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DEVELOPMENT OF A LOW COST EMP PROTECTION CONCEPT FOR EMERGENCY --ETC(U)
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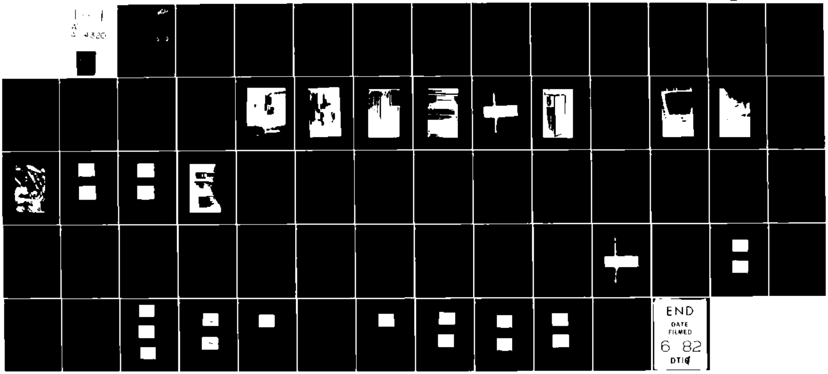

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Electromagnetic pulse (EMP) shielding, isolation, and protection for emergency operations center type communications equipments has been reduced to a minimum size and cost through development testing, utilizing a concept of shielding, single entry, and in-line transient voltage protection. Shielding for direct induced EMP is balanced against protectors for direct connected EMP to result in EMP voltages at equipment input connections on the order of 5 to 10 volts peak with simulated EMP fields on the order of 10 kV/m and direct connected EMP of thousands of volts peak.

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CONTENTS

GENERAL DISCUSSION

The need exists to provide improved survivability for a large number of Federal Emergency Management Agency (FEMA) host and non-risk area county, and local Emergency Operations Centers (EOCs) from the electromagnetic pulse (EMPs) effects of nuclear attack. EMP protection for these EOCs should assure the continued operation, electrically, of emergency power systems and their controls, life support equipments and communications equipments during and subsequent to the effects of high altitude EMP. All of the blast hardened Federal Regional Centers have had extensive EMP protection installed, including large, ferrous-metal shielded enclosures containing the communications equipments. The majority of state EOCs have had EMP protection system retrofits installed which included small bolted metal shielded enclosures ranging in size from 8 x 8 feet to 12 x 20 feet for selected communications equipments, and with EMP transient limiting protectors installed on the individual susceptible life support equipment components on a single point failure analysis or point by point basis.

The cost of EMP protection retrofits is dominated by the cost of the shielded enclosure, purchase and installation. The state EOC EMP installation costs were an order of magnitude less than those for the Federal Centers, partially because shielded floor space requirements were smaller, but also because they used a standard design package concept and a single purchase contract for a large number of units. Similar cost savings were realized in large quantity purchase, using a standardized list of EMP transient limiting protectors, shielding and grounding devices. Engineering and installation for state EOCs was also performed on a repetitive basis for the EMP retrofits, with sufficient flexibility to allow for a range of shielded enclosure sizes, varying building modification requirements and a wide range of types and vintages of life support equipments.

The final step in reducing further the EMP retrofit costs for communications systems is to reduce the shielded enclosure size to the bare minimum where it can be accommodated in existing spaces without modifications while still providing the necessary EMP shielding of communications equipments, and the required controlled routing and EMP protection of connecting conductors and cables for power, signal and control functions.

THREAT

The major EMP threat for EOCs located out of direct nuclear target areas is from high ltitude (HEMP). HEMP will probably be the result of a deliberate enemy action exploding one or more nuclear weapons in the atmosphere above 100 kilometers in altitude over the continental United States for the specific purpose of disrupting power and communications on a broad scale. The confusion and loss of communication which would result would be utilized ostensibly to cover up further planned immediate offensive military actions. High altitude nuclear explosions rapidly ionize the upper atmosphere in such a fashion as to generate an electromagnetic pulse which is then radiated to line of sight surface areas on the earth. The EMP which would be generated would appear simultaneously at the earth's surface as a far-field plane wave, double-exponential impulse with a rise time on the order of 10^{-8} seconds (ten nanoseconds) and a decay to half value on the order of 10^{-7} (one hundred nanoseconds). These times will vary some depending on direction from the burst.

The electric field magnitude of EMP incident over a broad area at the earth's surface will vary from a maximum of 50 KV/meter horizontally polarized and 15 KV/meter vertically polarized depending on direction from the burst. Metal conductors illuminated by HEMP will act as antennas and the resulting induced EMP voltages and currents will probably be destructive to any connected susceptible electrical components not otherwise protected with electromagnetic shielding or transient voltage protection. The effect of the short time duration, large magnitude radiated EMP is to induce exponentially damped sinusoidal currents in illuminated conductors at their characteristic half-wave resonant frequencies and corresponding harmonics.

Conductors longer than a meter will typically experience thousands of peak volts or greater. Conductors typical of power service connections to low voltage power distribution transformers will receive hundreds of thousands of peak volts (thousands of peak amperes). Distribution lines will experience millions of peak volts until arc-overs and faulting occur at connections and components. These will trip distribution breakers, damage power system supervisory and control systems and cause power outages. Emergency power systems are expected to be damaged during EMP so that they will not be available for emergency power, unless EMP protection is provided.

In addition to damaging EMP directly induced on metal conductors and cables, and on electrical circuits in equipment cabinets, there is a secondary induced EMP conducted along long conductors exposed to EMP which then run near or which are connected directly to susceptible electronic circuits.

The more recently developed families of solid state electronic equipments, are extremely susceptible to transient voltages. Even the static voltages, resulting from human body contacts, are sufficient to destroy many of the newer circuit board components. Special handling procedures, coatings and shielding have become necessary to protect these newer equipments during normal handling, packaging and shipping, installation, maintenance and repair functions. Survival during EMP of such equipments will require elaborate electromagnetic shielding, grounding, transient isolation and protection designs.

EMP PROTECTION DESIGN APPROACH

The first assumption necessary for the success of the low cost approach to EOC communications equipment EMP protection described in this report is that the total numbers of equipments requiring protection is minimal and that it is possible to make their interconnections simple and straightforward. The equipment to be protected is preferably rack mountable within one to several standard size rf shielded electronic equipment cabinets (22" x 26" x 72" typical). One metal panel will be utilized as a single entry into the protected system of all external electrical connections, including power, antenna, telephone, signal and remote control functions. This single entry panel will be either an isolated 4 x 8 metal panel, or it will be the outer wall of one shielded metal equipment cabinet. The purpose of a single entry panel is to provide a first point of control and protection with EMP voltage limiting devices on all entering conductors. It also provides the controlled entry point into the hub of a system of electromagnetic shielding consisting of shielded equipment cabinets, connected ferrous conduits and signal and antenna cable shields. It further establishes a radio frequency counterpoise against which all system EMP induced voltages in contained wiring may be referenced as common mode transients and brought under control of common mode voltage limiting protectors. It also provides for a shielding system of interconnected cabinets devoid of loops. Further advantages of the protection system will be the development of a standard package and module concept for ease of engineering, design and installation. It will also provide for lower cost quantity purchase of protectors and shielding materials.

The previously developed standard package single entry panel and bolted shielded enclosure concept used for state emergency operation centers has been modified to reduce the size and cost of the required shielded enclosures to a minimum, while still retaining the control and shielding necessary for equipment survival.

Success of this entry panel, conduit and shielded equipment cabinet approach depends on a combination of shielding against direct radiated EMP and control and limiting of secondary EMP conducted to the entry panel by connected power, signal and control conductors and antenna cable shields.

Some EOC communications equipments which cannot be reasonably operated from installations within the standard enclosures, but which are necessary for system operation, such as remote control units, remote transmitters or equipments too large for cabinet rack mounting will be treated on an individual basis with EMP protectors and shielding measures as necessary within the scope of available funding and engineering support capabilities. This also will include EMP protection for life support equipments which must be treated on an individual basis, but with a standard single point failure analysis approach such as was utilized in EMP protection at state EOC's.

SINGLE ENTRY PANEL

The significant features of the entry panel seen in Figure 1, are the terminal blocks and grounding strip used to install EMP protectors, seen in the signal entry box, Figure 2, lower left, and in close-up in Figure 3. External run shielded signal cables enter the box from the rf cable tray on the upper left and individual cable pair shields are connected to the grounding strip in the center of the box. From here, the pairs are terminated on terminal block connections to the left and right. Here EMP protectors, which may include metal oxide varistors (MOV's), gas gaps, bi-polar zeners and diode pairs are installed between terminal block connections for each conductor and the ground strip with minimized protector lead lengths. Three terminal block connections are utilized for each shielded pair, with the shield carried through on one connection. The pairs then exit to the junction box on the upper right where they enter ferrous conduits for the run to the equipment cabinets.

The single entry panel features will include a two-pole power filter for single phase 120 volt ac power entry, a shielded signal cable entry box, and a shielded antenna cable entry box. Single phase, 208/120 volt ac power connection will require a three-pole filter.

Power conductors enter the junction box upper right of Figure 2, from a short section of conduit and enter the top of the two filters and are connected to the unprotected end. The protected power feeds through the entry panel into the power breaker panel. The power circuit ground conductor is fed through the junction box directly into the power breaker panel on the back by means of a ground stud connected electrically to the entry panel. Antenna cables feed through the entry panel by means of panel jacks seen in the box on the right of Figure 1, where coaxial tee EMP protectors are installed on the antenna cables.

EMP PROTECTOR INSTALLATION

EMP protectors will be chosen from the standard list, Appendix I, and installed from individual pair conductors to ground strips at terminal blocks provided. It is important to utilize shielded pairs both entering and leaving the entry panel protector box in order to provide the most effective means of stopping the EMP induced voltage transients at the protector installation point. Routing of cable entrances and exits must be arranged to minimize coupling of currents in the shields of the entrance cables, into conductors in the exit cables. Protector installation means are designed to minimize the lead length necessary to connect the protector from each pair conductor to the ground bus and to minimize open end loops resulting from bringing the shielded pairs out of their shields in order to make contact with the protectors at the terminal block terminals. The significance of lead lengths and end loop inductance is treated in Appendix A-2 of this report. The length of the pair shield ground wire to ground bus and case must also be minimized to maximize protection by the protector. This is accomplished by using a copper grounding strip seen in the center of Figure 3, which makes electrical contact along its entire length to the metal box by means of a silver loaded cold solder material. The individual shielded pairs seen have an aluminum foil shield run with a grounding wire in contact to make ground connections. Where the pair is broken out directly over the grounding strip, this ground is carried through the terminal block and connects to the pair shield on the load side of the terminal block. A further improvement in the grounding strip for the tests is seen in Figure 4 where a grounding strip was added on the output side of the terminal block. A final improvement is seen in Figure 5 where a screw terminal block is nested in a U-Channel grounding strip.

The terminal block seen on the right side of Figure 3, is similar to many encountered in EMP retrofits at EBS radio station and telecommunications racks. The wire connections are wrapped and soldered making it difficult to add protector leads. Miniature spring clips are used here on one side of the protectors to facilitate easy connection and disconnection. The other side of the protector is hard wired and soldered to the ground strip. Another commonly encountered telecommunications terminal block is connected with wire wraps, not soldered. This small spring clip will be useful for protector connections at those terminal blocks also. A major consideration in EMP protector installation is the design and locating of the grounding bus to minimize protector ground lead lengths at terminal blocks. This problem will be overcome here by the development of a package ground bus terminal block unit and installation procedure to be utilized in all of the EOC EMP retrofits. Sufficient spare terminals will be provided to connect either a few, or many signal conductors to accomodate different numbers and types of equipment connections. Where possible this package protector unit should be installed in line with multi-conductor cable runs inside shielded equipment cabinets, intercepting cables which are entering the cabinets from outside runs. This package unit is seen in Figure 5.

Installation of protectors on existing terminal blocks of the type seen on the right in Figure 3, and on wire wrap type blocks results in a very ineffective system of protection because the lead lengths and open loop areas required to connect with any conceivable grounding strip are excessive.

Power filters are utilized to provide an effective means of removing large induced EMP voltage transients anticipated on all commercial source power systems. The filter works in combination with the transient limiting device to provide a high impedance in-line with the power conductor at other than the power frequency, and a low impedance to ground, so that low impedance shunting by transient limiters and filter capacitors is effective.

Antenna cables and other coaxial shielded cables are treated individually in this EMP protection system. Transient currents are removed from exterior run cable shields at the bulkhead adapter penetration provided at the entry panel. Common mode induced EMP voltages are reduced to acceptable levels using coaxial-tee or other similar in-line protectors at the entry point. If the cable shields are controlled by bulkhead penetrations at the entry panel, the in-line protectors can be inserted at the equipment connection terminal if this is more convenient than the entry panel. Choice of the proper in-line protector includes consideration of operational voltages and frequencies, and voltage standing wave (VSWR) problems at connections. For transceivers which use a common antenna connection for both transmitting and receiving, the receiver usually requires an additional low level protector installed inside of the equipment beyond the transmit/receive relay switches. At HF or lower frequency bands, solid state receivers connected to their own antennas usually require a two-stage high/low power EMP protection. There is normally sufficient distance or time delay between the entry panel and the equipment connection to apply the high power protectors (gas gaps) at the entry panel, and the low power protectors (diode bridges) at the equipment connection.

SHIELDING

Shielding in this series of tests was provided by metal boxes with conductive coatings and overlapping covers at the entry panel, the metal conduit connecting to the equipment cabinets, signal and antenna cable shields, and by the outer surface of the equipment cabinets. The equipment cabinets in future prototype EMP packages will be selected from rf shielded types readily available providing a minimum of 60 dB shielding effectiveness, as measured in accordance with MIL-STD-285 procedures. This will be 20 db better than the shielding provided by the equipment cabinet and entry boxes seen in Figure 6 and used in this test. This lower level of shielding was sufficient for the tests. An additional 20 dB will allow for protection against an order of magnitude greater threat level of EMP fields than the 10KV/m vertical electric field available in this series of tests. Individual features of prototype cabinets will include an rf gasketed door and panel front closures and honeycomb wave-guide below cut-off air filters over ventilation cooling ports.

TEST EQUIPMENT

EMP Test Cell. An EMP coaxial test cell was constructed to provide a test volume sufficiently large to accommodate a full size EOC protection system unit. A welded steel 100x40x20 foot shielded enclosure was modified by suspending six parallel conductors for a length of 75 feet, at a height of 12.5 feet above the metal floor. Each suspended conductor was terminated individually at the building end wall in a copper sulfate resistor experimentally matched in resistance to provide a minimum impulse reflection at the feed point. Terminating resistance values varied from 430 to 540 ohms, as measured with a bridge at 550 KHz. Spacing of the six conductors varied from two feet for outboard pairs to six feet between the center two. Total test conductor spread was 20 feet. Vertical and horizontal electric field profiles were measured in the test area with an EFS-1 meter using a CW source to drive the test cell. A fairly uniform field distribution was available, as seen in Figure 7. The six test cell conductors were fed in parallel by coaxial cable connection from a remote test pulser. The 100 foot, 50 ohm, RG218/U cable from the pulse source was connected to the six test cell conductors at a point just outside of an additional 20x20x10 foot enclosure, utilized to shield measuring equipment near the feed point, seen in Figure 8. The wall of the enclosure provided the ground return connection. The innermost suspended conductors had added length and inductance at the feed point so that the test pulse field would be in phase over the test volume. Means were provided at the end of the test cell so that measuring equipment could be located outside the cell, shielded from the test fields. One of the six conductors was terminated in a copper sulfate resistance divider, seen in Figure 9, so that direct voltage measurements could be made of the test pulse within the voltage range of the available high voltage probe. The six conductor parallel feed connection provided a mismatch impedance to the 50 ohm feed cable at the connection point of about 88 ohms (determined by pulse reflection technique), which did not effect the test pulse shape. Maximum peak voltage at the feed point without arc-over of connections was about 67 KV, giving a calculated vertical electric field gradient in the test volume of about 10 KV/meter. Test pulse rise time at the feed point was about 12 nanoseconds. The rise time at the pulser, into the 100 foot feed cable was four nanoseconds. The long feed cable was used to isolate the source .007 μf capacitor and the source circuitry so that the test pulse delivered to the area was free from low impedance source reflections until late in the pulse-time history. Conductor losses contributed to additional increase in the rise time available over the test panel, resulting in slightly less than the 20 nanoseconds observed at the load end of the test cell.

Measurement Equipment. Measurement equipment included a Tektronix 475 oscilloscope with a P6015 high voltage probe. A Stoddart rf current probe shunt loaded with 1.2 ohms for a flat response with frequency was used for current measurements. The oscilloscope provides a 200 MHz bandwidth. The high voltage probe rated to 40 KV peak, 100 megohms impedance with three picofarads shunt capacitance input is designed for fast impulse measurement. The transfer impedance of the current probe as a function of frequency was measured using a 50 ohm calibration fixture and a CW source from 50 KHz to 50 MHz. The measured current probe transfer impedance curve is seen in Figure 10.

Test Pulser. The test cable pulser used was a Physics International FRP-125, consisting of a cylindrical housing containing a .007 μf cylindrical capacitor in a coaxial configuration for minimizing inductance and minimizing pulse rise-time. The housing also contained a variable gap switch in SF_6 gas to allow for changing the discharge breakdown level between about 10 and 125 KV DC. The unit was manually triggered from the charging control cabinet, from one to several times for each test picture depending on the oscilloscope sweep rates used. Multiple test traces were repeatable and provided a means of increasing the trace density on the oscilloscope for photographing the image with a C-30 Polaroid camera using Type 410, 10,000 speed film.

The test pulser, seen in Figure 11, was housed in a metal shielded trailer located outside of the test cell building. A recording of the test pulse measured with a high voltage probe and rf current probe at the load end of the test cell at the $CuSO_4$ resistance divider is seen in Figures 12 and 13, at a mid-range voltage setting. Rise time is 20 nanoseconds, peak voltage was 32.7K and peak current 66.8 amps. A voltage and current recording at full test voltage is seen in Figures 14 and 15, measured at the resistance divider, with the measuring equipment located on the exterior of the test cell shielded building.

TESTING RESULTS

All runs of cables, conduits and cable trays connecting to the entry panel were suspended under the test line at a height of 8 feet for a distance of 60 feet. Using what was considered a moderately severe vertically polarized electric field level of 10 KV/m, the induced voltages and currents were measured in the variety of cables, conductors and conduits, and connected through the entry panel and EMP protectors to the equipment cabinets, as seen in Figures 1 through 5. The induced simulated EMP responses were measured to determine the critical parts of the EMP protection system. A balance was sought to minimize the measurements for direct induced and conducted EMP voltages (from connected cables and conductors) as observed at the simulated load terminals. Direct induced voltages were measured on a 62 inch wire suspended diagonally inside the cabinets. In addition, reasonable configuration and equipment changes were made in attempts to reduce the maximum induced and conducted voltage levels measured at protector installation terminals.

The first configuration utilized was a single entry panel (4x8 feet) obtained from a state EOC shielded enclosure package, and feeding from here to two unshielded equipment cabinets, seen in Figure 16. Ten foot lengths of flexible conduit with conductor jumpers, were used to interconnect power and signal conductors between the entry panel and the cabinets. Both shielded and unshielded pair cables were used to connect from outside to the entry panel and from the entry panel to equipment cabinets. Antenna coaxial cables were connected through bulkhead connectors at both entry panel and cabinets without using conduit. Results of simulated EMP tests in this configuration are presented in Table I.

The first improvement made was to cover the seams in one cabinet with one inch wide metal tape. Radio frequency gaskets were added to front and rear panels and door respectively, with conductive silver epoxy coatings on the mating surfaces. Flexible conduit connections were also treated with the conductive silver. Seam enamel was not removed under the metal tapes. The results of measurements for this configuration are seen in Table II.

The next improvement was in the shielding of one cabinet. The seams adjacent to the cable and conduit entries were treated with silver epoxy after removing the enamel with a cutting disk. Conduits carrying signal conductors were changed to rigid steel conduit (EMT). The power conductors were left in the superior type flexible conduit (Anaconda UA Sealtite). This configuration is seen in Figure 1, and the test results are presented in Table III.

Another parameter changed was the size of the entry panel. This was increased from 4x8 feet to 6x8, and then 8x8 feet. Induced currents in the connected conduits on the back side of the entry panel were compared, as well as currents in conductors on the input side of the entry panel. Results are seen in Table IV.

For the final test configuration the entry panel was removed, and the wall of one shielded equipment cabinet was used as the entry panel, (Figure 6). In addition, all seams of the cabinet were filled with silver epoxy. Individual foil shielded twisted pair cables were used both into the entry panel, and from the panel to the equipment connection location inside. This configuration is seen in Figure 4. The addition of a grounding strip on the exit side of the punch block was significant in reducing loop-to-loop coupling across the protector block. The Christmas tree block seen on the right in Figure 4 was wired with one pair of diode protectors and aluminum foil shielded twisted pairs to observe the minimum conducted voltage for this type block. Results of this final configuration are seen in Table V.

In order to increase the level of simulated conducted EMP threat to the maximum as well as to produce voltages at the entry panel large enough to fire the higher voltage protectors tested, the connected conductors were directly driven at a point near the test cell feed point, about 55 feet from the entry panel. The twelve pair shielded cable, three pair unshielded cable and antenna coaxial cable were directly driven at peak voltage levels limited to less than the insulation break-down of the cables of concern. The resulting voltages reaching the protectors at the entry panel were several orders of magnitude larger than those resulting from these cables being driven for their full length directly under the test cell conductors with the 10 KV/m electric field strength. These tests were designed to simulate maximum peak voltages that would occur from very long connected conductors to EOC equipments. The results of direct driven tests are presented in Table VI.

Shielding effectiveness of the equipment cabinet, before and after shielding measures were added, was determined both by MIL-STD-285 loop-to-loop measurements, as well as by comparing transient test cell peak voltages induced in a 62-inch long unterminated, conductor hung outside the cabinet, and diagonally inside the cabinet with the door open, and with the door closed. The wire length was chosen to simulate long leads between equipments installed inside of one equipment cabinet. Measurement results are seen in Table VII.

Further experimental testing was done to determine means of minimizing the direct coupling from source to load sides of conductor pairs at protector installation terminals, and to determine means to minimize protector lead inductance effects. First in significance is the necessity to remove shield induced currents from pair shields at locations where they will not be close to the open wire loops (unshielded section of pairs) at the location of installed protectors. The ideal solution is to run shielded signal/control conductor pairs in metal conduit or covered trays to keep these shield currents low. This is not always practical, especially with EMP retrofits at existing facilites. The second best solution is to run all control/signal conductors in foil shielded individual twisted pairs with the individual shield drain wires terminated on a proper grounding strip, similar to the arrangement seen in Figure 3. Here, the shield drain wire is carried through the strip on a set of terminals and picked up again on the output side, in addition to terminating the shields of incoming pairs on the grounding strip. A better grounding means is provided by running a grounding strip along each side of the terminal block as seen in Figure 4. An even more effective arrangement which does not depend on electrical continuity of the ground strip against the metal box is to use a U-channel grounding strip with the terminal block nested in its bottom as seen in Figure 5. Here the pair shields are grounded to the strips on both input and output sides of the protector installation. This ground/terminal arrangement will be recommended for future EOC EMP packages.

Testing was conducted to determine the best means of orienting the protector at the terminal block installation location. There is a necessary minimum inductance of the protector installation determined by the physical size and length of the protector body. This is considered in Appendix A-2. The effect of this minimum length lead inductance may be reduced even further by arranging the protector to run close alongside the pair conductor at its connection between the ground strip and the terminal board. This results in mutual inductance coupling that effectively cancels part of the minimum inductance of the protector lead. This is further improved by winding two turns of the pair conductor around the protector lead just ahead of the terminal board connection. The response to a fast transient with and without the aforementioned protector orientation is seen in Appendix A-2, Figures A2-4, 8 and 9, where #22AWG wire shorts were arranged on a grounding strip and terminal block similar to Figure 5 in the parallel, mutual inductance opposing configuration as well as at right angles to pair conductors. For the right angle short circuit tests, three terminals were used and the drain wire brought across in the center terminal so that the effects of a short circuit at right angles could be observed as well as calculated. The mutual inductance cancelling self-inductance is seen in Figure A2-9, to be the best arrangement compared to the right angle short test results seen in Figure A2-4.

Calculations and tests were made of the coupling that occurs between adjacent conductors at the protector installation block caused by the small sections of open transmission line (open wire loops) formed by the unshielded section of conductors as a go, and the U-channel ground as the ground return. These are presented in Appendix A-2, Figures A2-14 through 21.

The expression for coupling from a small open wire to open wire transmission line for lower frequency ac and transient currents is given in Reference (1). For the case of ac currents the effects of these open loops are treated further (called pigtails) in Reference (2), which examines the coupling effects of pigtail lengths ranging from 0.5 cm to 8 cm, with line characteristic impedances of 50 and 1,000 ohms.

Appendix A-2 treats a fast double exponential transient case for connections formed at a screw-type barrier terminal block as seen in Figure 5. One pair of shielded conductors with and without protectors was used as the source wire loops and an adjacent pair of conductors was used as the victim or receiving wire loops. In the experimental test, the ultimate protector was simulated by a #22AWG solid shorting conductor between the source pair conductor and the grounding strip. The test results are plotted in Figure A2-5. The measured pulse response lags the experimentally predicted response in all of these measurements with longer rise times and slightly lower peak values. Part of this effect can be blamed on the bandwidth limitation of the oscilloscope (200 MHz) available. A factor is the approximate representation of the measured test pulse with a simple double exponential. Another factor is the neglect of stray coupling capacitance in the models for protector installations.

A fourth probable cause of apparent delay is the resonant ring-down effect caused by excitation of the connected test cable shields in quarter and halfwave length resonances. This is a deficiency of the experimental set-up, where it is necessary to use a shielded enclosure to isolate the test pulser from the experimental terminal block and protectors to assure interference-free measurements. However, this test configuration is representative of a typical installation where equipments are contained in metal cabinets or enclosures and ends of cable shields are grounded to the equipment chasis.

The two important characteristics of the voltage pulse which passes the protector in terms of its potential damage factor to connected equipments are its peak value and time duration. These are sufficiently alike between measured and predicted transients described in Appendix A-2, to allow a determination of the significant effects of protector lead inductance, arranged with and without cancelling mutual inductance, and open wire loop coupling between adjacent pair conductors.

DISCUSSION

The significance of the testing results shown in Table I is that direct induced voltages in the cabling running from the entry panel to the unshielded cabinets is greater than that induced in the long runs of shielded pairs running in the rf cable tray. This was evident by the absence of EMP protector clipping in the recorded oscilloscope voltage measured at the entry panel. Only the long run of free hanging unshielded pairs resulted in induced voltages significantly greater than those induced in cables running from the entry panel to the cabinets only. One reason for this poor performance can be seen from the results of current measurements shown in Table II. All of the flexible conduits were jumpered with #4 AWG conductors. When the ends of the conduits were treated with silver epoxy, a significant reduction of currents in the contained cables occurred, but not sufficient to achieve the desired result, and a change to steel EMT rigid conduit was made.

Another significant factor in the induction of transient voltages in cables between the entry panel and terminal blocks in the cabinets is seen in Table VII. Here significant induced transient peak voltages were measured and recorded in a 62-inch conductor suspended inside the cabinets. This was used to measure the shielding effectiveness of the cabinets to the test transient fields. Cables connected to the internal terminal blocks in the cabinets, enter from near the cabinet bottom and rise several feet to the terminal blocks. Some of the cables are unshielded pairs and the induction of significant common mode induced voltages would be expected. For the shielded pairs, the shield would have significant currents which would then couple through mutual inductance to the pair conductors from long open loops formed at the terminal blocks.

The effect of increasing the entry panel size from 4x8 through 8x8 foot is shown in Table IV. Here a change in the induced conduit currents on both sides of the entry panel was measurable, but not significant to the problem. This can best be explained by considering the range of frequencies encountered in the measured induced voltages, 1.4 to 54 MHz seen in Tables I, II, III and V. At the low frequency end, the diagonal length of the 8x8 foot panel is .016 wavelengths. At the highest frequency it is 0.6 wavelengths. Thus, over the range of observed exponentially damped sinusoidal induced voltages and currents the largest panel used is not a significant counterpoise. In addition, the surface area and resulting stray capacitance to ground of the 8x8 foot panel is of the same order of magnitude as the stray capacitance of the equipment cabinets. This results in a sharing of the currents shunting to earth, between the panel and the cabinet. For an installation with several equipment cabinets connected in series, the effect of the entry panel would be further diminished.

The change of entry from the single 4x4 through 8x8 foot panels to the wall of the improved shielded equipment cabinet resulted in improved performance as seen in Table V, where the two lowest level protectors showed indications of clipping the induced transients to very acceptable levels.

The progression of improvements in entry panels, equipment cabinets and protector terminal block grounding connections that occurred during the simulated EMP testing were designed to minimize both the direct induced and conducted transient voltages and currents arriving at the equipment terminal connection blocks inside the cabinets. Ideally, shielding against direct, incident EMP fields should provide sufficient shielding effectiveness to limit induced voltage transients measurable at the equipment terminals to equal or lower values than that provided by the lowest level voltage clipping EMP protectors use. The testing started with standard, enameled seam, unshielded metal equipment cabinets, and flexible conduits, but significant improvements in the shielding of both were necessary to finally reach the above mentioned goal.

EMP fields arriving from a great distance will result in a greater reduced penetration of shielded cabinets than is apparent from measurements made using prescribed MIL STD 285 source antenna distances. However, secondary induced EMP fields resulting from EMP currents induced in typical facility conductors will be expected to result in only moderately less penetrating fields, because these sources will be much closer to the protected equipment cabinets. This effect results from the addition of reflection losses and penetration losses in determining the effective shielding effectiveness measured. The reflection losses are greater, the farther the source is from the shielding, but the penetrations losses are the same. Because of this effect it would be possible to improve the final protection of a shielded system by using a preferred placement of the equipments relative to facility conductors. The shielding effectiveness measured and presented in Table VII after all improvements were made resulted in 20 to 37 dB of Magnetic field shielding effectiveness at 100 KHz, and 65 dB of transient peak electric field shielding effectiveness. This level of protection was considered to be barely sufficient for the test field strengths used which could be considerably less than the maximum high altitude EMP and secondary induced EMP currents. Since equipment cabinets with 80 to 100 dB of electric field shielding effectiveness are available at reasonable cost, a minimum of 80 dB from 10 KHz to 100 MHz is recommended for EOC protection. In order to correlate with magnetic "Sniffer" measurement at 100 KHz magnetic, using FEMA provided test equipments, a minimum magnetic field shielding effectiveness of 60 dB at 100 KHz is recommended.

Direct drive conducted EMP tests were made with results given in Table VI. These test levels used are considered to be closer to anticipated EMP than the induced field strengths used, because the levels were set just below the anticipated insulation breakdown strength of the cables used. During EMP, terminal connections, cable insulations, and components such as transformers are expected to fault, limiting the peak voltages that will arrive at connected equipments. The 330 ohm terminating resistors used at the equipment terminal boards were a mismatch to the measured 33 ohm shielded pair to ground impedance, but were felt to be sufficiently representative of anticipated equipment input and output impedances. The effect of terminating a pair in a high impedance is to observe a higher transient voltage than would be coserved on a matched impedance load. For an open or infinite impedance output, for example the transient voltage peak measured would be double that into a matched load.

Progressive improvement of the protector terminal and ground strip and the mode of installation of the protector resulted in the U-channel ground strip and nested screw terminal block seen in Figure 5. The protector, with two turns of the insulated pair conductor wrapped around its lead adjacent to the screw terminal is best installed on the source side of the terminal block to minimize magnetic loop coupling to adjacent pairs at the terminal strip. The effect of protector lead lengths, open loop coupling, and location of the protector using the improved U-channel ground strip are treated theoretically and experimentally in Appendix A-2. Direct drive transient tests were made using the EMP protector test unit developed for FEMA use. A moderately severe test voltage transient rise gradient of 48 KV/μs was used to represent typical expected conducted EMP voltages on long connected pair conductors. Greater pulse rise gradients would result in proportionally higher passed peak voltages across protector lead inductances. The best ultimate voltage transient protection level measured and shown in Figure A-2-13 is provided by adding a diode stack protector at the equipment connection end of the cable pair from the protector terminal block. Limiting of transient voltages to this level, 2-3 volts peak, should be adequate for any FEMA protected equipments. In the final version of the EOC EMP protection package, high current rated protectors such as metal oxide varistors and gas gaps will be recommended for first stage protection at the single entry panel terminal block, followed by the lowest voltage rated zener or diode at the equipment connection that is compatible with operational voltages.

To this point, no specific mention of earth or ground return, other than the equipment case or entry panel metal, used to ground off the protector ground strips is made. For the tests conducted, the metal floor and walls of the large test cell were a semi-perfect ground counterpoise. The only connection made to this floor was the safety power ground wire and the beginning of the power EMT conduit running to the entry panel. Occasionally, the rf cable tray was grounded at its beginning. Because EOCs will be encountered with a variety of distances between equipments to be protected and the earth plane, it will be necessary to establish a protection system that does not rely on close proximity to the earth plane. In the tests conducted, the entry panel and equipment cabinet were insulated from earth deliberately, and were only connected through the AC power and stray capacitance. For the purposes of the protection system used, the conduit, entry panel, or equipment cabinet case are the ground plane. Common mode for induced transients is established between conductors in conduits with the conduits as a return. At the terminal blocks, the box or entry panel is the common mode ground return for installed protectors. For personnel safety purposes, and the 60 Hz power connection, it will be necessary to bring a ground conductor from the power source to the power filter at the entry panel location. If threaded ferrous rigid conduit is used for power, it may be used for the safety ground connection. The neutral power conductor will be filtered as well as the hot power conductor, resulting in a requirement for a three pole filter for 208/120 single phase power connections.

Figure 1. Shielded equipment cabinet fed by 4x8 foot single entry panel.

Figure 2. Single entry panel components.

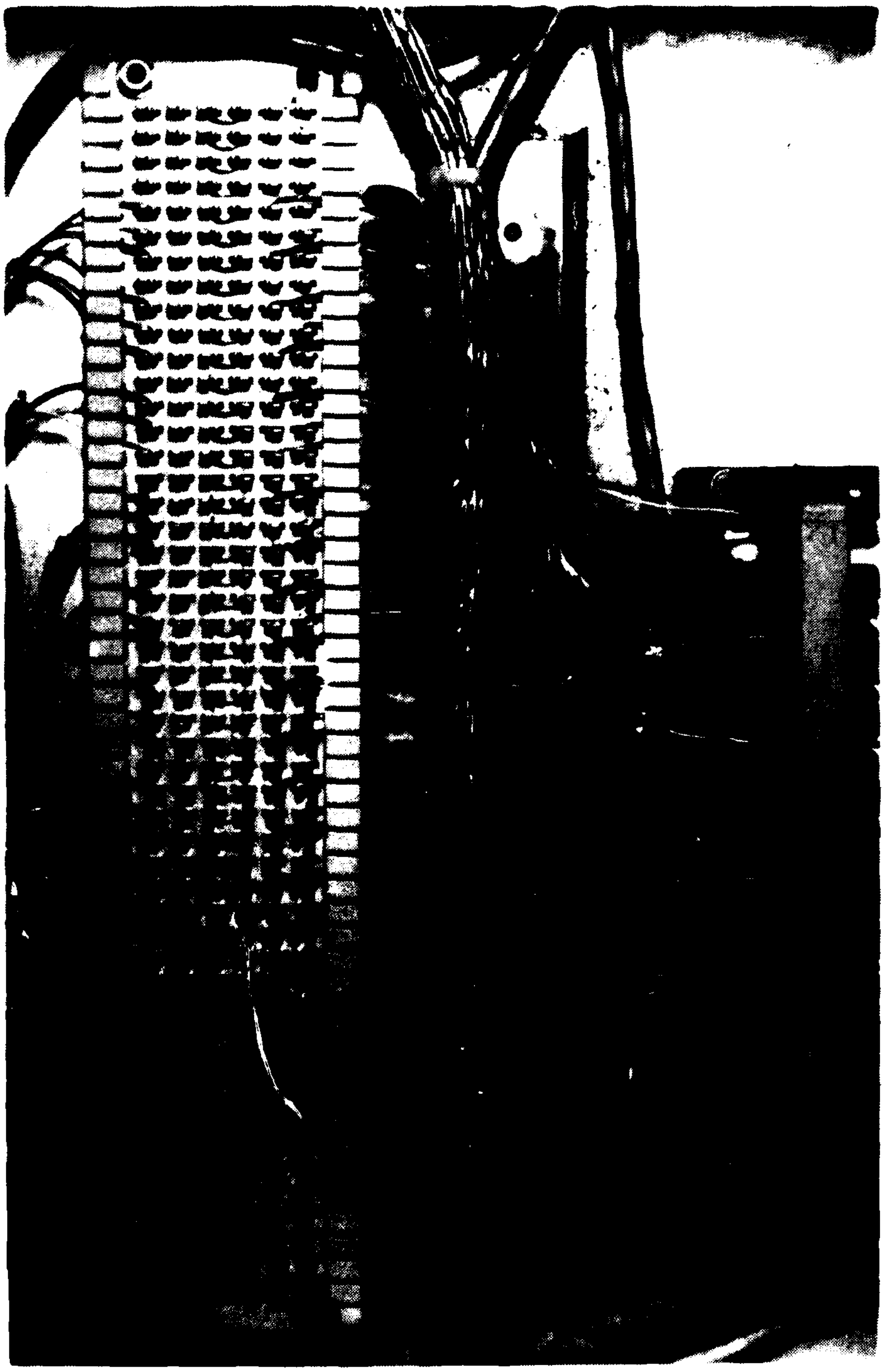


Figure 3. Punch block and Christmas tree block in single entry box.

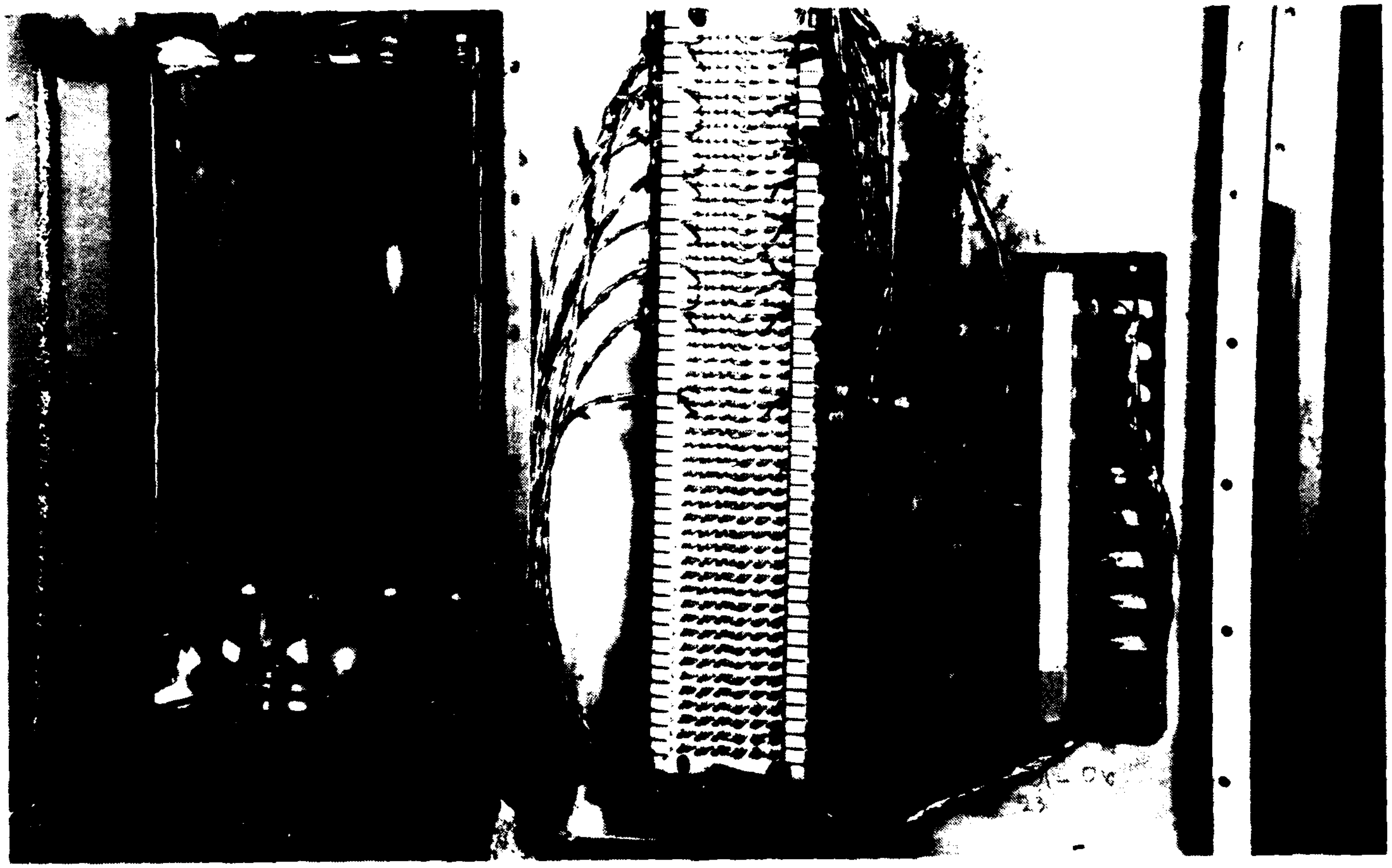


Figure 4. Single entry panel box on shielded equipment cabinet.

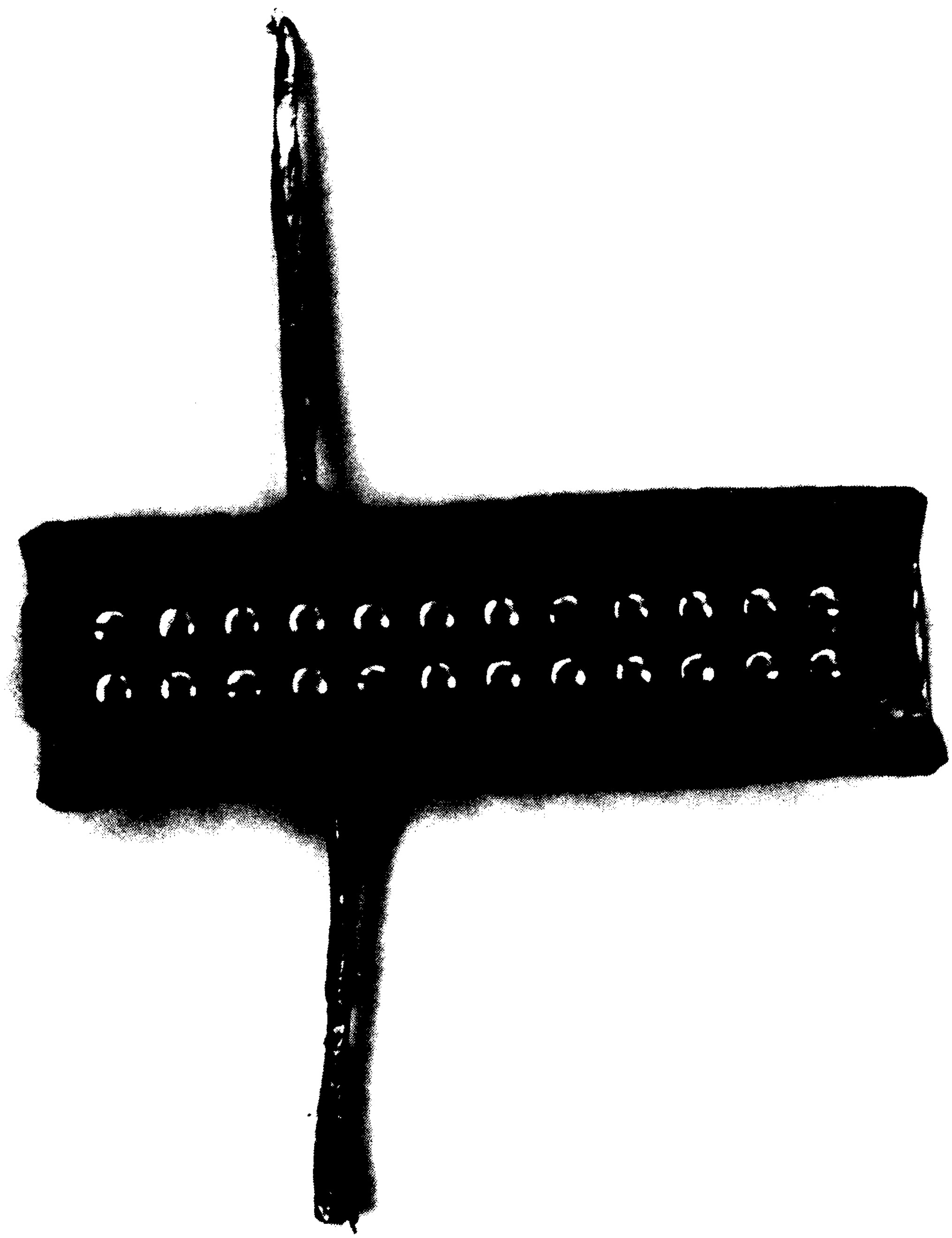


Figure 5. Preferred U-channel ground strip and screw terminal block for EMP protector installation.

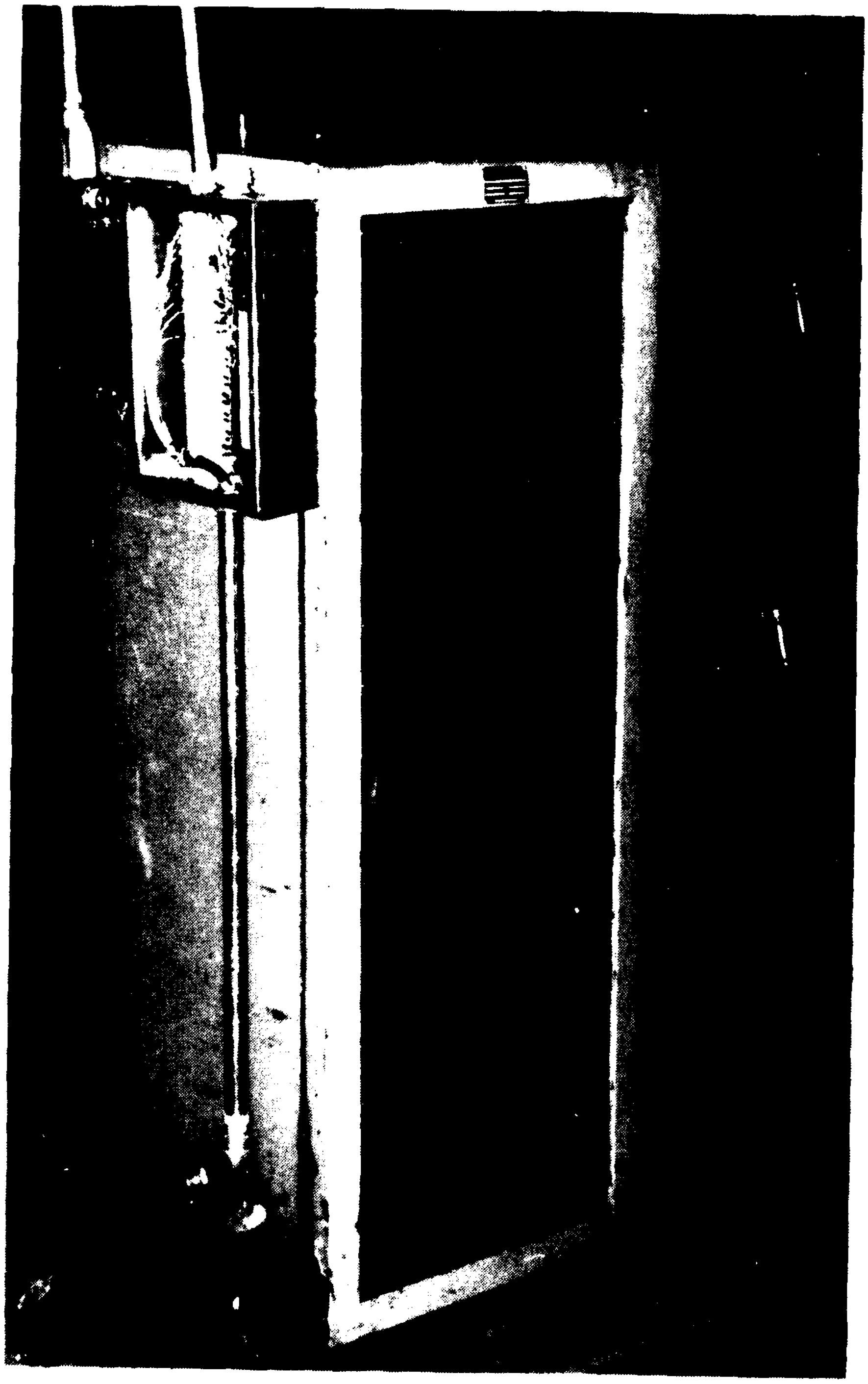


Figure 6. Shielded equipment cabinet used to mount the single entry panel.

4 3 2

All Measurements in RMS Volts/Meter

Vertical Distance Below Test Conductors in Feet

Entry Panel

Cabinet "A"

1	3.6	5.7	2.3	6.4	3.2	5.7	7.0
2	3.6	4.6	2.6	5.0	3.2	4.3	4.5
3	3.7	3.7	3.0	4.0	3.3	4.0	4.0
4	3.4	3.4	3.5	3.3	3.5	3.5	3.2
5	3.2	2.9	3.4	3.6	3.3	2.7	2.5
6	2.7	2.7	3.2	3.2	3.2	2.4	2.3
7	2.4	2.4	3.0	3.1	3.2	2.2	2.0
8	2.0	2.2	2.8	2.8	2.4	2.0	1.7
9	1.8	2.0	2.6	2.5	2.3	1.8	1.6
10	1.6	1.8	2.4	2.4	2.1	1.7	1.6
11	1.5	1.7	2.2	2.1	2.0	1.6	1.4
12	1.6	1.75	2.4	2.4	2.2	1.75	1.5

4 6 8 10 12 14 16 18 20

HORIZONTAL DISTANCE IN FEET

Figure 7. Measured CW Field Strength Over Entry Panel Test Area at 2.7 MHz

Figure 8. Feed point for EMP test cell conductors.

Figure 9. $CuSO_4$ terminating resistance divider.

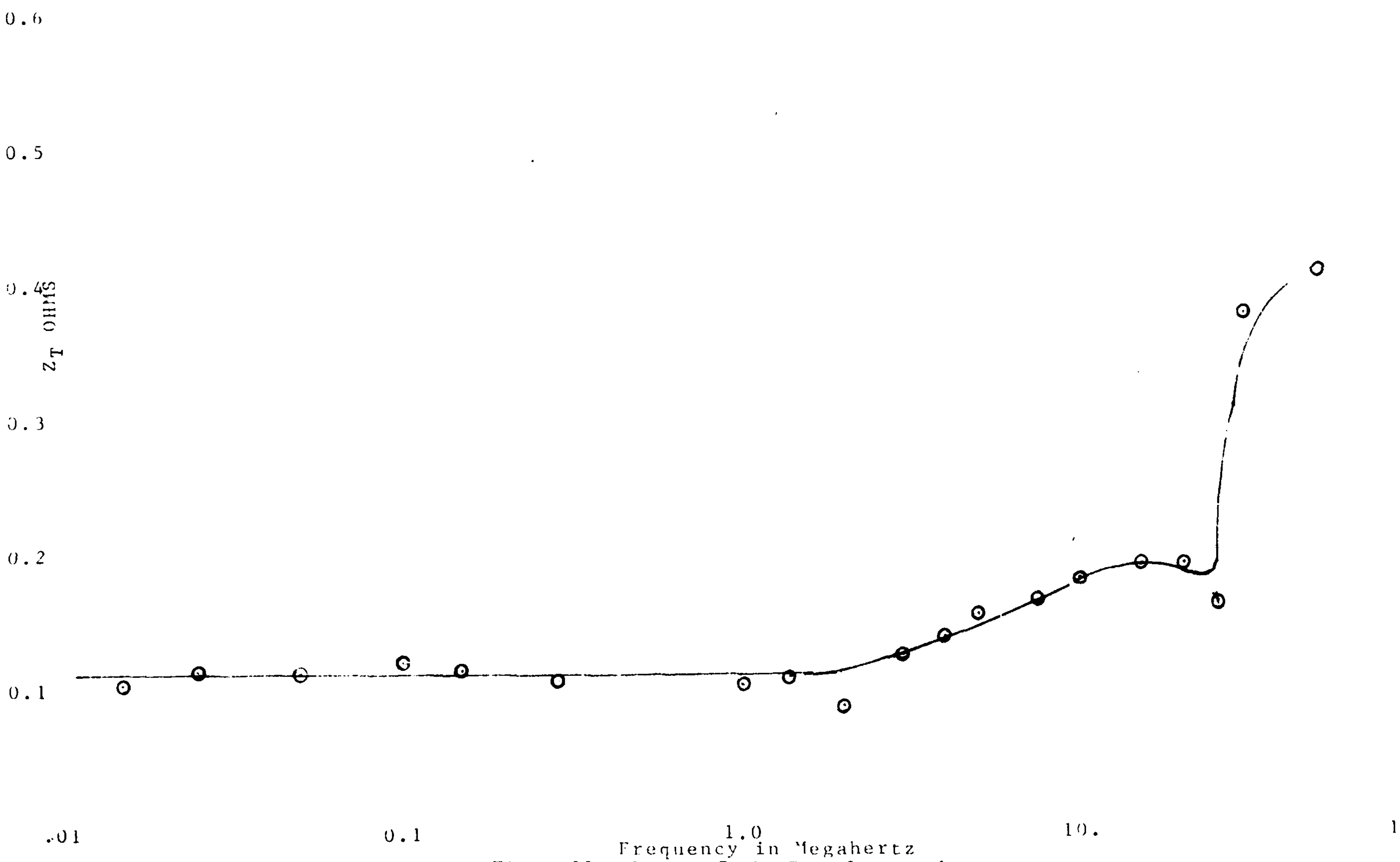


Figure 10. Current Probe Transfer Impedance

Figure 11. EMP cable pulser, FRP-125.

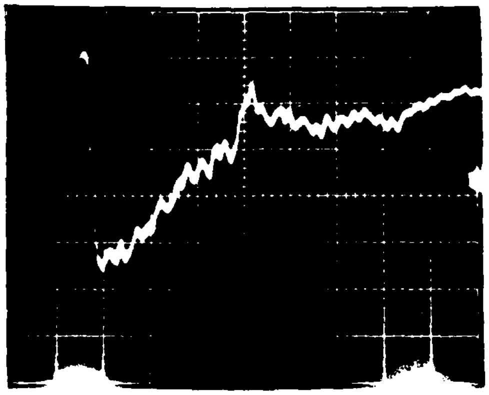


Figure 12. Test voltage measured at the terminating resistance divider. 32.7KV peak, 20 nanoseconds rise time.

Figure 13. Test current in one conductor, measured at the terminating resistance divider. 66.8 amps peak.

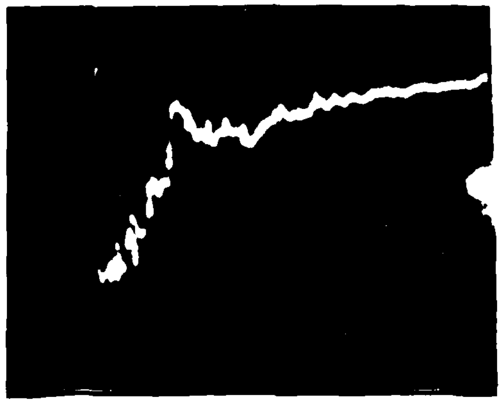


Figure 14. Test voltage measured at the terminating resistance divider. 65.7 KV peak. 200 nanoseconds/div.

Figure 15. Test current measured at the terminating resistance divider. 133.9 amps peak. 100 nanoseconds/div.

Figure 16. Unshielded equipment cabinets and 4x8 foot single entry panel.

TABLE I

INDUCED VOLTAGE MEASUREMENTS AT 10KV/METER WITH EQUIPMENT CABINETS UNSHIELDED AND 4x8 FOOT ENTRY PANEL

TEST CABINET	CABLE CONFIGURATION	PROTECTORS INSTALLED (Conductor to Ground)	PEAK VOLTAGE MEASURED	PEAK TO PEAK VOLTAGE MEASURED	EARLY FREQUENCY MHz	LATE FREQUENCY MHz	OTHER CONDITIONS (Voltage was measured pair conductor to ground unless otherwise stated.)
A	12 pair cable in RF tray prs. individually foil shielded.	25V AC MOV	19 Volts	35 Volts	22.5	4.2	Insufficient induced voltage to fire protector.
"	"	200V DC Zener	29.6	54.6	19	1.3	Insufficient induced voltage to fire protector. 24V Peak to Peak modulation at lower frequency.
"	"	130V AC MOV	14	22	19	--	Insufficient induced voltage to fire protector.
"	"	250V AC MOV	13.7	24	13.5	3	" " " " "
"	"	275V AC MOV	8	12	19	--	" " " " "
"	"	Parallel Diodes	14	20	18		
"	"	10V DC Zener	18	30	18		
"	"	2V DC Zener	5	8	22.5		Reduced band width measurement (20 MHz).
"	3 pair cable in RF tray prs. individually shielded.	130V AC MOV	22	32	16	1.4	Insufficient induced voltage to fire protector.
"	"	10V DC Zener	25	37	45	1.6	
"	RG-213/U, hung under test line.	None	9	17	12	3.6	*Measured into 50 ohm loading.*
B	Unshielded, 3 pair cable hung under test line.	230V DC Gas Gap	260	504	29	15.6	Insufficient voltage to fire protector.
"	"	75V DC Gas Gap	190	360	26		" " " "
A	3 pair shielded, entry panel to A only.	None	32	59	19	11	Pairs run in "Greenfield" flexible conduit with #4 AWG Jumper 330/330 ohm terminations, each end to chassis.
A	12 pair shielded, entry panel to A only.	None	18	35	45	3	Pairs floating at entry panel, but shield wire connected to chassis each end, 330/330 ohm termination at cabinet.
A	12 pair shielded, entry panel to A only.	None	2	4	17		Pair conductors floating each end, but ground wire connected to chassis.
B	3 pair shielded, entry panel to B only.	None	7.0	12	27	20.7	Runs in superior type UA "Sealtite" flexible conduit, [illegible] 330/330 ohm terminations, each end, ground wires conne[illegible]
B	"	None	13	24	34	18	Pair floating at measured end, ground wire connected, flexible conduit contains an unshielded 4 pr. cable from rf tray.
B	"	None	24	42	34		Pairs and ground wires floating each end, measured shield wire to ground.
B	"	None	48	77	25	12.5	Measured one open shield wire to ground, 3 pair cable floating each end - runs in "UA Sealtite."

TABLE IIA
INDUCED VOLTAGE AND CURRENT MEASUREMENTS AT 10KV/METER
WITH ONE PARTIALLY SHIELDED CABINET AND 4x8 FOOT ENTRY PANEL

CONDUCTOR MEASURED	PROTECTOR INSTALLED	PEAK VOLTAGE IN VOLTS	PEAK CURRENT IN AMPERES	PEAK TO PEAK VOLTAGE	EARLY FREQ. MHz	LATE FREQ. MHz	OTHER CONDITIONS
12 pair shielded cable entry panel to A only.	None	7		13	54		Measured, conductor to ground, 330/330 ohm, terminations each end to ground.
12 pair shielded cable in rf tray.	25V AC MOV	20		38	10	4	Cable extended along power conduit, out of tray, 30 foot to the floor at beginning and end.
"	14V AC MOV	26		46	20.9	3.9	" " "
"	Parallel Diodes	15		29	42		" " "
"	10V DC Zeners	28		49	42		" " "
Flexible EF conduit entry panel to A	None	--	27.8		42	15.6	Current probe around "Anaconda EF" flexible conduit.
Cables in above conduit.	None	--	10		42	15.6	Current probe around all cables in above conduit.
"	None	--	1		50		Ditto above, except ends of conduit bonded to EP and cabinet A with silver epoxy.
Unshielded pair cable in EF conduit, EP to A	None	115		215	42	15.6	330/330 ohm terminations each end. Measured conductor to ground, shares EF conduit with exterior run, 12 pair shielded cable.
"	None	75		150	42	15.6	Ditto above after conduit ends grounded with silver epoxy at entry panel and cabinet A.
Greenfield Flex EP to A	None		38.9		50	17.8	Current probe around Greenfield conduit.
"	None		27.8		50	17.8	Ditto above after flex ends treated with silver epoxy.
Cables in above conduit.	None		1.1		50	17.8	Current probe around all cables in above conduit.
"	None		3.3		50	17.8	Ditto above before treatment with silver epoxy on flex terminations.
Unshielded cable Hangs under test line	Parallel Diodes	38		59	25	4.4	EF conduit contains 12 pair shielded cable from rf tray 3 pair unshielded free hung cable, and EP to A only shielded pairs.
"	14V AC, MOV	33		54	25	4.4	Ditto above.

TABLE IIB
INDUCED VOLTAGE AND CURRENT MEASUREMENTS 3.4 KV/METER
WITH ONE PARTIALLY SHIELDED CABINET AND 4x8 FOOT ENTRY PANEL

CONDUCTOR MEASURED	PROTECTOR INSTALLED	PEAK VOLTAGE IN VOLTS	PEAK CURRENT IN AMPERES	PEAK TO PEAK VOLTAGE	EARLY FREQ. MHz	LATE FREQ. MHz	OTHER CONDITIONS
12 pair shielded in cable tray.	Parallel Diodes	10		19	15.5		Measured pair conductor to ground in cabinet.
"	200V DC Zener	9		18	14.3		" " "
"	10V DC Zener	7.5		14.5	13.9		" " "
"	2V DC Zener	7.5		13.5	13.9		" " "
"	230V DC Gas Gap	6		11	14.3		" " "
4 pair free hang unshielded.	Parallel Diodes	12		21	14.7		" " "
"	14V AC MOV	35		58		9.6	Measured pair to ground in cabinet.
12 pair shielded from EP to Cabinet only	330 - termination	12		23	15		Measured open pair to ground in cabinet.

TABLE III
INDUCED VOLTAGE MEASUREMENTS AT 10KV/METER
WITH A SHIELDED CABINET AND A 4x8 FOOT ENTRY CABINET

CABLE CONFIGURATION	PROTECTOR INSTALLED	PEAK VOLTAGE IN VOLTS	PEAK TO PEAK VOLTAGE	EARLY FREQ. MHz	LATE FREQ. MHz	OTHER CONDITIONS
12 Pair shielded in rf tray with cover	2V DC Zener across pair at entry panel	14	24	17.8	2.4	Measured pair to pair in cabinet, no protector action observed.
"	Diodes across pair at entry panel	15	32	17.8	7.4	" " "
"	Diodes pair to ground	4	7.5	25	12.5	" " "
12 pair shielded in rf tray with cover off	" "	10	19	25	12.5	" " "
12 pair shielded in rf tray with cover on	2V DC Zener	3	5.5	25	12.5	" " "
12 pair shielded in rf tray with cover off	"	11	21	15	12.5	" " "
Free hang - unshielded 3 pair cable	Diodes pair to ground	14	26			Measured pair to pair in cabinet.
"	14V AC MOV	20	38			"
"	#22 AWG shorts pair to pair to ground at entry panel	12	22		13.9	Measured pair to pair in cabinet.
"	" "	10	19		13.9	Measured pair to ground in cabinet.
3 pair shielded in rf tray with cover off	14V AC MOV pair to ground	20	39	25	12.5	Protectors on Christmas Tree type block at panel measured pair to ground in cabinet.
12 pair shielded in rf tray with cover on	Diodes, pair to pair in cabinet	5	10		13.8	Measured pair to pair at cabinet.
12 pair shielded in rf tray with cover on	" "	7	9.2		13.8	" "
3 pair shielded in rf tray with cover on	10V DC pair to ground zener	17	32	18	6.3	Measured pair to pair, Christmas Tree block at panel.
"	" "	15	29	18	15	Measured pair to ground, Christmas Tree block at panel.
12 pair shielded in rf tray with cover on	Short circuit pair to pair to ground at entry panel.	6	10	18		Measured pair to ground in cabinet.
"	" "	11	21	18	8	Measured pair to pair in cabinet.

TABLE IV

INDUCED CURRENT MEASUREMENTS AT VARIED TEST LEVELS, SHIELDED CABINET AND 4x8, 6x8 and 8x8 FOOT ENTRY PANELS

CONDUCTOR MEASURED	ENTRY PANEL	CURRENT PROBE LOCATION	TEST SOURCE	PEAK CURRENT IN AMPERES	PEAK TO PEAK CURRENT	PEAK CURRENT IN RES. DIVIDER	FIRST PEAK	OTHER CONDITIONS
Outboard Conduit to cabinet	4x8	Next to entry panel	UGT-15 1.7KV/m	13.6	27	21.4	2.6a	Power conduit grounded at beginning.
"	8x8	" "	"	11.4	21.4	21.4	11.4	" "
"	6x8	" "	"	10.7	16.5	21.4	2.5	" "
"	8x8	" "	"	7	14	21.4	7	Power conduit floating at beginning.
Inboard conduit to cabinet	4x8	" "	"	13.6	27.2	21.4	6.8	Power conduit grounded at beginning.
"	6x8	" "	"	11.4	22.8	21.4	11.4	" "
"	8x8	" "	"	13.6	23.6		7.14	" "
2 ea RG 213/U cables and 3 pair unshielded	4x8	Before entry panel	"	11.4	17.6	21.4	6.4	Power conduit grounded, one coax and unshielded cable hang under test line.
"	4x8	" "	"	10	15.7		5.7	Power conduit floating, one coax and unshielded cable hang under test line.
#4 AWG Jumper	6x8	Next to entry panel	"	10.3	19.3	21.4	3.2	" "
"	8x8	" "	"	10.4	19.3	21.4	3.6	" "
Power Conduit	4x8	" "	"	14.3	24.3	21.4	11.4	Power conduit grounded, one coax and unshielded cable hang under test line.
"	6x8	" "	"	25.7	47.1	21.4	25.7	" "
"	8x8	" "	"	22.8	25.8	21.4	18.9	" "
"	8x8	" "	"	17.1	27	21.4	17.1	Power conduit ungrounded, one coax and unshielded cable hang under test line.
"	8x8	" "	UGT-20 2.8KV/m	36	68.6	36	32	Power conduit grounded, one coax and unshielded cable hang under test line.
#4 AWG Jumper and Sealtite	4x8	" "	"	6.4	11.4	36	1.85	
"	6x8	" "	"	6.1	10	36	1.4	
"	8x8	" "	"	6.1	10	36	1.4	
rf tray	8x8	" "	"	28.6	57	36	22.9	
2 ea RG-213/U and 3 pair unshielded	8x8	" "	"	12.9	12.9	36	8.6	

TABLE IV (CONT)
INDUCED CURRENT MEASUREMENTS AT VARIED TEST LEVELS,
SHIELDED CABINET AND 4x8, 6x8 and 8x8 FOOT ENTRY PANELS

CONDUCTOR MEASURED	ENTRY PANEL	CURRENT PROBE LOCATION	TEST SOURCE	PEAK CURRENT IN AMPERES	PEAK TO PEAK CURRENT - AMPERES	PEAK CURRENT IN RES. DIVIDER		OTHER CONDITIONS
							FIRST PEAK CURRENT	
Power Conduit	8x8	Entry Panel Input	10KV/m	135.7	242.9	129	135.7	First peak current sum of all three connected input conductors 228.6a.
3 pair free hang and 2 RG 213/u cables	8x8	"	"	6.14	111.4	129	52.9	"
RF tray	8x8	"	"	107	161.3	129	40	"
Outer conduit to cabinet A	8x8	Entry Panel	"	42.9	62.9	129	18.6	First peak current sum of all connected output conduits 54.3a.
Inner conduit to cabinet A	8x8	Output "	"	42.9	71.5	129	21.4	"
#4 AWG Flex Jumper	8x8	"	"	14.3	27.2	129	14.3	"
								12.5 dB attenuation, input to output

TABLE V

INDUCED VOLTAGE MEASUREMENTS WITH EQUIPMENT CABINET USED AS THE ENTRY PANEL

CABLE CONFIGURATION	PROTECTOR INSTALLED	PEAK VOLTAGE IN VOLTS	PEAK TO PEAK VOLTAGE	EARLY FREQ. IN MHz	LATE FREQ. IN MHz	PEAK CURRENT IN RES. DIVIDER	OTHER CONDITIONS
Diagonal wire hung in cabinet, 62 inch		700	1200	100	50	129a, 10KV/m	Door open, wire floating, measured from wire to ground.
"		5	8.5	50		" "	Door closed, 43 dB shielding.
12 pair shielded in cable tray to Telco	2V DC - Zener	2.3V	3.1	41.6 (Noise)		" "	4V noise peaks superimposed protector fired and clipped.
block "	Parrallel Diodes	1.2	2	78	54	" "	Protector fired clipped.
"	14V AC MOV	9	15	100	50	" "	No clipping observed.
"	230V DC Gas Gap	7.8	11.6	62.5	13.2	" "	"
RG 8/U in rf tray	3.3V DC Coaxial tee	7.0	13.0	19 (Noise)	1.7 (Clipped)	" "	52 inch conductor hung from center conductor at beginning end; protector fired & clipped.
12 pair shielded cable in rf tray to Telco	14V AC MOV	.7	1.3	92		39a, 3KV/m	Insufficient voltage to fire protector.
block "	Parrallel Diodes	.75	1.25	89	31	" "	" "
"	2V DC - Zener	12	17	8.3	.9	Direct drive 6.7KV into cable	Cable pairs direct driven against shields and rf tray and ground, voltage clipping was observed.
"	Parrallel Diodes	1.35	2.35	8.5	.8	" "	" "
12 pair shielded to Christmas Tree block	2V DC diodes	7.2	10.1	20.8	2.2	" "	" "
"	Short circuit	1.9	2.5	93.8	7.8	" "	" "
12 pair shielded to Telco Block	"	.44	.64	62.5	8.3	" "	" "
"	14V AC MOV	85	160		.87	" "	" "
"	25V AC MOV	95	180		.96	" "	" "
"	16V DC Zener	40	74		.96	" "	" "
"	250V AC MOV	1500	2260		1.0	" "	Single pair direct driven pair to shield and ground.
"	230V DC Gas Gap	720				" "	Single pair direct driven pair to shield and ground. 32 ns clipped pulse width.

TABLE VI

VOLTAGE MEASUREMENTS WITH CABLES DIRECTLY DRIVEN

CABLE CONFIGURATION	PROTECTOR INSTALLED	PEAK VOLTAGE IN VOLTS	TIME TO ZERO CROSSOVER	EARLY FREQ. MHz	LATE FREQ. MHz	OTHER CONDITIONS
12 pair shielded to entry panel						12 pair individual shield cable driven direct, at beginning, with all pair conductors parallel against shields, 3.8KV peak, 4 ns rise time.
"						Measures 11.8KV peak into 50 ohm load at 12 pair cable feed point.
"	3 30 Ω resistor termination only	4KV	208ns			Measured one pair conductor to case in cabinets.
"	230V DC Gas Gap	2.4KV	60ns		6.3	" "
"	"	3KV	32ns	17.9	3	Measured pair to pair in cabinet.
"	10V DC Zener	12V	80ns	5	.71	Measured pair to ground in cabinet.
"	Parrallel Diodes	5V	60ns	25		" "
"	230V DC Gas Gap pair to pair at E.P.	1400V	40ns	19		Measured pair to pair in cabinet.
"	75V DC Gas Gap	1250V	16ns			Measured pair to ground.
"	130V AC MOV	504	180ns		1.32	Measured pair to ground in cabinet.
"	200V DC Zener	400	180ns		1.36	" "
"	25V AC MOV	136	104ns	7.4	1.39	" "
"	2V DC Zener	5.9	40ns	9.6		" "
"	275V AC MOV	610	120ns	12.5	1.36	" "
"	"	1000	97ns	16	1.36	Measured pair to pair.
"	145V DC Gas Gap	1800	13ns			Measured pair to ground.
"	230V DC Gas Gap	2400	19ns			" "
"		4.8	40ns	25	6.8	Shielded pair run from 4x8 entry panel to cabinet only; pair floating each end, grounds connected measured pair to ground in cabinet.
"		4	50ns	96	6.8	Shielded pair from 4x8 entry panel to cabinet only; all grounded at entry panel and floating at cabinet measured pair to ground in cabinet.
"		8.6	64ns		7.3	Ditto above, except floating each end. Measured pair conductor to ground in cabinet.

TABLE VI (CONT)

VOLTAGE MEASUREMENTS WITH CABLES DIRECTLY DRIVEN

CABLE CONFIGURATION	PROTECTOR INSTALLED	PEAK VOLTAGE IN VOLTS	TIME TO ZERO CROSS-OVER	EARLY FREQ. MHz	LATE FREQ. MHz	OTHER CONDITIONS
4 pair unshielded free hung under test line	None	1500V First 2000V Max		25	6.3	4 pair free hung unshielded cable direct driven against ground and rf cable tray. Measured to ground at cabinet.
"	"					14KV peak at drive point, 8 ns rise time. Two pair grounded at entry panel, 2 pair into 330 at cabinet.
"	Diodes-Parrallel	26	20	25	7.4	Measured pair to ground at cabinet. 3KHz clipped ± .6V after 3..
"	14V AC MOV	33	20	7.1	1.1	" "
"	Parrallel diodes at panel and cab.	5	20		6.5	3KHz square clipped pulse, ±.65V after 3.4 μs.
"	25V AC MOV	75	500	7.7	0.9	

TABLE VII

SHIELDING EFFECTIVENESS MEASUREMENTS IN SHIELDED EQUIPMENT CABINET USING 62 INCH DIAGONAL WIRE PICKUP

SIZE OF ENTRY PANEL	PEAK VOLTAGE DOOR OPEN	PEAK VOLTAGE DOOR CLOSED	PEAK CURRENT IN RESISTANCE DIVIDER	APPARENT ATTENUATION	OTHER PERTINENT TEST CONDITIONS
					Diagonal wire floating at ends for all tests, measured at one end to case with high impedance probes.
4x8	170V, 330 pk to pk	20V, 39V pk to pk	129a, 10KV/m	18.6 dB	No Cabinet B shielding measures provided on any seams. Door panels Cables in place between entry panel and cabinet.
4x8	100V, 175V " "	34V, 68V pk to pk		9.4 dB	Cabinet A door and rear panel seams with rf gaskets. Air slots in door not covered. No shielding measures provided on other enameled seams. Cables in place between entry panel and cabinet.
8x8	450V, 950V pk to pk	8V, 15V pk to pk	129a, 10KV/m	35 dB	All seams treated with silver epoxy, 2 EMT conduits, 1 Type UA flexible "Sealtite" to entry panel. Air slots in door not covered.
4x8	200V, 390V " "	5V, 9V pk to pk	36a, 2.8KV/m	32 dB	" "
					Made MIL-STD-285 loop to loop measurements at 100KHz on cabinet with all seams coated with silver epoxy and cables removed. Measured shielding effectiveness ranged from 20 to 37 dB, with lowest readings at hinged door uncovered air vent slots, top and bottom.
4x8	1KV, 1.75KV pk to pk	10V, 19V pk to pk	129a, 10KV/m	40 dB	With diagonal 62 inch #16 wire hung 22 inches below test conductor to resistance divider and 51 inches above floor. 17.5KV peak was measured for an apparent 64.9 dB to wire inside closed cabinet. All seams treated with silver epoxy. Cables except power removed.

APPENDIX A-1

SUPPRESSOR IDENTIFICATION FOR SYSTEM DIAGRAMS

1. Coaxial Tee In-Line Transient Suppressor

   a. FCC 250-75-UHF
   b. FCC 450- 3.3-PHONO
   c. FCC 250-230-UHF
   d. FCC 450-75-N
   e. FCC 450-100-UHF
   f. FCC 450-75-UHF
   g. FCC 450-130-UHF
   h. FCC 450-130-N
   i. FCC 450-3.3-BNC
   j. FCC 250-75-N
   k. FCC 450-6.8-BNC
   l. FCC 450-3.3-UHF
   m. FCC 450-3.3-N
   n. FCC-250-350-UHF
   o. FCC-250-470-UHF
   p. FCC-250-1000-N
   q. FCC-250-1000-UHF

2. Communication Gas Gap

   a. CG-75-L C.P. Clare
   b. CG-230-L C.P. Clare
   c. CG-145-L C.P. Clare

3. RF Transient Suppressor, Diode Bridge Configuration

   a. FCC 450-6.8-L
   b. FCC 450-3.3-L

4. Metal Oxide Varistor

   a. V130LA10A GE
   b. V130PA20A GE
   c. V275LA20A GE
   d. V275PA20A GE
   e. V39ZA6 GE
   f. V480PA20A GE
   g. V480LB20A GE
   h. V22ZA3 GE

4. Metal Oxide Varistor (cont'd)

   i. V510LB40A GE
   j. V480PA40A GE
   k. V150LA20B GE
   l. V130-HE-150GE
   m. V250PA40C GE
   n. V320PA20C GE
   o. V275-HE-250GE
   p. V250LA15A GE
   q. V480-HE-450 GE

5. Bipolar Semiconductor Transient Suppressors

   a. GHV-2 GSI
   b. GHV-4 GSI
   c. GHV-7 GSI
   d. 1.5KE7.5C or P6KE8.2C GSI
   e. GSV-103 GSI
   f. 1.5KE16C GSI
   g. 1.5KE36C GSI
   h. 1.5KE68C GSI

7. Grounding, Counterpoise, and Jumper Materials

   a. 1 inch tinned copper braid
   b. Conductive epoxy
   c. Rubber sealant tape
   d. Electrical tape
   e. 2/0 crimp terminal for copper braid
   f. 3/8-24 bolt, flatwasher, lockwasher, nut, cadmium plated.
   g. Emory cloth
   h. Hose clamp, stainless steel, ½ to 1-inch
   i. Hose clamp, stainless steel, 1 to 2 inches
   j. Ground clamp 5/8-1" (J)

7. *Grounding*, Counterpoise, and Jumper Materials (Cont'd)

   k. Ground Clamp 1¼-2" (J-2)
   l. Ground Clamp 2½-4" (J2124)
   m. 3/4-inch copper tubing
   n. 1/2-inch copper tubing, 60 ft. coil
   o. Terminal lug, 4-14 AWG
   p. #4 AWG copper conductor, bare
   q. 3-inch copper strip
   r. 1-inch wide copper strip

8. Gas Gaps

   a.
   b.
   c. UGT-3 C.P. Clare
   d. UGT-4 C.P. Clare
   e. UGT-5 C.P. Clare
   f.
   g. UGT-7.5 C.P. Clare
   h.
   i.
   j. UGT-10 C.P. Clare
   k.
   l.
   m.
   n.
   o. UGT-15 C.P. Clare
   p.
   q.
   r.
   s.
   t. UGT-20 C.P. Clare
   u.
   v.
   w.
   x. SG-30 C.P. Clare
   y. SG-40 C.P. Clare
   z. TG-60 C.P. Clare

9. Plug-In MOV KIt

   a. 3-prong 130V, male plug
   b. Cube tap
   c. V130LA10 MOVs
   d. #14 AWG stranded ground lead
   e. Crimp terminal
   f. In-Line Cord Protector

10. Gas Gap Installation Materials

   a. Tungsten wire
   b. Standoff insulator NL523W03-016 - 3-inch
   c. Replaceable fuse and clips 3-inch
   d. Insulator - 6-inch
   e. Replaceable fuse and clips 4-inch

11. Surge Arresters

   a. Lightning arrester, pole mounting, single phase GE9L15BCA006
   b. Lightning arrester, 3KV, single phase GE9L28AFJ101
   c. Secondary Surge Arrester, 0-650 volts, 3 phase GE9L15BCC003
   d. Home Lightning Protector, 120/240, 3 wire, single phase *GE9L15DCB002*

12. Crimp-On Terminal Lug

   a. Ring tongue for #8 stud, #22-18 wire
   b. Spade with flange for #6 stud, #22-18 wire
   c. Butt connector for #22-18 wire
   d. Male tab for #18-14 wire
   e. Female tab for #18-14 wire

13. Hardware, cadmium plated steel

   a. 3/8-24 x 1-inch bolt
   b. 3/8-24 nxt
   c. 3/8 flatwasher
   d. 3/8 internal-external lockwasher
   e. 10-32 x 3/4-inch machine screw
   f. 10-32 x 3/8-inch machine screw
   g. #10 internal-external lockwasher
   h. #10 flatwashers
   i. #8 sheet metal screws
   j. #8 internal-external lock washers
   k. #12 Star-lock washers
   l. #8 flatwashers

13. Hardware, cadmium plated steel (Cont'd)

    m. Pop rivets
    n. 1/4" Star-lock washers

14. Miscellaneous

    a. EMP labels
    b. Crimper
    c. Riveter
    d. Drills, #21, #29
    e. Tap 10-32
    f. Shrink tubing
    G. Teflon sleeving

APPENDIX A-2

Coupling of EMP Transients at Protector Installation Locations

Following the EMP protection concept utilized, the shielded pair signal and control cables and conduit protected power conductors are run from exterior locations to the single entry panel boxes where protectors are installed. From here they run to individual equipment connections inside the shielded cabinets. At the point where the shielded pairs are connected to the EMP protectors on a connection block, the pairs must necessarily come out of the pair shielding for some minimum distance to make connections. The small loop formed by the pair conductor terminal block connection, and the shield wire and case ground return is like a small section of open transmission line with a protector shunting from near its center (at a high impedance until it conducts) to ground. Each end of the open loop connects to a section of the shielded pair. In the experiments conducted in this study, the shielded pair cables were aluminum foil wrapped, 22AWG pairs with a drain wire. Characteristic impedance of these pairs was determined experimentally to be approximately 66 ohms pair to pair and 33 ohms pair to shield.

Transient currents flowing in the shield wire can induce a voltage from the pair conductor to shield in the section where the protector is installed. Also, transient currents in pair conductors can induce current in adjacent pair conductors in the protector section. Further, the peak voltage limiting provided by the protector shunting the pair conductor to ground is limited to the voltage drop across its lead inductance. When you are attempting to reduce fast rise EMP transient voltages passing protectors to connected loads down to levels consistent with operational signal voltages, considerable care must be taken in the design and layout of the protector terminal block and ground bus connections to minimize necessary lead lengths, loop areas and routing of shield currents.

First, we will examine the transient voltage drop across a wire jumper, simulating a shorted protector shunting a shielded pair conductor to shield with the minimum possible lead length determined by the protector body and lead length. The shielded pairs were connected to a screw terminal block nested in a U-channel grounding strip similar to Figure A-2-1. Three terminals were used to bring the pair and shield drain wire across the terminals with about 7/16" spacing. In this experiment an incident transient voltage is approximated by a double exponential of the form

$$V_i(t) = V_o(e^{-\alpha t} - e^{-\beta t}).$$

$$= 1027\,(e^{-.023\times10^9 t} - e^{-.123\times10^9 t})\,\text{Volts} \qquad \text{(2A-1)}$$

The same test transient plotted in Figure A-2-2 and recorded in Figure A-2-3, was utilized in all of the experiments so that changes in response of the various configurations could be compared directly. The transient voltage used had a 12 nanosecond rise time, a peak value of 570 volts into 33 ohms, the characteristic impedance of the pair conductor to shield. Time to 50% was approximately 60 nanoseconds from pulse initiation. The pulse source had a series resistance matching the line impedance so that reflections from the source direction were minimized.

The shielded pairs were connected with matched terminating resistors so that the connected lines looked like infinite lines as far as end reflections were concerned. On the terminal block source side, a shielded pair was driven common mode with the pair conductors connected in parallel and driven against the shield as a return. On the receive side, a five foot length of shielded pair conductors was terminated in 33 ohm resistors to the shield wire. In the first experiment, the right angle short at the terminal block between each pair conductor and the shield wire was treated theoretically as a pure inductance short across a transmission line. The expression for the transmitted voltage, $V_L(t)$, passed the short impedance Z_L is expressed as the following from reference (1):

$$V_L(t) = \frac{2Z_L\ Z_o/(Z_L + Z_o)}{Z_o + Z_L\ Z_o/(Z_L + Z_o)} V_i(t) = \frac{2Z_L\ V_i(t)}{2Z_L + Z_o} \quad \text{(2A-2)}$$

Here the incident voltage is $V_i(t)$. Z_L is the impedance of the short circuit, and Z_o is the characteristic impedance of the incoming and outgoing transmission line connections, (one pair conductor to shield). Using Laplace transforms, we have in the S domain:

$$V_L(s) = \frac{2\ L\ s\ V_o}{2Ls + Z_o} \left(\frac{1}{s + \alpha} - \frac{1}{s + \beta}\right)$$

$$= V_o \frac{s}{(s + Z_o/2L)} \left(\frac{1}{(s + \alpha)} - \frac{1}{(s + \beta)}\right) \quad \text{(2A-3)}$$

where $Z_L(s) = j\omega L = sL$

and $V_i(s) = V_o \left(\frac{1}{s + \alpha} - \frac{1}{s + \beta}\right)$

Converting back to the time domain gives:

$$V_L(t) = V_o \left\{\frac{(Z_o/2L)\ e^{-(Z_o/2L)t} - \alpha e^{-\alpha t}}{(Z_o/2L - \alpha)} - \frac{(Z_o/2L)\ e^{-(Z_o/2L)t} - \beta e^{-\beta t}}{(Z_o/2L - \beta)}\right\} \quad \text{(2A-4)}$$

The inductance in microhenries of a minimum length short circuit lead installed at right angles to the pair connections similar to those seen in Figure A-2-1 can be calculated approximately from a handbook formulae for a wire above a ground plane, Reference (2) as follows:

$$L = .002\ell \left(2.3026 \log_{10} \frac{4\ell}{d} - Q + \mu\delta\right) \qquad (2A\text{-}5)$$

where: ℓ = length of the conductor in cm.

$\frac{\ell}{2h} \leq 1$, h = height above ground in cm.

D = conductor diameter in cm.

Q = a value from Table 3, Reference (2).

μ = 1 for non-ferrous metals.

δ = 0 at high frequencies.

For the experimental minimum short circuit the length ℓ was 1.1 cm, the height h was 0.95 cm, the diameter D was .0635 cm, and the factor Q was 1.287, resulting in an inductance of .007 microhenries. Using this inductance, and the exponential constants from equation 2A-1 substituted in equation 2 A-4, we result in the voltage passed the short circuit recorded in Figure A-2-4 and plotted in Figure A-2-5.

A better theoretical approximation, to the experimental case is made if we add a small series inductance approximately equal to the short circuit inductance before and after the short. We then have as a final expression in the time domain:

$$V_o(t) = \frac{V_o Z_o}{3L} \left(3\,\frac{\left(e^{-\alpha t} - e^{-\frac{Z_o t}{L}}\right)}{Z_o/L - \alpha} - 3\,\frac{\left(e^{-\beta t} - e^{-\frac{Z_o t}{L}}\right)}{Z_o/L - \beta} - \frac{\left(e^{-\alpha t} - e^{-\frac{Z_o t}{3L}}\right)}{Z_o/3L - \alpha} + \frac{e^{-\beta t} - e^{-\frac{Z_o t}{3L}}}{Z_o/3L - \beta} \right) \qquad (2A\text{-}6)$$

If we let Z_o = 33 ohms, L = .007 μh, $\alpha = .023 \times 10^9$, $\beta = .123 \times 10^9$, and V_o = 1027 Volts in equation 2A-6, and compare this approximation with the previous curves, we see the resulting Figure A-2-5. The theoretical curves are slightly higher in peak value, and lead the measured response by a few nanoseconds. Part of the problem in exactly matching the theoretical curves to the measured curves is the choice of a simple double exponential expression to represent the test transient. Radiated fields generated by the test generator circuits tend to arrive at the recording equipments ahead of conducted signals, distorting the low level leading edge of measured transients.

The fit of the theoretical test voltage curve to the measured curve in Figure A-1-2, was greatly enhanced by adding a time delay (4 nanoseconds) to the plot of the theoretical curve in Figure A-2-2. A small part of this apparent delay can be blamed on the low pass filtering resulting from band width limitations of the Tektronix-475 (200 MHz band width) oscilloscope. An additional slight delay could be caused by probe capacitance at the terminal block connections (not included theoretically). Another contributing factor is thought to be the stray capacitance of the shield of the five foot transmission line length connected to the output side of the terminal block. Voltages at the terminal block were measured by an oscilloscope and probe which were floating with respect to the counterpoise formed by the shielded enclosure wall. A shielded enclosure was also used to isolate the test pulse generator from the terminal block and measurement equipments. The U-channel ground at the terminal block was connected to the wall of the shielded enclosure at the point where the driven shielded pair penetrated the wall. An exponentially damped sinusoidal modulation was seen on most of the pair to shield measured curves which corresponded in frequency to a quarter wavelength resonance of a five foot length conductor. This was the length of the attached, terminated section of shielded pair cable used to connect a matched transmission line load to the terminal block.

Next, we will consider the effect of the lead inductance of a protector, which has been installed in a configuration which provides for mutual inductance between the protector leads and the protected pair conductor. The protectors seen installed at the terminal block in Figure A-2-1, are silicon diodes, with two parallel, but opposing direction diodes, packaged in one unit. This is the smallest protector physically as well as lowest voltage clipping device used in the FEMA EMP protection programs. As seen in Figure A-2-1, protectors are connected from the screw terminals back to the U-channel ground strip, alongside the pair conductors. The mutual inductance of pairs of wires over a ground plane is plotted in Figure A-2-6, along with self inductance for a single wire over a ground plane. Inductance formulae are obtained from reference (2). The curves are approximations for the mutual and self-inductance of conductors attached as seen on the terminal block and U-channel ground configuration of Figure A-2-1. Installed in this configuration, the mutual inductance tends to cancel out part of the self-inductance of the protector leads.

First, we will examine a protector installation with no connected output pairs. With similar treatment given in equations 2A-1 and 2A-2, we have an expression for the voltage at the protector screw terminal referenced to the ground strip as follows:

$$V_L(t) = V_o \left(\frac{\alpha e^{-\alpha t} - (Z_o/2(L-M))\, e^{-(Z_o/2(L-M))t}}{(\alpha - Z_o/2(L-M))} - \frac{\beta e^{-\beta t} - (Z_o/2(L-M))\, e^{-(Z_o/2(L-M))t}}{(\beta - Z_o/2(L-M))} \right) \qquad (2A-7)$$

where L is the self-inductance of the protector replaced with a short circuit, it is also the inductance of the length pair conductor between the screw terminal and the penetration through the grounding channel, laying alongside the short circuit. In this treatment, mutual inductance between pair conductors on adjacent terminals were neglected in comparison with mutual inductance M of the closely spaced short circuit to pair conductor. Using the same exponential expression given in equation 2A-1 for the test transient, and values for self inductance L and mutual inductance M from Figure A-2-6 for dimensions of d, h. ℓ, and D measured at the terminal block and ground strip of Figure A-2-1, we show the expression and curve in Figure A-2-7 where values of the constants were as follows:

$L = .009\ \mu h$	$V_o = 1027$ Volts
$M = .006\ \mu h$	$\alpha = .023 \times 10^9$
$Z_o = 33$ ohms	$\beta = .123 \times 10^9$

If the above circuit configuration is connected to a terminated transmission line load, the expression for voltage out V_{Zo} (t) becomes:

$$V_{Z_o}(t) = \frac{V_oZ_o}{L-M}\left(\frac{2.34(e^{-\alpha t} - e^{-(2.62Z_o/(L-M))t})}{(2.62Z_o/(L-M) - \alpha)} - \frac{2.34(e^{-\beta t} - e^{-(2.62Z_o/(L-M))t})}{(2.62Z_o/(L-M) - \beta)} - \frac{.342(e^{-\alpha t} - e^{-(.382Z_o/(L-M))t})}{(.382Z_o/(L-M) - \alpha)} + \frac{.342(e^{-\beta t} - e^{-(.382Z_o/(L-M))t})}{(.382Z_o/(L-M) - \beta)}\right) \quad (2A-8)$$

These theoretical expressions are plotted in Figure A-2-7 in comparison to the measured curves, seen in Figures A-2-8 and A-2-9, using the above constants for L, M, Z_o, V_o, α and β. The circuit diagrams for the two cases are also shown in Figure A-2-7. This short circuit would be the lowest level possible passed transient at the terminal block with the particular test voltage used. If we now install the minimum clipping level protector, the parallel diode stack (GSV-103), as seen in Figure A-2-1, we result in a recorded voltage transient measured pair to ground seen in Figure A-2-10. For the same test transient, the 36 volt peak passed the diodes compared to 15 volts passing the short circuit (Figure A-2-9). Part of the beneficial mutual inductance was lost in the diode installation because the body of the protector forces the pair conductor and protector lead further apart. Most of this mutual inductance can be recovered by wrapping two turns of the pair conductor around the protector lead (determined experimentally), just ahead of the protector body at the screw terminal connection. The result is seen in Figure A-2-11, with a 17.8 volt peak. The differential voltage (pair to pair) is seen in Figure A-2-12, with a 4-volt peak. In a practical installation, the transient voltages passing the diode protector because of lead inductance, can be reduced to nearly background noise level by adding an additional diode protector at the equipment or load connection. The results can be seen in Figure A-2-13. This reduction occurs because the current level is very low, remembering that the voltage across the inductance $V_L(t)$ is proportional to the time rate of change of the current

$$V_L(t) = L\, di/dt$$

When conductors run in parallel within the same metal shield or tray, or run above a common ground plane, there is a mutual coupling of common mode signal currents among the conductors both through magnetic and capacitive coupling, (Reference (3)). For clusters of individual foil shielded pairs, the shield currents will couple, but the protected pairs will, because of the superior foil shielding, have greatly reduced common mode voltages induced. The induced common mode voltage is approximately equal to the DC resistance of the shield times the shield current. At the locations where individually shielded pairs are brought out of the shields to terminal blocks or equipment connections, there exist small open wire loops formed between the pair conductors fastened to the terminals and the ground plane where coupling can cause voltages to be induced in the pairs, (Reference (4)). By using a U-channel ground strip and foil shielded pairs as seen in Figure A-2-1, this open loop mutual inductance coupling to adjacent pair conductor loops can be minimized.

Let us consider two adjacent sets of foil shielded pairs, connected through a block and ground strip as seen in Figure A-2-1. Both conductors in one source pair will be driven in a common mode against the shield from a remote transient voltage source, and the receiving pair will be terminated in characteristic impedance loads at each end. The loop formed at the terminal block by the driven pair will be [illegible]lled the receiving loop. First we will consider the mutual inductance coupling between the closest adjacent source and receiving loops (inboard) at the terminal block. We will neglect capacitance coupling which is very small in the loop area. Also, magnetic coupling from the source conductor loops to the further removed (outboard) receiving pair conductor loop will be neglected at first. We see in Figure A-2-6, that the mutual inductance decreases rapidly with separation distance, for dimensions typical at the terminal block and ground strip. The magnitude of the error resulting from neglecting the coupling between the outboard conductor loops of the source and receiving pairs will be observed in the measurement of differential mode (pair conductor to pair conductor) induced voltage. The differential mode voltage would be zero if both conductors in a shielded pair received the same common mode induced voltage at the open loop area at the terminal block. We will diagram the simplified circuit in Figure A-2-14 where only one conductor in each shielded pair is shown. Considering only mutual inductance coupling, we have the following mesh equation for the receiving loop:

$$0 = I_1 \, (-j\omega M) + I_2 \, (Z_o + Z_o + j\omega L_2) \qquad \text{(2A-9)}$$

then $$I_2 = \frac{j\omega M I_1}{2Z_o + j\omega L_2} \qquad \text{(2A-10)}$$

also $$V_2 = I_2 Z_o = \frac{j\omega M Z_o I_1}{2Z_o + j\omega L_2} \qquad \text{(2A-11)}$$

Considering again the response to a double exponential transient we let

$$I_1(t) = \frac{V_1(t)}{Z_o} = \frac{V_o}{Z_o} \, (e^{-\alpha t} - e^{-\beta t}) \qquad \text{(2A-12)}$$

using Laplace transforms we have in the S domain

$$V_2(s) = \frac{sM \, V_o}{L_2 \left(s + \frac{2Z_o}{L_2}\right)} \left(\frac{1}{s+\alpha} - \frac{1}{s+\beta}\right) \qquad \text{(2A-13)}$$

converting this expression back to the time domain gives

$$V_2(t) = \frac{V_o M}{L_2} \left(\frac{(\alpha e^{-\alpha t} - (2Z_o/L_2) \, e^{-(2Z_o/L_2)t})}{(\alpha - 2Z_o/L_2)} - \frac{(\beta e^{-\beta t} - (2Z_o/L_2) \, e^{-(2Z_o/L_2)t})}{(\beta - 2Z_o/L_2)} \right) \qquad \text{(2A-14)}$$

We will let V_o = 1027 Volts, $\alpha = .023 \times 10^9$, $\beta = .123 \times 10^9$

Zo = 33 ohms, ℓ = 1.8", h = .36", D = .22" (Center Section)

d = .025" D = .43" to .87" (End Sections)

Finding inductance from Figure A-2-6, we have

$$M = .0044\ \mu h \text{ (nearest source and receiver conductors)}$$

and $L_2 = .03\ \mu h$

If we now calculate mutual inductance from the remote source conductor to the inner, or nearest, receiver loop conductor, we have

$$M = .001\ \mu h$$

We see from expression 2A-14, that the coupled voltage in the receiving circuit is directly proportional to the mutual inductance M. The measured and calculated transient voltages are plotted in Figure A-2-14. Here we have one theoretical curve for coupling between one source pair conductor loop with test current induced and one receiving conductor loop in the adjacent pair. Then if we add to the first curve the mutual inductance effect of a second test pair conductor, further removed in distance but directly additive because they are coherent in time, we get the larger curve seen in Figure A-2-14. The conductors in the source pair were driven pair to shield in parallel. The recorded voltage trace in the receiving loop circuit is seen in Figure A-2-15.

Shorting out the source pair conductors to ground at the load side of the terminal block results in approximately double the induced voltage in the receiving pair as seen in Figure A-2-16. This is as expected since short circuit current is double the matched load current in a transmission line, and by installing the shorts on the load side of the terminal block, the size of the source loop is the same as before it was shorted. The pair to pair differential mode induced voltage is seen in Figure A-2-17 and is not equal to zero because there is a difference in coupling distance (and mutual inductance) between source pair loops and the nearest and the most remote receiving pair loops. If we install the short circuit alongside the pair conductor on the source side of the terminal block, then we have reduced the size of the source coupling loop to a bare minimum. As a result, the coupled voltage from open loops at the terminal block from a driven source, pair loop to a receiving pair loop is reduced to a low level as seen in Figure A-2-18 measured pair to ground, and Figure A-2-19 measured pair to pair. If we make this same measurement with the short circuits replaced with diode protectors, as seen in Figure A-2-1, we see the coupled pair to ground measurement in Figure A-2-20, and pair to pair in Figure A-2-21. For the test transient used, this diode pair represents the largest level of current during firing of the protector, of all of the protectors utilized, and thus the greatest potential coupling to adjacent pairs.

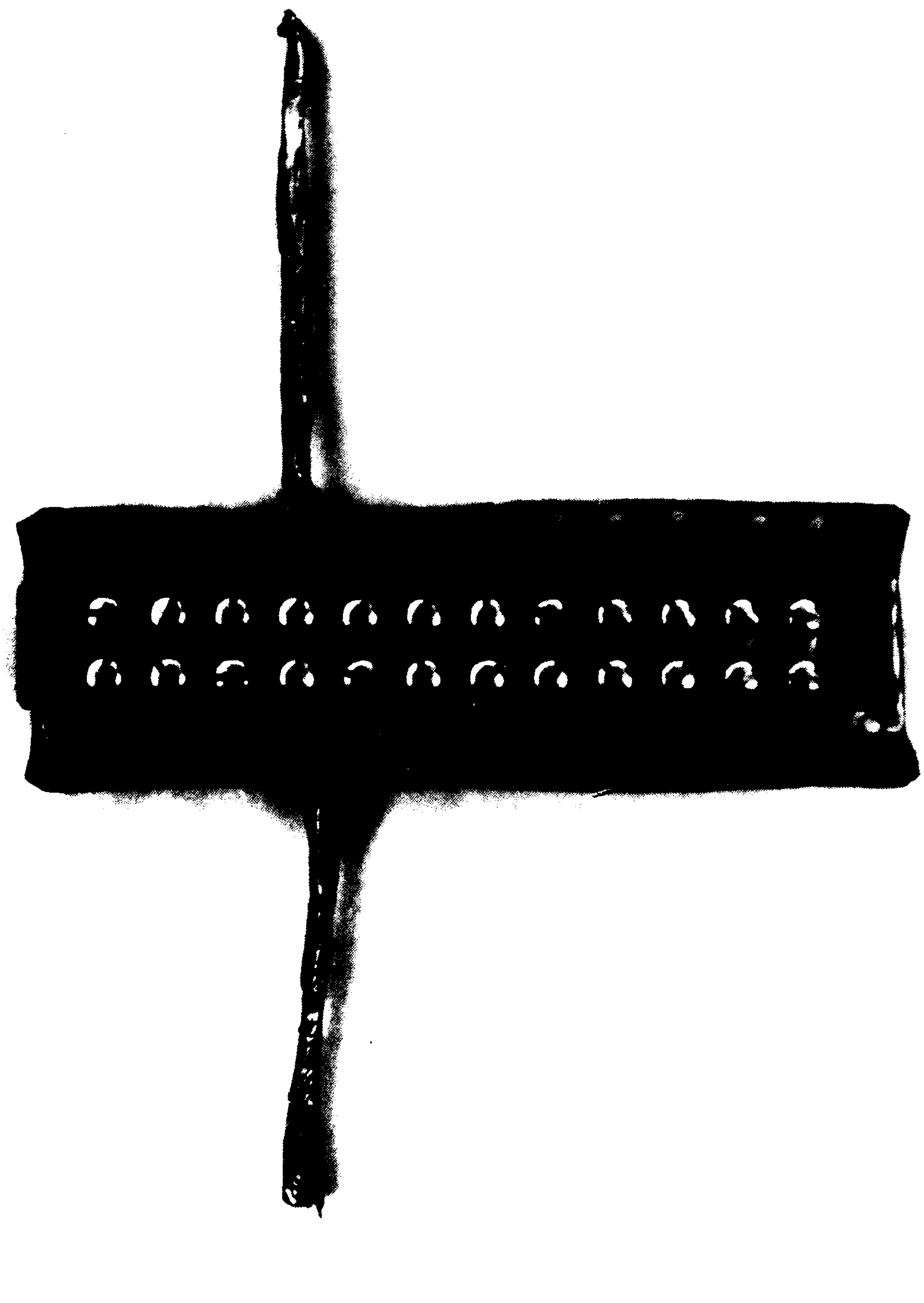


Figure A-2-1. Terminal block nested in a U-channel ground strip.

TEST TRANSIENT - $V(t) = 1027(e^{-.23 \times 10^{8}} - e^{-1.23 \times 10^{8}})$

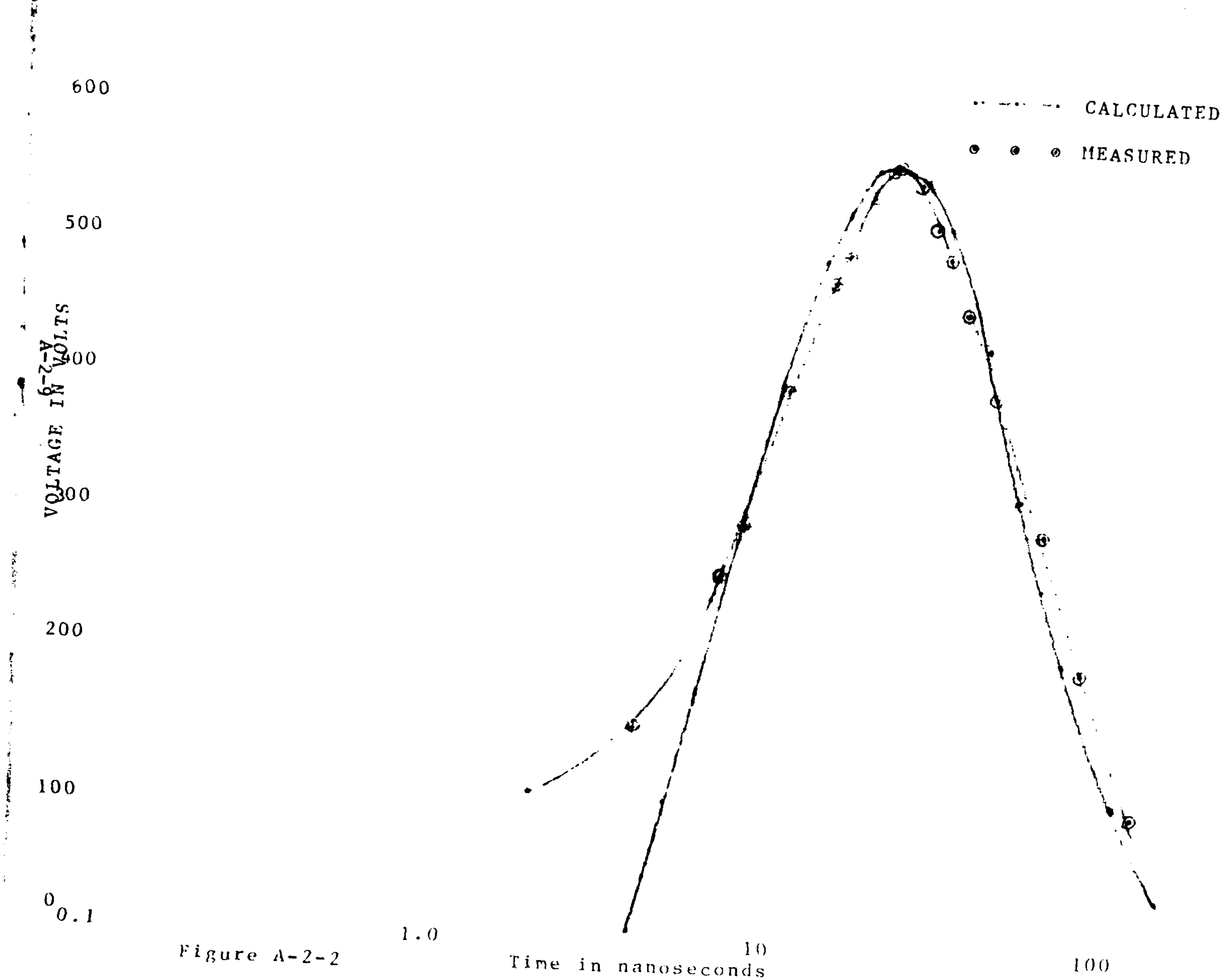


Figure A-2-2

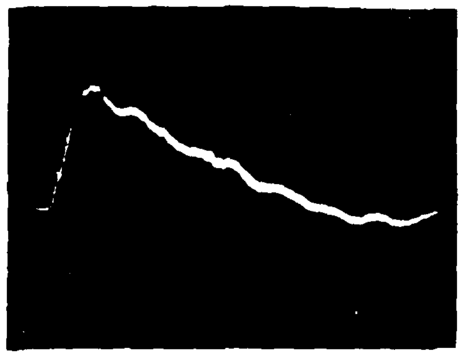


Figure A-2-3 Test transient recorded at the terminal block. 568 Volts peak, 20 nanoseconds/division.

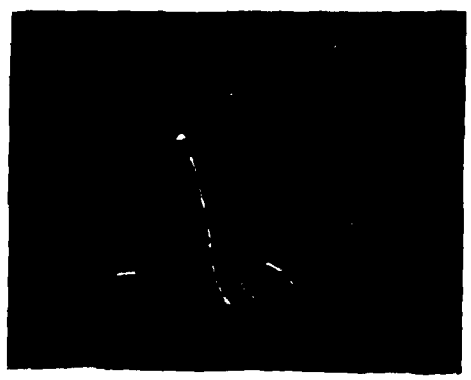


Figure A-2-4. Transient recorded at the short circuit. 32 Volts peak, 10 nanoseconds/division.

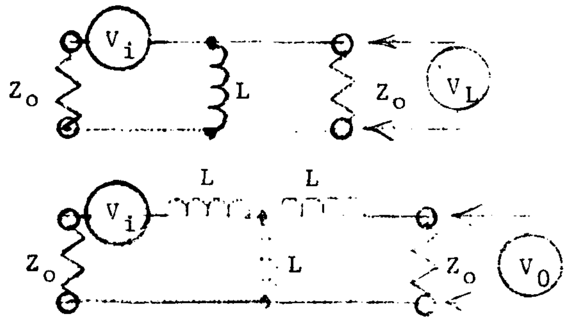
TRANSIENT PASSED BY TRANSMISSION LINE SHUNT

$$V_L(t) = 1027(\,.072\, e^{-.123 \times 10^9 t} - .0593 e^{-1.833 \times 10^9 t} - .0127 e^{-.023 \times 10^9 t}$$

$$\begin{aligned} V_0(t) = {} & 1032(e^{-.023 \times 10^9 t} - e^{-4.714 \times 10^9 t}) \\ & -1054.7(e^{-.123 \times 10^9 t} - e^{-4.714 \times 10^9 t}) \\ & -1042.4(e^{-.023 \times 10^9 t} - e^{-1.5714 \times 10^9 t}) \\ & +1114.3(e^{-.123 \times 10^9 t} - e^{-1.5714 \times 10^9 t}) \end{aligned}$$

o———o———o Experimental Curve

•- - - • - - - • Calculated Curve



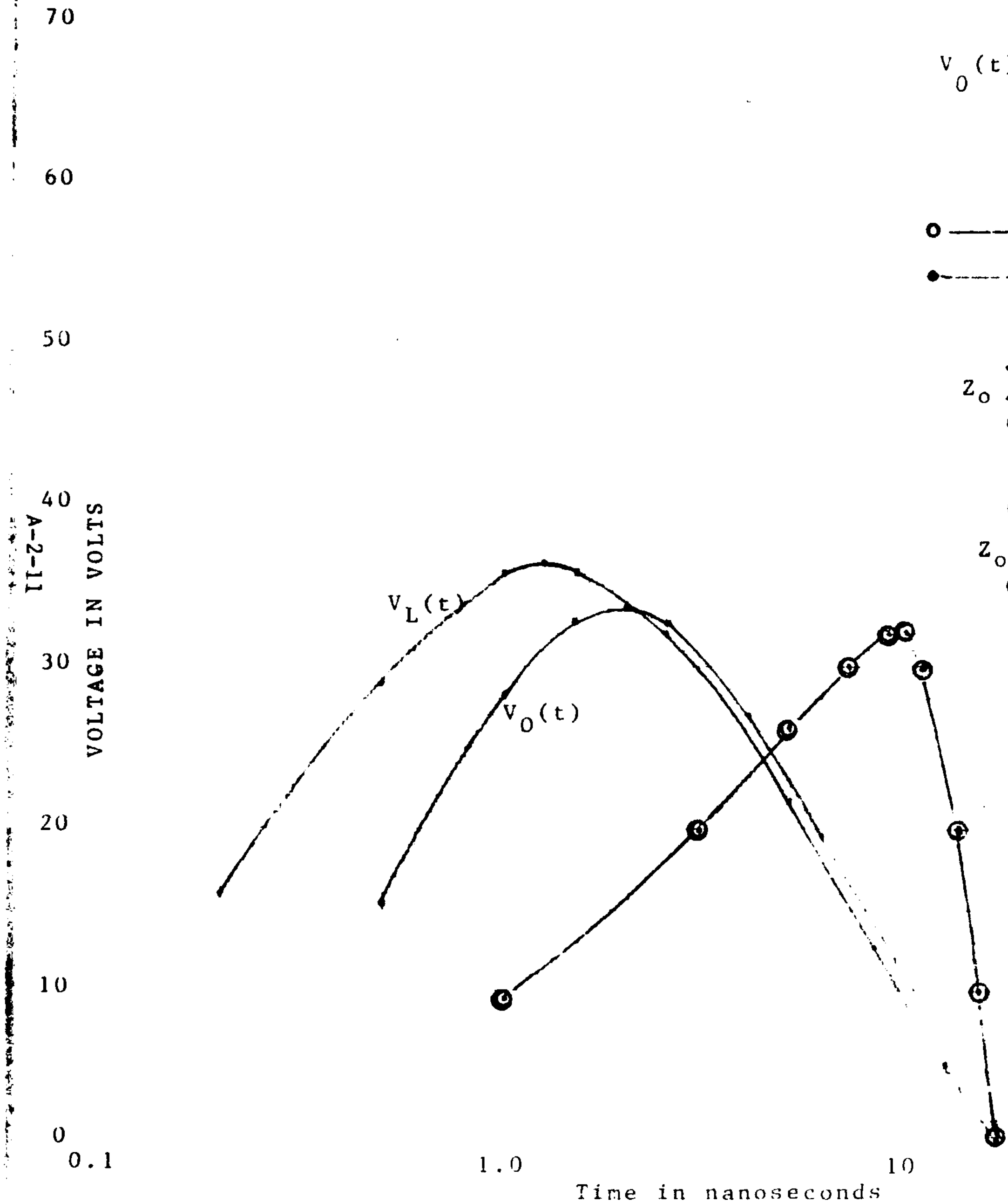
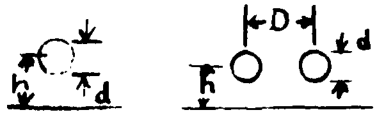


Figure A-2-5

$$L = .002\ell\,(2.3026L_{10}\ 4h/d - P)$$

$$M = .002\ell\,(2.3026L_{10}\ 2h/D - P + D/\ell)$$



MUTUAL AND SELF INDUCTANCE OF A WIRE AND PAIR OF WIRES ABOVE A GROUND PLANE

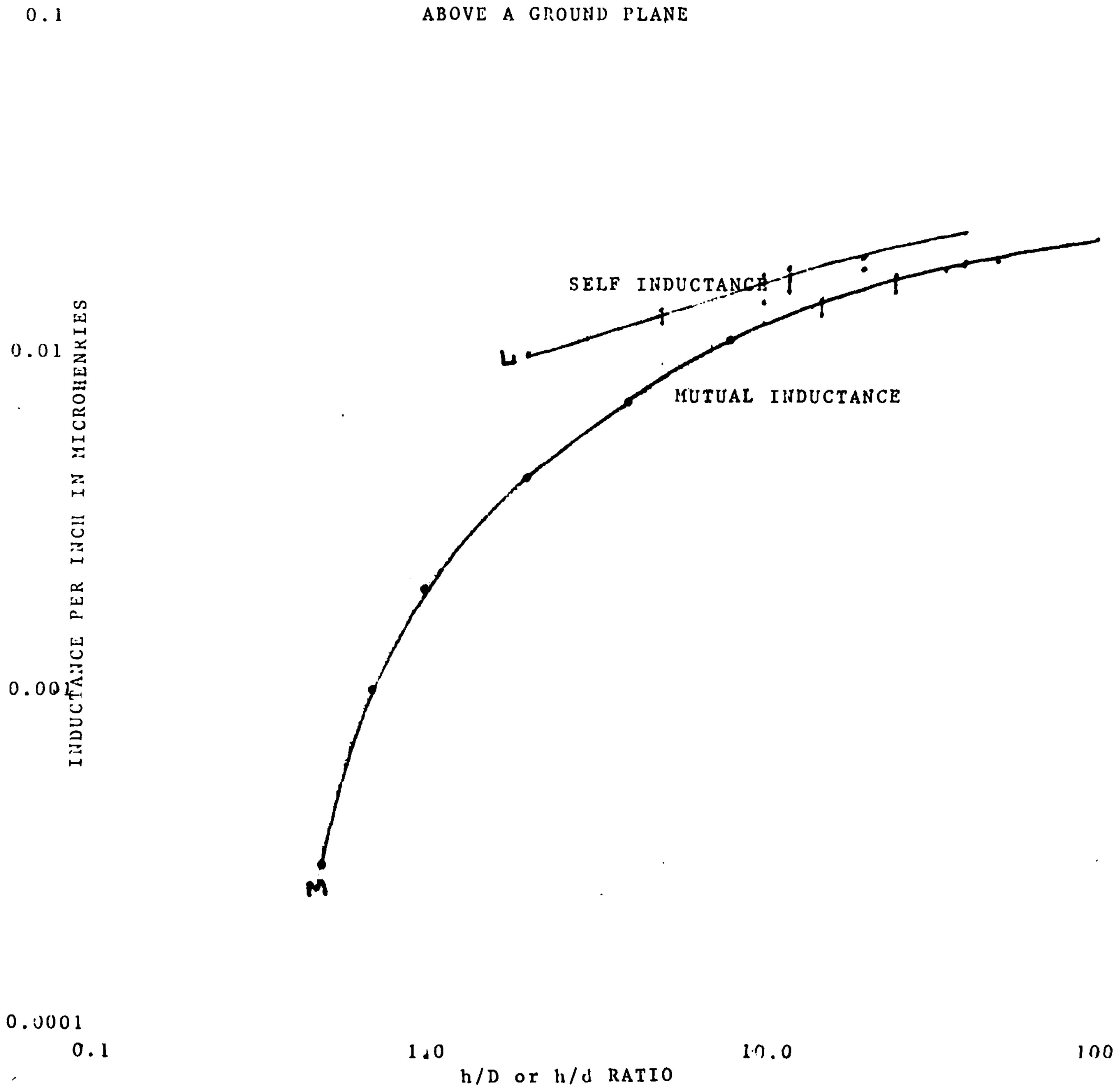
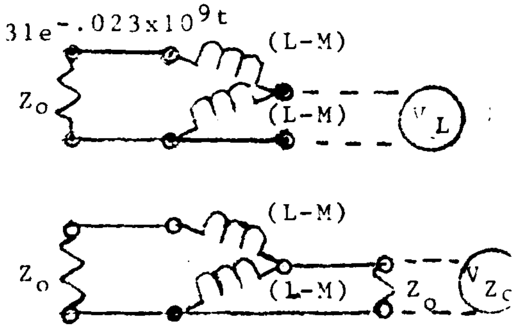


Figure A-2-6

TRANSIENT PASSED THE SHORT CIRCUIT WITH MUTUAL INDUCTANCE

$$V_L(t) = 23.49e^{-.123x10^9t} - 4.31e^{-.023x10^9t} -19.18e^{-5.5x10^9t}$$



$$V_{Z_o}(t) = 919.2(e^{-.023x10^9t} - e^{-28.8x10^9t}) -922.5(e^{-.123x10^9t} - e^{-28.8x10^9t}) -923.4(e^{-.023x10^9t} - e^{-4.2x10^9t}) +946.1(e^{-.123x10^9t} - e^{-4.2x10^9t})$$

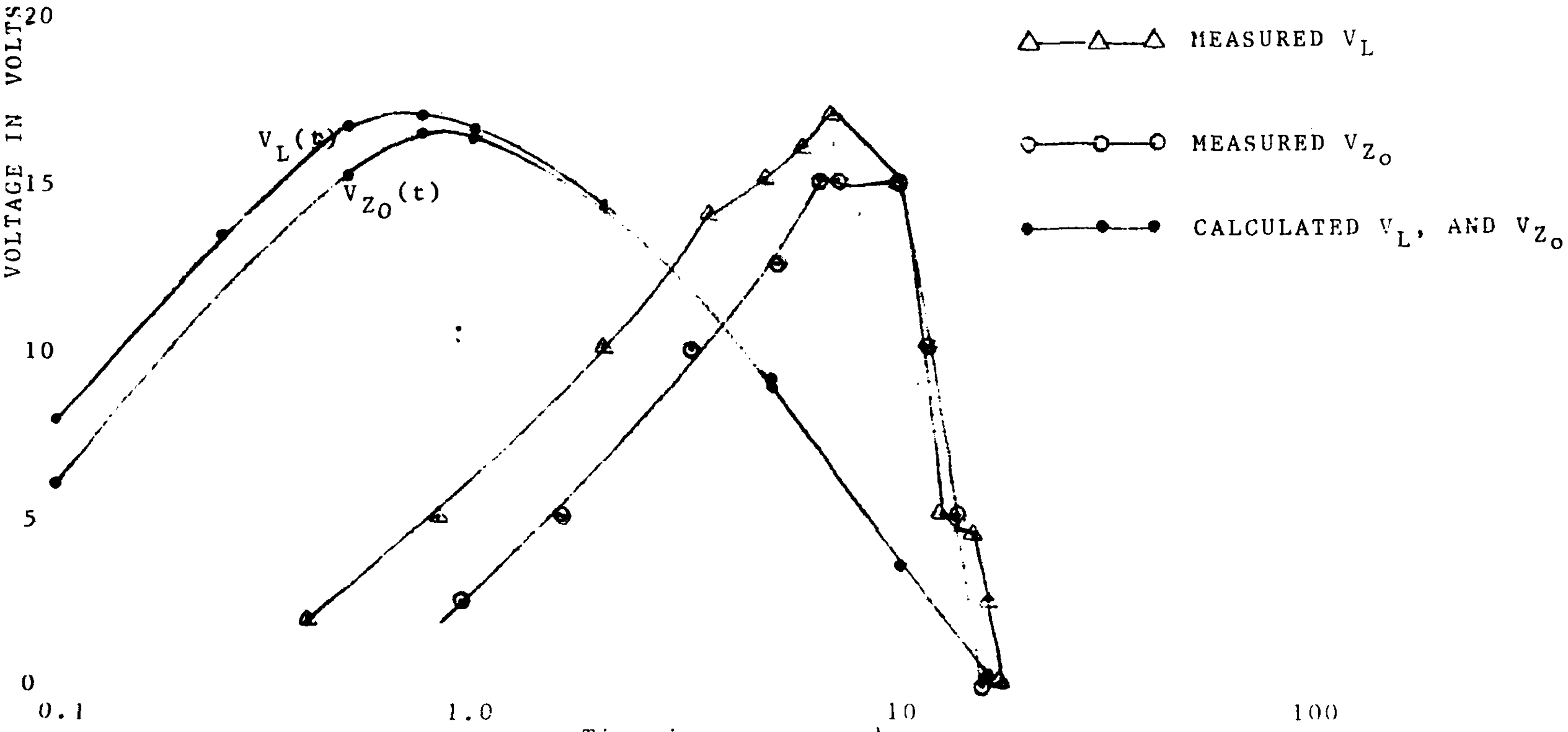


Figure A-2-7

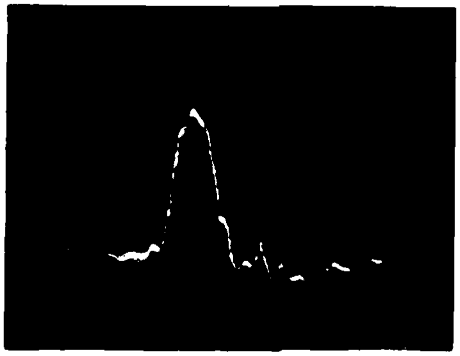


Figure A-2-8. Transient passed short circuit with mutual inductance, no load. 10 nanoseconds per division, 17 Volt peak.

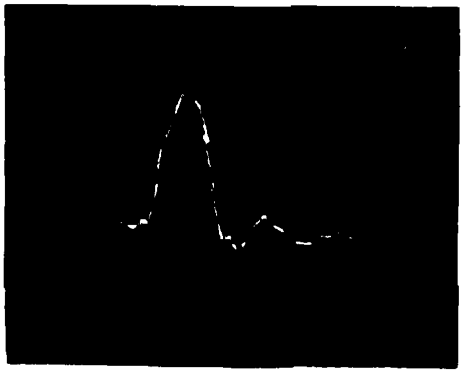


Figure A-2-9. Transient passed short circuit with mutual inductance, with transmission line load, 10 nanoseconds per division, 15 Volt peak.

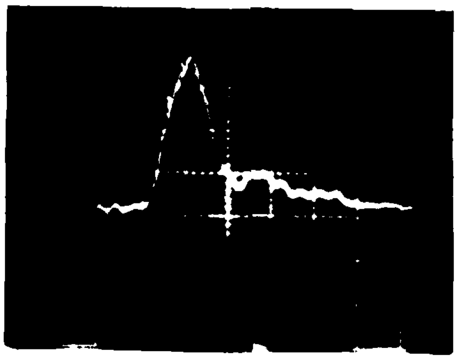


Figure A-2-10. Transient voltage passed GSV-103 protectors installed as in Figure A-2-1, measured pair to ground at terminal board connection, 36 Volts peak, 10 nanoseconds per division.

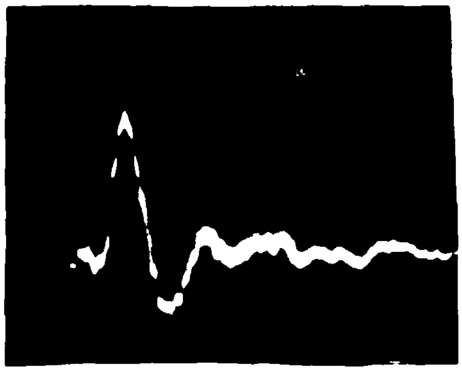


Figure A-2-11 . Transient voltage passed GSV-103 diode protectors on source side of terminal block. Includes two turns of pair lead wrapped around protector lead.
17.8 Volts peak, 20 nanoseconds per division.
Measured pair to ground at end of connected shielded pair cable.

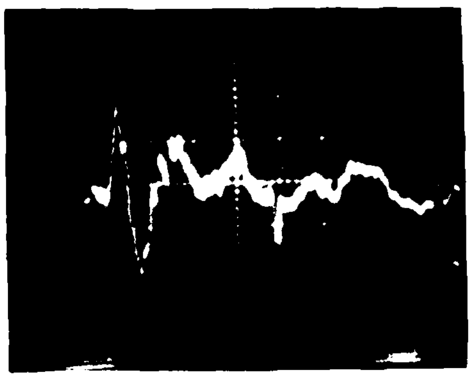


Figure A-2-12 . Same as above picture except measured pair to pair at end of connected shielded cable, 4 Volts peak.

Figure A-2-13. Transient vcltage passed hy the GSV-103 protector seen in Figure A-2-1 , further reduced by an additional GSV-103 at the load end of the connected shielded pair. +2.3 Volt peak at beginning of trace, -1 Volt peak after 0.8 µs. 100 nanoseconds per division.

Figure A-2-14. MUTUAL INDUCTANCE COUPLING AT THE TERMINAL BLOCK FROM PAIR TO PAIR

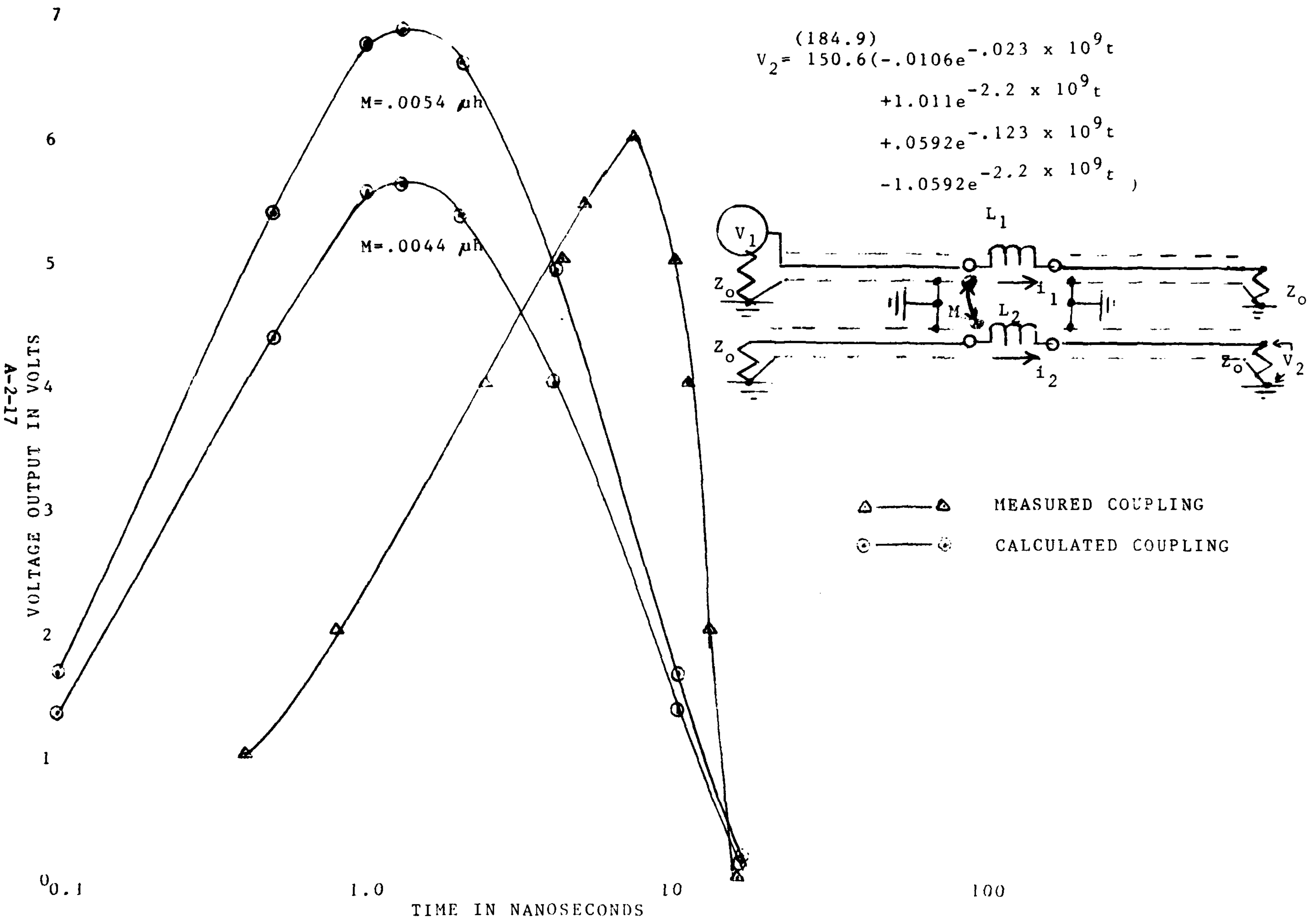


Figure A-2-15. Mutual inductance coupling between adjacent pairs at the terminal block similar to figure A-2-1. 568 Volt peak on source pair at load terminal. 6 Volts peak, 20 nanoseconds per division, measured pair to ground.

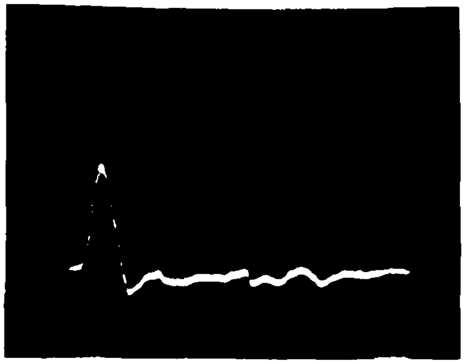


Figure A-2-16 . Mutual inductance coupling between adjacent shielded pair conductors at the terminal block. Short circuits on the load side of the terminal block on the driven pair. 12 Volts peak, 20 nanoseconds per division. Measured pair to ground cn coupled pair.

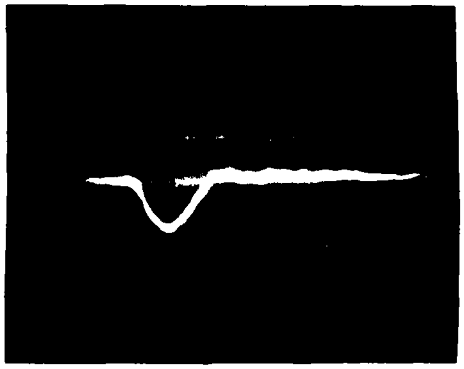


Figure A-2-17 . Same as picture above except measured pair to pair on the coupled pair. 5 Volts peak, 10 nanoseconds per division.

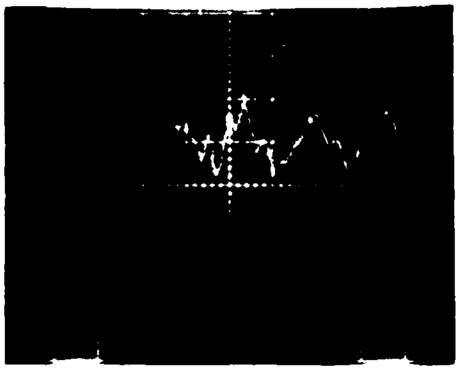


Figure A-2-18 . Mutual inductance coupling between adjacent shielded pair conductors at the figure A-2-1 terminal block. Short circuits installed on the source side of the terminal block on the driven pair. 1 Volt peak, 10 nanoseconds per division. Measured pair to ground on the coupled pair.

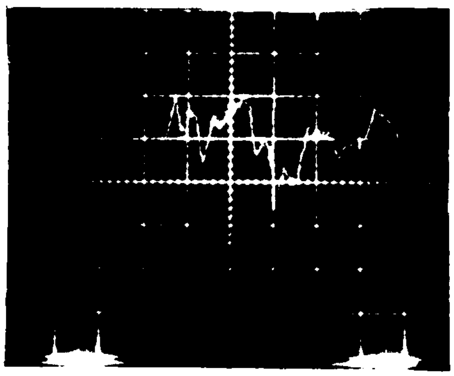


Figure A-2-19. Same as picture above except measured pair to pair on the coupled pair. 1 Volt peak, 10 nanosecond per division.

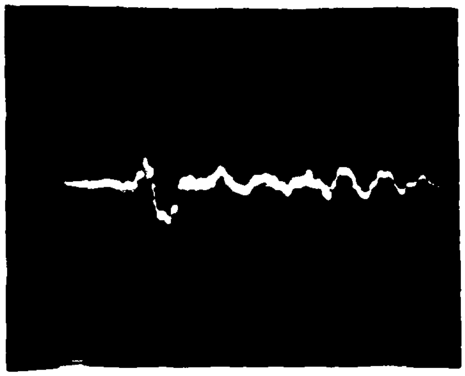


Figure A-2-20. Open loop magnetic coupling to adjacent shielded pair at the terminal block. GSV-103s installed on the driven pair, on the source side of the terminal block. 0.8 Volts peak, 20 nanoseconds per division. Measured pair to ground.

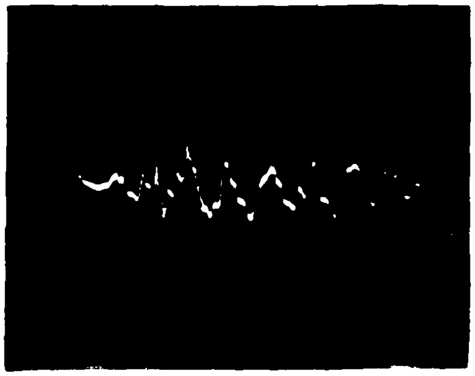


Figure A-2-21 . Same as above picture except measured pair to pair, and 0.5 Volts peak.

APPENDIX A-2 REFERENCES

1. John L. Stewart, "Circuit Analysis of Transmission Lines," p-39, John Wiley and Sons, Inc. 1958.

2. Terman, "Radio Engineering Handbook" pp 3016-18.

3. R. J. Mohr, "Coupling Between Open and Shielded Wires Over a Ground Plane," IEEE Trans. Electromagnetic Compatibility, vol. EMC-9 No. 2, pp 34-45, September 1967.

4. Clayton R. Paul, "Effect of Pigtails on Crosstalk to Braided-Shielded Cables," IEEE Trans. Electromagnetic Compatibility, vol. EMC-22 No. 3, pp 161-172, August 1980.

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