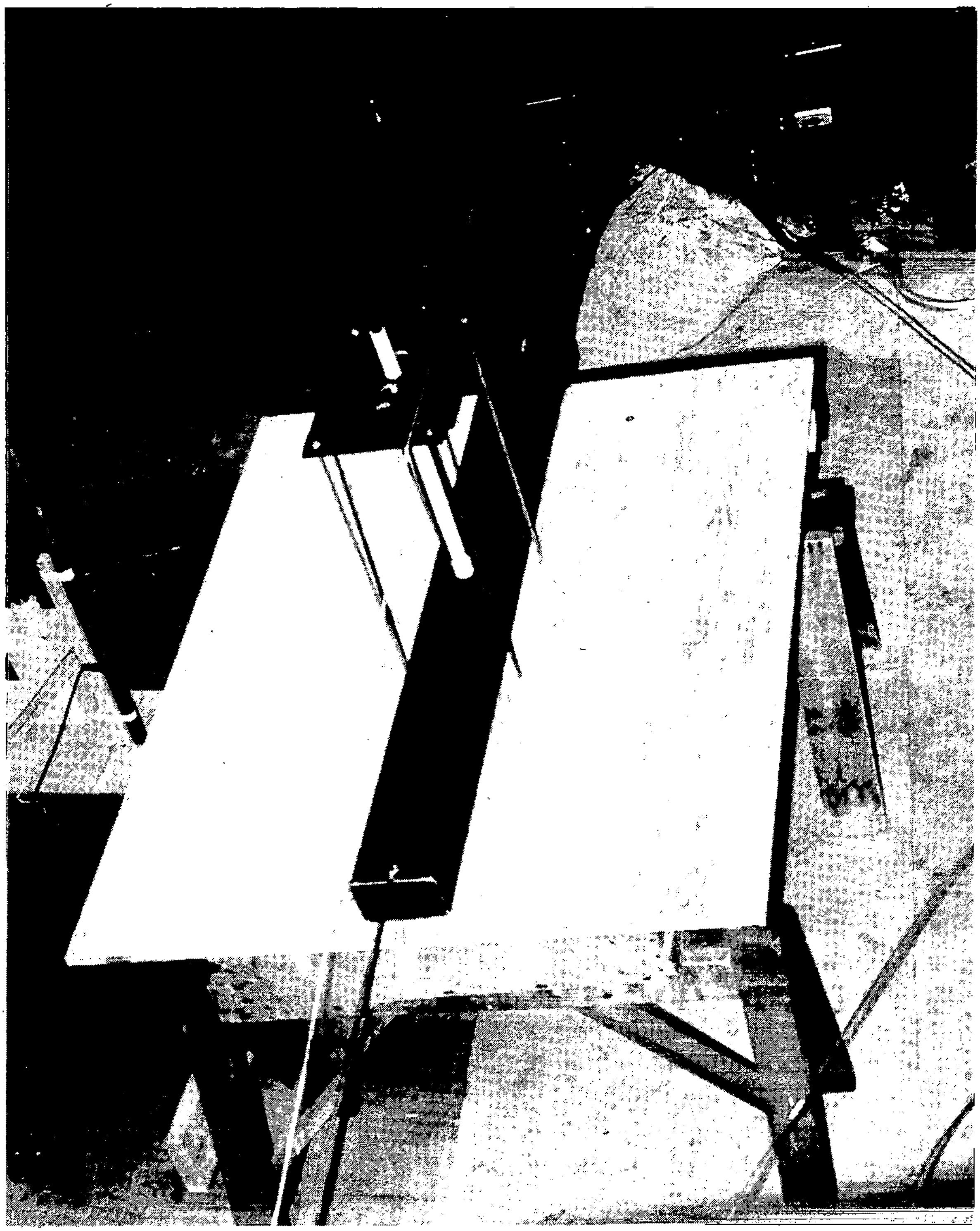

Figure 41 - Rectangular Box in Test Position at GE HVL

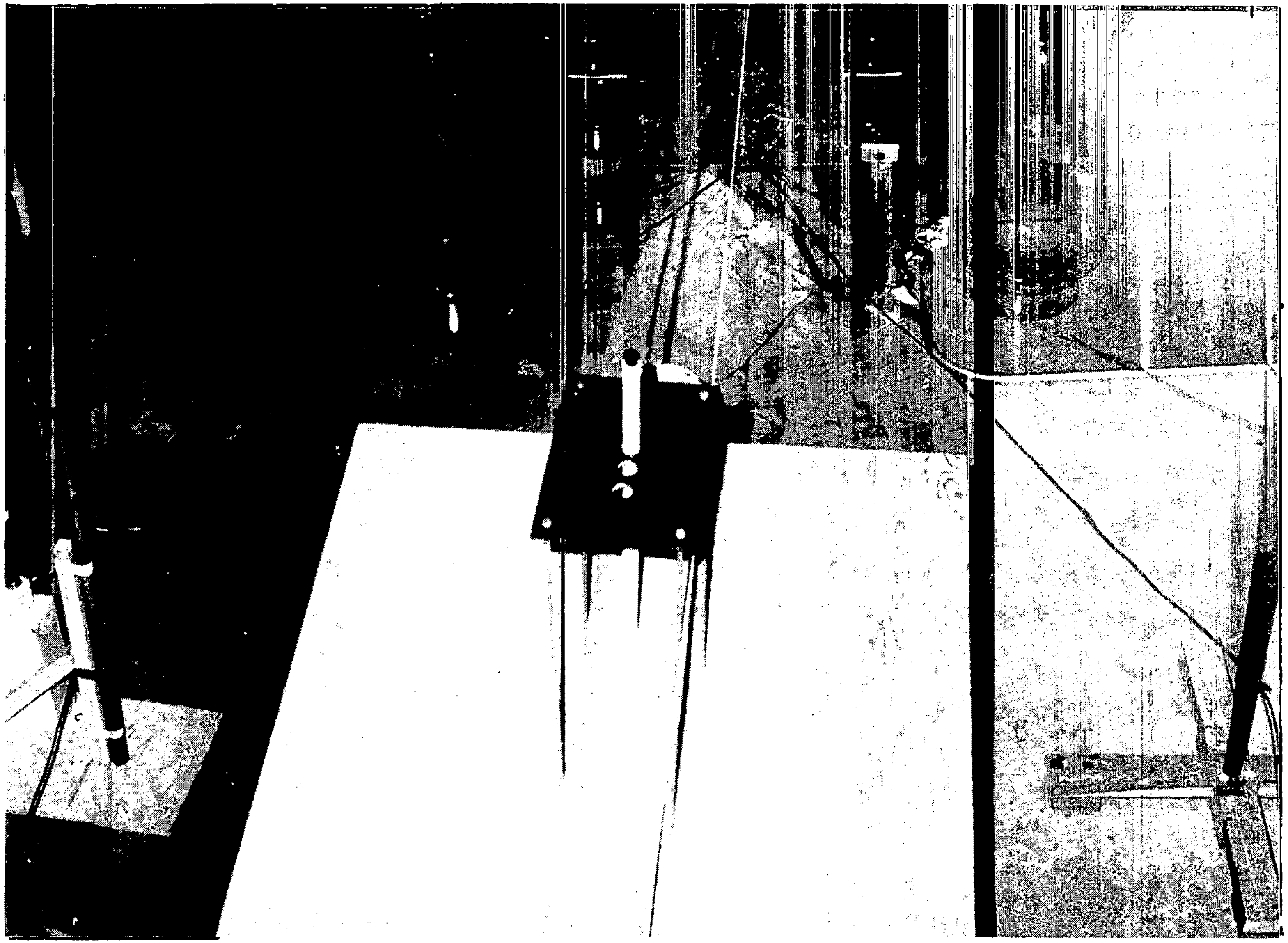

Figure 42 - Largest Diameter Pipe in Test Position at GE HVL

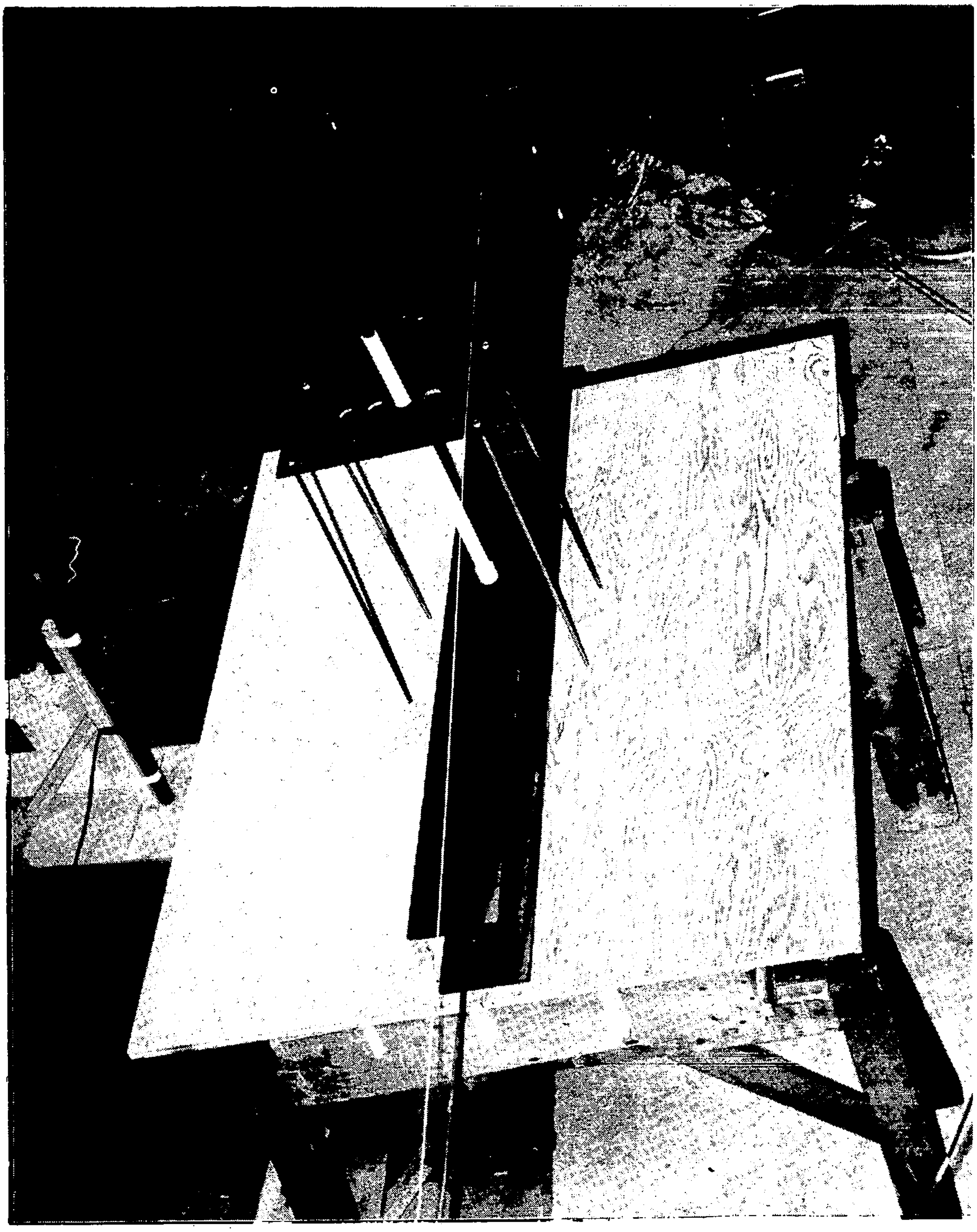

Figure 43 - H-Beam in Test Position at GE HVL

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TABLE 13

Structural Shape Test Results

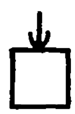
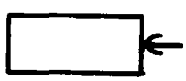
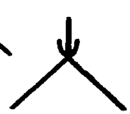
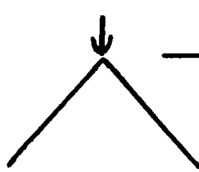
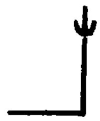
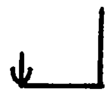
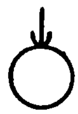
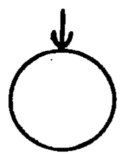
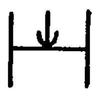
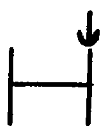
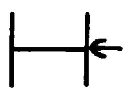
Test No.	Shape Tested	LCD Position	Length of Tape Erased at 10 kA (cm)	26.5 kA (cm)
Unipolar Simulated Lightning Test Current (5 x 18 μsec)				
40	1" channel		6.2	
41	2" channel		6.7	
42	2" channel		4.8	
43,73	6" channel		0.0	18.1
44,74	6" channel		0.95	14.3
45,72	6" channel		0.0	14.8
46	1" box		4.8	
47,64	2" box		3.6	4.5
48,65	4" x 6" box		0.0	13.8
49,66	4" x 6" box		0.0	12.4
50	1" angle		4.5	
52,68	2" angle		3.6	17.1
51,67	2" angle		3.0	16.7
55,71	6" angle		0.0	1.4

TABLE 13 (cont'd)

Structural Shape Test Results

Test No.	Shape Tested	LCD Position	10 kA (cm)	26.5 kA (cm)
Unipolar Simulated Lightning Test Current (5 x 18 μsec)				
53,69	6" angle		0.7	11.4
54,70	6" angle		0.0	22.9
56	1" pipe		4.6	
57,62	2" pipe		3.5	15.7
58,63	6" pipe		0.0	11.0
59,75	6" H-beam		0.0	0.0
60,76	6" H-beam		0.0	2.0
61,77	6" H-beam		0.0	11.9

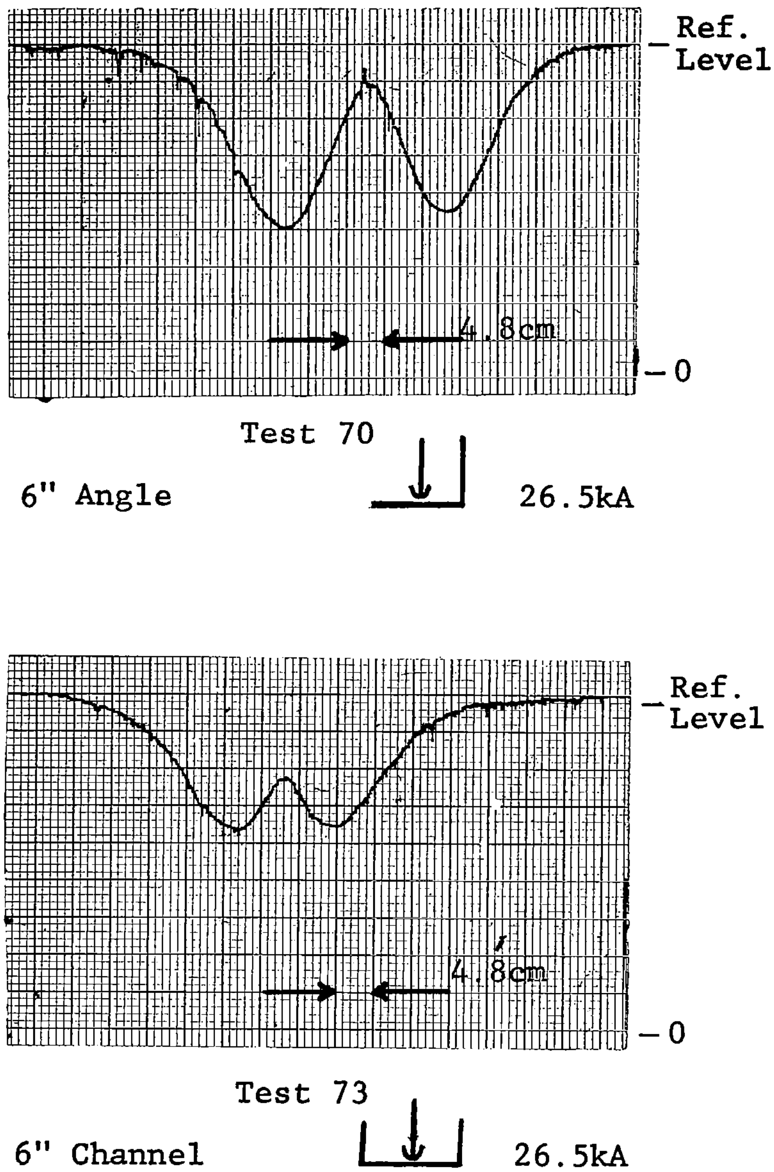


Figure 44 - Structural Shape Test Results.

can be obtained several ways. A computer program, MAGFLD, (Ref. 12) written specifically to calculate such magnetic field intensities, is suggested. By using the plots and knowing the magnetic field intensities required to erase the tapes, an analysis of the LCD readings taken next to structural shapes can be made which will give the magnitude of the current which caused the erasure.

The test results show, in cases where the rigorous analysis outlined above is not warranted, that judicious placement of the LCD can minimize errors. Always place the LCD on an outside corner, i.e. the apex of the angle iron, back side of the channel or the flat side of the H-beam. Also, the maximum dimensions of the structure usually denote the minimum current detectable, i.e. 6" member cannot detect current of less than ~12 kA.

Flashbulb Sensor Calibration Tests

When an LCD with a reel type tape is used to monitor an unobserved structure, the tape must be read to determine if a lightning stroke has occurred. Since reading an unexposed tape represents lost effort, NASA-KSC developed a flashbulb current sensor to detect when a stroke occurred at an unattended location.

The flashbulb current sensor is basically a toroidal coil of wire positioned around the conductor being monitored. The ends of the coil are connected to a photo flashbulb. When a lightning current passes through the conductor, the changing magnetic field passes through the coil of wire and induces voltages and currents in it. When sufficient energy has been delivered to the flashbulb to ignite the element, the bulb fires. The present study was conducted to determine the peak current required to fire the flashbulb.

Test Procedures

The tests were conducted concurrent with the cassette tape calibration tests. The test circuit and current waveshapes reported there apply here.

Two coils and two types of flashbulbs were tested. The coils, supplied by NASA-KSC, were constructed by wrapping 16 and 31 turns of AWG #20 wire around a core of 0.95 cm diameter

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12. Fisher, F.A., Plumer, J.A. "Lightning Protection of Aircraft", NASA Reference Publ. 1008 Oct. 1977 pp. 269-291

tygon tubing. The coils are made into toroids by connecting the two ends together with a flexible plastic plug. The average coil diameter is 5 cm. The flashbulbs used were M3 and bulbs removed from a Sylvania Blue Dot Flashbar.

The tests were conducted by applying repeated current pulses to the conductor. Each succeeding pulse had a higher crest current, until the flashbulb fired. Five flashbar bulbs each were tested on the 31 and the 16 turn coils. The M3 bulbs were tested on the 31 turn coil.

Test Results

A summary of the results is given in Table 14. The bulbs, when tested on the 12 x 43 μs, unipolar current, exhibited a 2 to 1 firing range. Approximately twice the peak current was required to fire the bulbs using a 16 turn coil (11 kA) as with the 31 turn coil (7 kA). Both bulb types, flashbar and M3, fired in the same peak current range.

TABLE 14

Flashbulb Current Sensor Calibration Data

Peak Current in Kiloamperes

Bulb Type	Bulb Resist. Ohms	16 Turn Coil Withstood	16 Turn Coil Fired	Bulb Resist. Ohms	31 Turn Coil Withstood	31 Turn Coil Fired
Unipolar Simulated Lightning Current (12 x 43 μsec)						
Flash Bar	0.9	12.0	12.8		3.3	4.8
"	0.7	9.3	10.3	0.5	10	11
"	0.8		8.5	0.9	4.2	4.8
"	0.8	11.1	12.0	0.9	4.8	5.2
"	1.1	9.3	10.3	1.1	6.6	7.2
Average			10.8			6.6
Standard Deviation			1.7			2.6
M 3				0.8	6.6	7.4
"				0.7	4.8	5.6

The open circuit voltage induced in the flashbulb sensor coil will be a function of the number of turns, the area enclosed by 1 turn, and the rate of change of the lightning current. The current delivered to the flashbulb will be a function of the open circuit voltage, the coil self-inductance, and the bulb resistance (itself a function of temperature).

When sufficient energy has been deposited in the bulb to ignite the element, the bulb fires.

In the present tests, reducing the number of turns in the coil increased the peak simulated lightning current required to fire the bulb. This leads to the conclusion that, for coils of ~ 30 turns, the self inductance of the coil is small and not restricting the circuit current. This means that the sensor sensitivity can be increased by using more turns. In other words, the flashbulb will fire at lower peak currents if more turns are added to the coil. There will be a point at which the self inductance of the coil will become large and adding further turns will not increase the sensitivity and may even decrease it.

The other variable in the flashbulb sensor circuit is the lightning current rate of change, di/dt. If the rate of change is reduced, the induced voltage is reduced and length of time the rate of change must be applied to fire the bulb increases. Therefore, the peak lightning current required to fire the bulb will be higher. Consequently, if the lightning current wave had a rate-of-rise double that used for these tests, the sensor may fire as low as 1/2 of the peak required here. The flashbulb sensor is waveform sensitive, but the exact extent of sensitivity would require more tests to determine. However, lightning current waveforms vary considerably so optimization of the sensor would not be practical.

Magnetic Link Tests

Magnetic links have been in use for many years and are installed at NASA-KSC launch facilities as backup current detectors. A direct comparison of data taken using magnetic links and LCD tapes on the same test was desired.

Test Procedures

During Tests 102, 103, 104 and 105, magnetic links were positioned at 5, 10 and 24 inches from the AWG #14 wire in the test fixture at Lightning Technologies high current laboratory. These tests were run concurrent with cassette tape calibration tests. The test procedures and currents used there, apply here.

After exposure, the magnetic links were measured using a ballistic galvanometer (Uni-Galv Model 35-010, Colman Instruments Inc., Maywood, IL) and a reading fixture. The equipment was obtained from the GE HVL and was not on a calibration schedule. The links were then shipped to NASA-KSC for reading. The Lightning Technologies, Inc. measurements were made to insure that no major changes occurred in the links during shipment.

Test Results

The magnetic link readings are summarized in Table 15. The Lightning Technologies, Inc. galvanometer readings are listed for reference only. The NASA-KSC readings were used to determine the peak currents listed.

The magnetic link data ranges from 20% to 40% higher than the actual peaks.

TABLE 15

Summary of Magnetic Link Data

Test No.	Peak Current kA	Galvanometer Readings: Lightning Technologies, Inc. 5"	10"	24"	NASA 5"	10"	24"	NASA Corresponding Currents kA		
Unipolar Simulated Peak Lightning Currents (12 x 43 μsec)										
102	5.4	43	5.5	1.5	40	5	2	7.2	6.3	12
103	9.9	153	31	3.5	125	26	2	12	12	12
104	14.2	240	94	7.5	200	80	6	19	20	16
105	23.0	260	186	25	230	160	22	29	29	26

APPENDIX

PROCEDURE FOR RECORDING/TESTING LCD REFERENCE SIGNAL

S.P. CLYATT

NASA-KSC

May 1979

INTRODUCTION

This document establishes the procedure to be used to record reference levels on Scotch and Ampex Grand Master tapes used in LCD calibration tests. The recordings will be made using either an Ampex 1160 or a Wollensak 524 tape recorder.

Calibration tests on LCD's containing these two tapes using laboratory simulated lightning currents will verify what, if any, difference in calibration factor exist between tape formulations. Both tapes will have identical reference signals recorded on them.

All reference signals recorded will be related to the signal level on a standard alignment tape. An alignment tape is a high quality, commercially available tape which has a 700 Hz signal recorded at flux density of 185 10^{-9} W/m. Using the alignment tape as a standard reference signal will be recorded on test tapes at multiples or fractions of its level. The maximum level that can be recorded without distortion or clipping will also be established through the use of the following procedures.

LEVEL SELECTION

1. Turn on Ampex recorder, as well as Fluke Voltmeter, and allow a five minute warm-up.

2. Play the level alignment tape through the Ampex recorder at 7 1/2 ips.

3. Record from the voltmeter in Table 1 each volume setting and its voltage (RMS) output.

4. Select the standard reference level from Table 1 as volume level 8 and record this voltage in Table 2.

5. Determine mathematically the percent voltages from standard voltage and record in Table 2.

6. Determine experimentally for each type tape, the recorder volume setting for each playback level and record in Table 2.

NOTE: The reference signal playback volume setting must be the same as the alignment setting in order that the output voltages reflect relative amounts of induced flux on each of the test tapes. When recording the reference signals, the record levels were experimentally determined, i.e., if the voltage upon playback was too high, then the signal generator output level setting during recording was lowered, etc.

TAPE GENERATION

1. Set recorder to 7 1/2 ips playing speed setting.

2. Set audio generator to 700 Hz with an output of 7 volts p.p. (2.48 V. RMS).

NOTE: As generator warms up fluctuations may occur in the output voltage. A check of the output is necessary before and during the recording of any signal.

3. Record approximately 100' of each type tape at each level listed in Table 2.

4. Adjust signal generator setting as needed to record proper input voltage.

5. Repeat previous steps (3 and 4) for over 100' of standard level, 100% signal for both type tapes.

6. Adjust volume setting for maximum signal level without distortion.

7. Record 50' of signal at maximum level.

8. Verify each length of tape for signal continuity.

9. Place each tape type on a roll where each signal level is clearly labeled.

SIGNAL VERIFICATION

1. Each tape should be verified by playing each signal and observe fluctuations not to exceed $\pm$ 50 mV.

2. Splice blank lengths of tape ($\sim$4') between lengths ($\sim$4') of each signal tape.

3. Playback tape through filter and to input of strip chart recorder, set at 20 min/sec and .2 V/mm.

4. Observe signal level changes which appear following blank tapes.

NOTE: The strip chart data is for reference signal levels following calibration. This verifies operation of filter, strip chart recorder and reveals signal characteristics for each level.

VOLUME SETTING	PLAYBACK VOLTAGE	
	PEAK TO PEAK	RMS
1	0.014	0.005
2	0.099	0.035
3	0.39	0.138
4	0.625	0.221
5	1.03	0.365
6	1.55	0.549
7	3.45	1.22
8	7.6	2.62
9	13.2	4.66
10	15.4	5.45

TABLE 1

LEVEL (%)	PLAYBACK VOLTAGE		RECORDER VOL. SETTING	
	PEAK TO PEAK	RM	SCOTCH	AMPEX
30	2.3	0.8	2.8	2.5
50	4.4	1.57	3.9	3.1
80	5.7	2.03	4.4	3.8
100	7.6	2.62	4.9	4.2
150	11.8	4.17	6.0	5.2
MAX. W/O DISTORTION	AMPEX - 25 SCOTCH 267	AMPEX 8.02 SCOTCH 9.44	7.5	6.9
NOTE: Generator Frequency-700HZ with 7V.p.p.output Recorder Speed - 7 1/2 ips Playback Volume Level 8.				

TABLE 2

1. Report No. NASA CR-3270	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CALIBRATION TESTS ON MAGNETIC TAPE LIGHTNING CURRENT DETECTORS		5. Report Date April 1980
		6. Performing Organization Code LTI
7. Author(s) K. E. Crouch		8. Performing Organization Report No. LT-79-51
9. Performing Organization Name and Address Lightning Technologies, Inc. 560 Hubbard Avenue Pittsfield, Massachusetts 01201		10. Work Unit No.
		11. Contract or Grant No. CC82279A
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code NASA KSC VO-A
15. Supplementary Notes Kennedy Technical Monitor: W. Jafferis		

16. Abstract

Development and application tests of a low cost, passive, peak lightning current detector (LCD) found it to provide measurements with accuracies of ±5% to ±10% depending on the readout method employed. The LCD, which was invented at the NASA/Kennedy Space Center, uses magnetic audio recording tape to sense the magnitude of the peak magnetic field around a conductor carrying lightning currents. The test results showed that the length of audio tape erased was linearly related to the peak simulated lightning currents in a round conductor. Accuracies of ±10% were shown for measurements made using a stopwatch readout technique to determine the amount of tape erased by the lightning current. The stopwatch technique is a simple, low cost means of obtaining LCD readouts and can be used in the field to obtain immediate results. Where more accurate data are desired, the tape is played and the output recorded on a strip chart, oscilloscope, or some other means so that measurements can be made on that recording. Conductor dimensions, tape holder dimensions, and tape formulation must also be considered to obtain a more accurate result. If the shape of the conductor is other than circular (i.e., angle, channel, H-beam) an analysis of the magnetic field is required to use an LCD, especially at low current levels.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Lightning Peak current measurement Magnetic tape Peak magnetic field	Unclassified - Unlimited Subject Category 35

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