

SERIES 2000
OPERATING INSTRUCTIONS
ELECTROSTATIC DISCHARGE SYSTEM

KeyTek Instrument Corporation

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260 Fordham Road
Wilmington, Massachusetts 01887

Specifications Subject to Change Without Notice

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WARRANTY

KeyTek Instrument Corp. warrants each instrument manufactured by it to be free from defects in material and workmanship for a period of one year from the date of delivery to the original purchaser, provided the instrument is used in accordance with the instructions in this manual. KeyTek's obligation under this warranty is limited to servicing or adjusting an instrument returned to the factory, transportation charges prepaid, for that purpose. This is the only warranty offered in connection with the sale of this instrument, no other warranty is implied. KeyTek is not liable for consequential damages.

If a fault in operation occurs, the following steps should be taken:

1. Notify KeyTek Instrument Corp. giving full details of the faulty operation, the model number and serial number of the instrument. On receipt of this information, service data or shipping instructions will be provided.
2. On receipt of the shipping instructions, forward the instrument prepaid and repairs will be made at the factory.

If it is necessary to return this instrument to the factory, it should be shipped in the original packing carton. If it is not available, use any suitable rigid container with adequate packing to protect the unit during transit.

WARNINGS

1. THE OUTLET TO BE USED MUST HAVE THE THIRD WIRE "SAFETY" GROUND IN PLACE! OPERATING SERIES 2000 EQUIPMENT WITHOUT THE THIRD WIRE GROUND IN PLACE WILL ALLOW ANY EXPOSED METAL ON THE GUN OR POWER SUPPLY TO BE ELEVATED TO AS MUCH AS 25KV.
2. OBSERVE ALL SAFETY PRECAUTIONS ON PAGE 111.
3. THE USER SHOULD UNDERSTAND THAT OBJECTS IN THE VICINITY OF AN OPERATING ESD SIMULATOR, WHETHER IT IS ACTIVELY DISCHARGING OR SIMPLY CAUSING CORONA, ARE LIKELY TO BUILD UP A CHARGE. THIS ESPECIALLY APPLIES TO UNGROUNDED OR UNGROUNDABLE OBJECTS SUCH AS PLASTICS, FURNITURE, AND PEOPLE. CARE SHOULD THEREFORE BE TAKEN TO GROUND ALL CONDUCTIVE OBJECTS, ESPECIALLY INCLUDING PERSONNEL, IN THE VICINITY OF THE ESD SIMULATION.

SAFETY PRECAUTIONS

1. Don't ESD test near personnel using pacemakers.
2. Don't ESD test near automatically-controlled machinery.
3. Don't leave ESD tester unattended with its trigger in "lock-on" position, and voltage dialed up, without suitable precautions.

If you must do so, provide adequate personnel barriers and large warning signs.

Preferable still is a personnel intrusion sensor that automatically removes power from the ESD tester.

4. Test only with the ESD return (the "ground strap") connected to ground. Use one of the following:
 - A. "Green ground" (i.e., the power-line third wire) at the EUT (Equipment Under Test),
 - B. "Green ground" at the same wall socket into which the EUT is connected, but not to any other wall socket,
 - C. EUT chassis or panel (after checking it is grounded),
or
 - D. A ground plane under the EUT, itself connected to one of the grounds identified in A., B. or C. above.
5. Establish routine calibration intervals for the ESD tester, particularly for output high voltage.
6. Interrupt testing to investigate any unusual operation, particularly of the ESD simulator's digital voltage display.

Unusual operation might be the result of internal component failure, which in an extreme case could possibly cause unprogrammed high-voltage, or a voltage higher than programmed, to appear at the tester's discharge tip.

ESD SIMULATOR INTERNAL COMPONENT LIFE CONSIDERATIONS

OPERATING TO MAXIMIZE THE ESD SIMULATOR'S USEFUL LIFE

When stressed at high voltage, all electronic components have life limitations. Critical components within the KeyTek ESD simulator's Polarity Selector and Discharge Networks, in particular, should provide over 2.5 million discharges or 1000 continuous hours at 25kV. More discharges and longer time intervals will result from operation at lower voltages.

Specific operating procedures can minimize high-voltage stress on the ESD simulator's internal components:

1. To maximize internal high-voltage component life (as well as for safety reasons), never leave the ESD Discharge Gun's trigger locked on, with the tip voltage dialed up, except during actual ESD testing.

Even when testing, try not to leave the tip voltage dialed up for extended periods.

2. Use of "Normal" rather than "Slow" ramp speed, selected via the push button switch on the Simulator Power Supply's front panel, will also minimize the time that internal components spend at high voltage.

Only use "Slow" when determining the voltage at which breakdown takes place by watching the display.

3. When a great deal of repetitive testing is planned, contact the factory in advance for information on replacement Polarity Selectors and Discharge Networks, as well as other components that may undergo severe prolonged high-voltage stress in such a program.

SUMMARY OPERATING INSTRUCTIONS

Use 1 per 10 secs for single shot. Use 1 per 0.5 secs (20/sec) for exploratory and self- or proximity-discharge.

Use 1 per 1, 3 or 10 secs for extended, fixed-position repetitive tests, preferably in NORMAL CHARGE mode for extended instrument life.

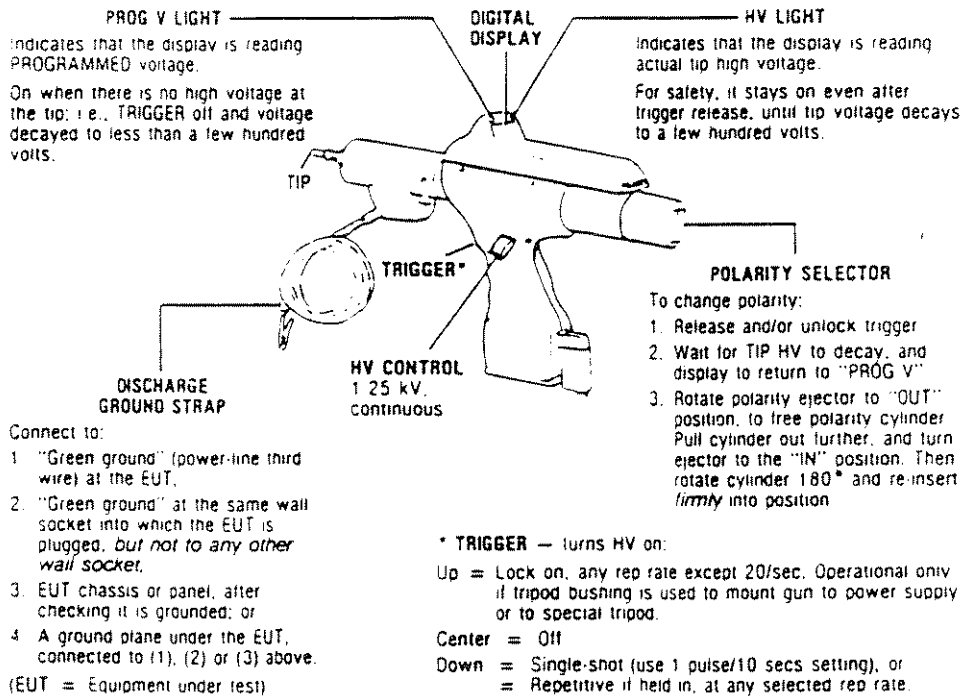
1 per 0.5 secs (20/sec) not operational in trigger lock-on, i.e. tripod-mount mode.

NORMAL ramps up high voltage at maximum speed, gives best instrument life; since components are at high voltage for the least time.

SLOW allows seeing breakdown voltage displayed; especially at 1 per 3 and 1 per 10 seconds.

NORMAL gives single shots except at very close spacings.

BURST gives multiple shots, particularly with appropriate Discharge Networks such as DN-3, DN-4 etc.



FOR AIR DISCHARGE, EITHER:

1. Pull trigger, set high voltage to desired level, approach EUT with tip till discharge occurs, or
2. Fix tip-to-EUT distance at less than programmed HV discharge distance. Pull trigger and cause discharge as HV tries to ramp past voltage corresponding to discharge distance.

SEE OPERATING INSTRUCTIONS FOR SAFETY PRECAUTIONS

ALSO SEE OPERATING INSTRUCTIONS FOR THE BEST WAYS TO MINIMIZE HIGH-VOLTAGE STRESS ON THE ESD SIMULATOR'S INTERNAL COMPONENTS
DOING SO WILL THEREBY MAXIMIZE SIMULATOR LIFE



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SECTION 1

1. General Information

1.1 Introduction

The KeyTek Series 2000 Electrostatic Discharge System consists of many units which can be put together to provide instrumentation for simulating the actual ESD air discharge, plus separate simulations for all five basic phenomena associated with the ESD event. As a minimum, an ESD-1 Discharger (or gun), a Discharge Network (DN-1, 2, etc.), Discharge Tip (DT-1, 2, etc.) and Model PSC-1 Power Supply/Control Unit are required to perform testing.

The basic KeyTek Series 2000 ESD Simulation System is housed in two interconnected units: the ESD-1 Discharger (or gun), which may be either hand-held or tripod-mounted, and its associated Power Supply/Control Unit PSC-1. The Discharger is made up of the basic handle, polarity switch, high-voltage set knob and digital display. The Power Supply/Control Unit includes selectors for repetition-rate, charge rate and burst/normal modes.

Interchangeable Discharge Networks, Current Injection Adapters and Tips all plug directly into the Discharger's barrel. The Discharge Network is also remotable via an optional cable, the EC-1, to provide a lighter, hand-held probe for extended testing without a tripod. In this latter mode, the Discharger itself may be mounted on the Power Supply/Control Unit via tripod mounting hardware, which is included.

Specific Series 2000 Model Groups have been identified, to help users select the ESD test capabilities most appropriate to their immediate needs. Thus Model Groups 2001, 2002, 2003 and 2004 provide progressively increasing capabilities for ESD test purposes.

Expansions and additions, selected from the next Model Group or from anywhere in the entire Series 2000, can be made at any time. See Table 1-1 on the following page for details.

TABLE 1-1

Series 2000 ESD Test Systems

NOTE: Additional modules may be needed for exact correlation with MiniZap models. (See next page).

Capability	Model #	Original Model Groups				New, Optimized True-ESD™ and Field-Emphasizing Model Groups (with Probe Remoting Cable)			
		2001	2002	2003	2004	2021 ¹	2022 ²	2023 ³	2024 ⁴
1. AIR-DISCHARGE SIMULATION									
Discharge: ±1 to ±25kV, single-shot and repetitive (interval: 10s, 3s, 1s, .05s). Built-in DVM directly measures stored high voltage.									
	ESD-1	•	•	•	•	•	•	•	•
	DN-1**	•	•	•	•	•	•	•	•
	DT-1	•	•	•	•	•	•	•	•
2. ACCESSORIES AND POWER SUPPLY									
Corona and Field-Enhancement Discharge Tip									
	DT-2	•	•	•	•	•	•	•	•
Proximity-Test, Self-Discharge Tip									
	FT-10	•	•	•	•	•	•	•	•
Power Supply/Control Unit									
	PSC-1	•	•	•	•	•	•	•	•
Carrying Case									
	CA-1A	•	•	•	•	•	•	•	•
3. AUXILIARY DISCHARGE AND FIELD TIPS									
Wedge, Simulating Tool									
	DT-3		•	•	•		•	•	•
E-Field (electric field) Simulator									
	FT-11		•	•	•		•	•	•
H-Field (magnetic field) Simulator									
	FT-12*				•		•	•	•
Discharge E-Field Collapse Adapter									
	FT-21*				•		•	•	•
4. DIRECT CURRENT INJECTION, including									
Fast Air-Discharge Mode, via:									
	10kV Fast-Approach Current Injection Adapter				•				•
	FA/CIA™-10†				•				•
	20kV Fast-Approach Current Injection Adapter		•	•	•		•	•	•
	FA/CIA™-20†		•	•	•		•	•	•
5. ADDITIONAL ACCESSORIES									
Carrying Case									
	CA-2A				•		•	•	•
Coax monitor for ESD current waveform. Includes Ground Plane (GP-1), Scope Cable with 50Ω Termination (TC-50), and Short Ground Strap (GCS-1).									
	CTC-1		•	•	•		•	•	•
Probe Conversion Cable: Remotes any Discharge Network as light, hand-held probe									
	EC-1			•	•	•	•	•	•
Tripod									
	T-1A			•	•				•
DC Output Calibration Attenuator									
	DCA-1				•				•
Field and Corona Sensor Group									
	FCS-1				•				•
Common Monitor Unit, HEC-1									
					•				•
H-Field sensor, HFS-1									
					•				•
E-Field sensor, EFS-1									
					•				•
Pre-Discharge corona sensor, CCS-1									
					•				•
6. ADDITIONAL DISCHARGE NETWORKS									
NEMA Part DC33 and MIL STD 883B Discharge Network (100 pF/1500 Ω)									
	DN-2				•				
Upper/lower-body-model Discharge Network (700 pF/100K/150 pF/150 Ω)									
	DN-3				•				
Segmented-body-model Discharge Network (700 pF/100K/150 pF/150 Ω/20 pF-50 Ω)									
	DN-4				•				
7. TRUE-ESD™ OPTION GROUP, TSD-1**									
Optimum basic human-body model network									
EIA Std. PN-1361 (Draft 6, 1985) Discharge Network (100 pF/500 Ω)									
	DN-6					•		•	•
True-ESD™ Hand-Tip/Discharge-Tip Combination									
	HT-10/DT-4					•		•	•

¹ Group 2021 adds True-ESD™

³ Group 2023 adds both True-ESD™ and fields, plus current injection.

² Group 2022 adds fields instead of True-ESD™ plus current injection.

⁴ Group 2024 adds True-ESD™ fields, current injection, field sensors, etc.

* Requires a CIA or FA/CIA™; FA/CIA-20 is recommended.

** DN-10 may be substituted directly for DN-1. IEC Current-Injector, CIA/V (for use with DN-10) may be directly substituted for entire TSD-1 (i.e., DN-6 and HT-10/DT-4).

* Patent pending.

Model 2000 (con't)

For exact correlation with standard MiniZap Models

To upgrade Groups 2001, 2002, 2003, 2004, 2021, 2022, 2023, 2024 for TRUE-ESD™ Fast Rise Current Injection (FR/CI™), and in accordance with the proposed revision to IEC 801-2 (150 pF/330Ω), the following must be included with each Model 2000 Group:

TRUE-ESD™ — fast rise air discharge with 150 pF/330Ω (MZ-10 or MZ-15)

DN-10 DN-10 provides 150 pF/330Ω
(may be purchased in lieu of standard DN-1 at no additional charge)

HT-10/DT-4 TRUE-ESD™ Hand-Tip/Discharge-Tip Combination
(included in 2021, 2023, and 2024 as standard)

Fast Rise Current Injection, (FR/CI™) with 150 pF/330Ω (MZ-15)

CIA / V* Battery powered, relay-operated current injection module providing the fast rise and the 150 pF/330Ω network, when used with the DN-10 above.

NOTE: Maximum test voltage at least 10kV. Relay operation is transparent to the user.
No auxiliary switch operation is required.

Relay life is approximately 5 million discharges. The potted HV relay may be factory replaced for between 40-50% of the current price of a new CIA/V. The CIA/V comes equipped with its own plug-in discharge tips, the DT-21 (IEC ball) and DT-22 (sharp point). Not compatible with DT-1 thru DT-5, and not usable with FT-12 or FT-21 as replacement for FA/CIA-20.

*Warranty on encapsulated internal relay is for 2 million discharges. Replacement cost is between 40 and 50% of the current price of a new CIA/V; consult factory.

1.2 General Performance Overview

1.2.1 Generator

1. Voltage continuously selectable from 1 to 25kV, in both polarities.
2. Library of interchangeable, plug-in discharge networks. Included are single R-C Networks to meet IEC, EIA, NEMA and MIL Standards. Also available are more complex Networks: to generate multiple pulses in a single discharge packet, and to simulate a segmented-body equivalent circuit. Custom Networks can also be furnished to meet special requirements.

Discharge Networks are remotable from the Discharger, via an optional additional cable, for test applications using the Discharge Network as a lightweight probe.

3. Discharge Networks, Discharge and Field Tips, plus Auxiliary Adapters for air discharge and all five of its basic components:*

Air Discharge Generation: simulates the basically unrepeatable, but highly realistic, real-world human discharge; for both direct and proximity testing.

5. Discharge Current-Wave Injection: provides highly-repeatable, standardized waves into the test piece, via Current Injection Adapters.

4. Discharge Magnetic-Field Simulation: a repeatable pulsed magnetic field which minimizes localized electric field and other air-discharge effects, to facilitate diagnostic work with the magnetic field alone. Uses a special Magnetic Field Tip, plus an appropriate Current Injection Adapter (20kV usually preferred).

*Number sequence, 1-5, is the order of occurrence during the actual air discharge. Items are listed in reverse order however, i.e. from 5 to 1; as that order approximates their relative simulation importance.

3. Discharge Electric-Field Collapse Simulation: a repeatable pulsed electric field which minimizes localized magnetic and other effects of the air-discharge event, again for diagnostic work. Employs the Electric Field Tip, plus an appropriate Current Injection Adapter (20kV usually preferred), and the Discharge Electric Field Adapter.
 2. Pre-Discharge Electric Field Simulation: permits repeatable, E-field and rate-of-approach E-field simulation, independent of operator position and approach speeds; via electronically-determined ramp speed. Uses E-Field Tip.
 1. Pre-Discharge Corona Simulation: generates a relatively repeatable, enhanced-field-generated corona, which in turn generates RFI to facilitate investigation of EUT sensitivity. Uses standard Ball or Point Discharge Tip, alone or in conjunction with the Self-Discharge, Proximity Field Tip.
4. Current Injection Adapters (CIA-5, 10, 20, etc.): available at different switching voltages. For current-injection (rather than air-discharge) operating mode, an Adapter is interposed between the Discharge Network and the Discharge Tip. When the Tip is then held directly against the test piece, the repeatable nature of the Adapter's precision switch characteristic insures that an equally-repeatable current wave is injected for QC and Production testing.

A Current Injection Adapter, preferably the CIA-20, is also used for simulating Discharge Magnetic Field and Discharge Electrostatic Field Collapse, to insure repeatability (see Section 2.3).

5. Interchangeable Discharge Tips: IEC-specified ball-finger DT-1, as well as point or awl (DT-2) and wedge or screwdriver (DT-3).

6. Interchangeable Field-Generator Tips and Adapters:

FT-10 Self-Discharge, Proximity Field tip

FT-11 Electric Field (E-Field Simulation) Tip; for both Pre-Discharge Electric Field and Discharge Electric Field Collapse simulation.

FT-12 Magnetic Field (H-Field Simulation) tip; for Discharge Magnetic Field simulation.

FT-21 Discharge Electric Field Adapter; only needed for Discharge Electric Field Collapse simulation.

7. Programmable Repetitive Operating Modes, In Addition to Single-Shot: pulses repetitive approximately every 10, 3, 1 and .05 seconds.*

The 10, 3 and 1-second nominal delays per pulse are provided for thorough ESD-testing of computers and other digital equipment capable of running in check-sum and parity modes; without applying discharges so close together that average surge power would itself begin to cause failures. A computer can thus be run for hours or even days in check modes during qualification testing, to insure against extra ESD-sensitivity points in the machine's cycle.

The nominal .05 second delay time, or 20/second rep rate, is far too fast for medium or high-voltage ESD testing because of the high average power it can apply to sensitive devices. It is used primarily for low-voltage, investigative work below a few kV, although it is completely operational, at slightly slower speeds, over the Series 2000's full 25kV range, should it be required.

The nominal .05 second delay time can also be useful for air-discharge proximity testing, and for all field testing, in which the discharge current flows only in the simulator's return, and therefore doesn't flow directly into the Equipment Under Test.

*.05 seconds for human body simulation capacitor to 150pf; proportionately slower for higher capacitor values in other Discharge Networks. Available only when the ESD-1 is in momentary, not lock-on, mode.

1.2.2 Monitors/Calibrators

1. Digital Stored Voltage Monitor (supplied with all units).

Located at eye level on the Discharge. It reads the low-voltage, programming signal to which the high-voltage will be slaved, until the trigger is depressed to generate the high voltage. It then switches over automatically to directly measure actual stored high-voltage output. Thus the reading decays quickly on discharge, clearly signifying charge dump. This visual indication of discharge provides positive identification of the ESD event, even at low voltages at which there is no spark.

2. Audible-Discharge Monitor (supplied with all units).

Beeper located within the Discharge handle. Informs the user when a discharge has occurred. Useful both for low voltages where there is otherwise littler audible indication of discharge, and at all voltage levels for indication of multiple discharges.

3. Calibrators

- CTC-1* PULSED OUTPUT VOLTAGE CALIBRATOR (with Model CA-1)

BNC output on this built-in, IEC-specified coaxial load permits discharge voltage-wave performance verification over the life of the equipment. Thus waves can periodically be calibrated for all available Discharge Networks, Current Injection Adapters, Discharge Tips, etc.

- HFS-1* MAGNETIC-FIELD VOLTAGE CALIBRATOR (with Model CA-2)

This pickup facilitates scope calibration of voltages generated by the Magnetic-Field (H-Field Simulation) Tip. It is also useful for measuring H-Fields generated by all types of discharge.

* For proper operation, must be used with the supplied, terminated cable, and an oscilloscope with at least 400MHz bandwidth.

EFS-1* ELECTRIC FIELD VOLTAGE COLLAPSE CALIBRATOR
(with Model CA-2)

Provides signal to scope proportional to rate-of-change of electric field, for calibration of the Electric Field (E-Field Simulation) Tip and Collapse Adapter used with the Discharge Electric Field Adapter. It is also useful for measuring E-field change generated by all types of discharge.

CCS-1 CORONA CALIBRATOR/MONITOR (with Model CA-2)

Furnishes output, of specified bandwidth, from RF-pickup sensor for oscilloscope monitoring.

4. DC Output Calibration Attenuator
Model DCA-1 (optional)

Attenuator network to allow scope or meter monitoring of DC stored on the discharge capacitor (10,000:1 ratio when loaded with 10 megohms).

* For proper operation, must be used with the supplied, terminated cable, and an oscilloscope with at least 400MHz bandwidth.

1.3 Specifications

1.3.1 General

Voltage Range: 1 to 25kV with Ball Tip (and without Extender Cable EC-1).
1 to 20kV with Point and Wedge Tips (DT-2, DT-3).
1 to 20kV with Extender Cable EC-1 and any tip.

Polarity: Operator-Selectable (plus or minus)

Operating Modes: Single-shot and repetitive

Repetition Rates: One shot per approximately 1, 3 or 10 seconds. Fast repetition rate of nominally 20/second, for discharge distances well within breakdown voltage settings, is also available; in momentary (not lock-on) mode.

Built-In Digital Voltmeter:

High Voltage

Trigger On: Measures and displays actual high voltage at the ESD Simulator's tip (+5% of reading \pm .2kV).

High Voltage

Trigger Off: Before tip voltage has decayed to below 300-500V, continues to measure and display tip high voltage (+5% of reading \pm .2kV).

After tip voltage has decayed to below 300-500V, displays "Program Voltage" -- the voltage that will appear at the tip when the high-voltage trigger is depressed. Note: Actual displayed voltage may be slightly lower than program voltage at levels above 25kV (with DT-1) or above 20kV (with DT-2 or DT-3 or EC-1). This is due to the voltage limit safety feature included within this equipment.

Display Indicators:

ACTUAL V Indicates that the DVM is displaying actual tip High Voltage, independent of trigger position. Stays on until tip voltage has decayed below 300-500V.

PROGRAM V Indicates that the DVM is displaying Programmed Voltage. Can be illuminated only when tip voltage is less than 300-500V.

Trigger Position:

Up: Lock-On*

Center: OFF

Down: Momentary On

*Note: Lock-On position is operational only when the ESD gun is tripod-mounted (special tripod bushing required), or is mounted to the PSC-1 power supply unit (supplied as part of all Series 2000 Systems).

This built-in personnel safety feature, the inability to operate in Lock-On mode when the ESD gun is hand-held, insures that a charge cannot continue to exist on the gun after it is put down.

Finally, 20/sec repetition rate is unavailable in Lock-On mode, to insure against use on actual equipment (which might receive too much energy in this mode), and to maximize ESD gun life.

Program Voltage

Adjust: Multi-turn, long-life potentiometer, mounted in thumb-accessible position on ESD gun handle.

Discharge

Ground Strap: Inductance equivalent to that of IEC-specified return, but with insulation adequate for 25kV. Length ~2000mm, or 6.5ft.

Normal/Slow Ramp Selector:

Slow Ramp
Position:

In Slow Ramp mode, for repetition rates of one shot per 3 seconds and one shot per 10 seconds, the high-voltage ramps up slowly enough to permit the digital voltmeter to display the voltage at which the simulated ESD breakdown occurs. Useful for applications in which the ESD gun location is fixed.

Normal Ramp
Position:

Preferred for most other work. The high voltage ramps up rapidly, thereby minimizing stress on internal high-voltage components, with consequently prolonged instrument life and reliability.

Normal (Single-
Shot)/Burst
Selector:

In Burst position, allows realistic simulation of multiple discharges even when the ESD tester is on a tripod or is otherwise in a fixed location. Also required is an appropriate Discharge Network like the DN3 or DN4. (Multiple ESD discharges usually occur from a rapidly-advancing human finger, or from an appropriate hand or finger simulator.)

1.3.2 Discharge Networks

1.3.2.1 Discharge Network DN-1 (IEC-specified)

Energy Storage Capacitor: 150pf $\pm 10\%$

Discharge Resistor: 150 Ω $\pm 5\%$

All performance specifications based on use of 100MHz bandwidth instrumentation, and shortest possible ground strap (~ 30 cm), as per IEC specifications. Discharge current is measured into an IEC-specified, coaxial 2 Ω load.

Risetime of discharge current: 5ns $\pm 30\%$

Duration of discharge current: 30ns $\pm 30\%$

Peak value of discharge current,
 $\pm 30\%$: 9A at 2kV
18A at 4kV
37A at 8kV
70A at 15kV

Note: Due to discharge arc characteristics, multiple discharges can occur with all Discharge Networks, including the DN-1. In most cases, these will occur at particular distances well under the maximum or critical distance.

1.3.2.2 Discharge Network DN-2

The DN-2 Discharge Network is designed to meet the requirements of NEMA Part DC33. Per the requirements of that document, the DN-2 includes a 100 pF +/- 10% charge capacitor and a 1500 Ohm +/- 10% discharge resistor. Because the DN-2 is an air discharge network, it will not produce a waveform per the requirements of MIL-STD 883C.

1.3.2.3 Discharge Network DN-3

The DN-3 Discharge Network is very similar to the DN-1 Network except for an internal modification to enhance multiple discharges. The output energy storage capacitor and resistor are the same as those in a DN-1: exact specifications are 150pf $\pm 15\%$, and 150 ohms $\pm 10\%$ respectively. For proper operation of this network, the Burst/Normal selector switch on the power supply/control unit must be in the Burst mode.

1.3.2.4 Discharge Network DN-4

The DN-4 Discharge Network is very similar to the DN-1 Network except for internal modifications to enhance multiple discharges and peaking. The output energy storage capacitor and resistor are similar to those in a DN-1; exact specifications are 150pf +15% and 150 ohms +10% respectively, except that a peaking circuit is added. For proper operation of this network, the Burst/Normal selector switch on the power supply/control unit must be in the Burst mode.

1.3.2.5 Discharge Networks DN-5 and DN-6 (EIA PN-1361, Draft 5, November 24, 1981)

The DN-5 has a discharge capacitance of 60pf and a discharge resistance of 10k Ω . The DN-6 has a discharge capacitance of 100pf and a discharge resistance of 500 Ω .

Although the EIA specifies each of these networks for use at only a single voltage (20kV for the DN-5, and 10kV for the DN-6), they are of course useable over the full operating range of the Series 2000 equipment. However, multiple discharges may be present, especially with the DN-5, at very small discharge spacings and/or lower voltages. This is due to the critical amount of energy needed to form and heat a spark channel so that the gap impedance falls to a low and stable value. Some of this energy can come from stray capacitances (which are inherent within any piece of electronic equipment). The main portion of energy, however, must come from the discharge network's capacitance thru the network's output resistance. The DN-5's 10K Ω output resistor severely limits the energy available, thus leading to the high probability of irregular performance.

In addition, the internal DN-5 capacitances associated with this large value resistance combine to produce narrow waveform overshoots in the range of 8-12 Amps into a CTC-1 target. (One would normally expect an output current of 20kV/10k Ω = 2 Amps). Experience has shown that real world human ESD events can show an overshoot of 12 to 30 Amps peak. The DN-5 therefore represents an excellent simulation of real world effects. However, if these overshoots present a problem, KeyTek can supply a DN-5A, which has an internal 500 Ω resistance, along with an RT-9500 9.5K Ω resistor tip. This combination allows the minimum amount of overshoot possible, on the order of 1 to 3 Amps. (It may well not be at all a realistic simulation, of course.) Consult factory for further details.

Discharge Capacitance

Tolerance: +15%

Voltage

Sensitivity: Typically less than 20%
capacitance decrease from
0 to 25kV.

Discharge Resistance

Tolerance: +10%

1.3.2.6 All Other Discharge Networks

Unless otherwise specified for a particular network, characteristics are:

Discharge Capacitance

Tolerance: $\pm 15\%$

Voltage

Sensitivity: Typically less than 10%
capacitance decrease from
0 to 25kV.

Discharge Resistance

Tolerance: $\pm 10\%$

1.3.2.7 Discharge Tips, Models DT-1,2,3

1. Model DT-1 is a ball Tip (IEC). The full 25kV is available with this tip.
2. Model DT-2 is a point tip, used for corona generation. Over 20kV is available with this tip.
3. Model DT-3 is a wedge (or screwdriver) tip. Over 20kV is available with this tip.

1.3.2.8 Hand and Tool Simulator HT-10 and DT-4

The Model HT-10 Adapter was designed to be used in conjunction with the new DT-4 Tool Tip, and any Series 2000 ESD simulator. The combination provides significant new capability for truly realistic simulation of electrostatic discharge from a hand-held metal object.

The Model HT-10 is a modular adapter that plugs into Series 2000 Discharge Networks. The Tool Tip Model DT-4, plugs into the front of the HT-10, to provide a highly-repeatable simulation of a hand with tool, bracelet, ring or key.

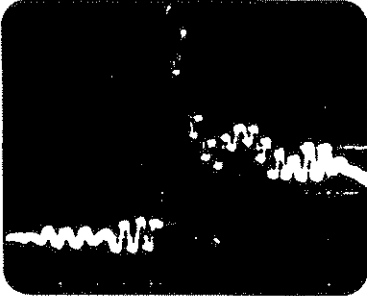
The HT-10 can be unplugged from the Series 2000 to permit testing without the initial spike, when it is desired to determine which specific failure modes the spike causes in the Equipment Under Test, or to meet various existing specifications in which other tips may be called for, such as the IEC Process Control ESD Standard, IEC 65 (Secr) 80.

When used in conjunction with the Series 2000, the HT-10/DT-4 combination generates, on discharge, a narrow, super-fast current spike of 2 to 4 nanosecond duration. This spike is superimposed on the normal, longer duration pulse from the specific Discharge Network being used.

At voltages up to about 5kV, the DT-4 tip generates both faster and higher-amplitude static discharge current waves, than does a finger or the rounded metal tip - the DT-1 - often used to simulate it. With a stored voltage of 5kV, narrow-spike amplitude from the HT-10/DN-4 combination is on the order of 10 to 30 amperes, independent of the internal resistance of the Discharge Network (DN) in use. In effect, the HT-10/DT-4 combination is a current source in parallel with the conventional R-C human-body network.

With higher stored voltages, corona effects usually make ESD less repeatable, often (but not always) resulting in slower wavefronts - 5 to 10 nanoseconds or longer. At these higher voltage levels the HT-10/DT-4 combination still gives much sharper Discharge Network risetimes - typically just a few nanoseconds. (Near 10kV in particular, the HT-10 performance is optimum with the DT-1.) These faster risetimes more accurately simulate the fast discharges from hands with metallic objects which take place under many real-life, fast-approach conditions, even at higher voltages.

TYPICAL ESD WAVEFORMS*

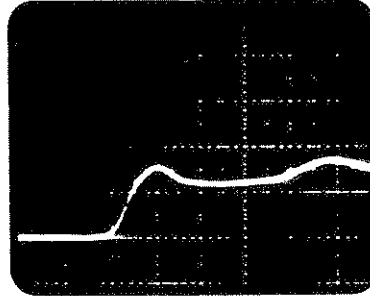


1. The real world discharge - it includes a steep initial spike from a hand with metal object: tool, bracelet, ring or key.

Spike dominates wave.

Peak current = 25A.
Risetime <.9ns

Scope scales:
2.5A/half cm
2ns/half cm

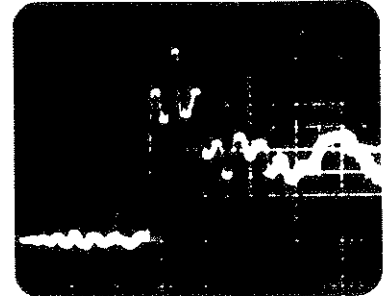


2. Discharge from an ordinary ESD simulator, with NO initial spike (C is 100 pfd, R is 500 ohms.)

NO initial spike
(Simulates human-body discharge without metal object.)

Peak current = 7.5A.
Risetime = 3ns

Scope scales:
2.5A/half cm
2ns/half cm



3. Discharge with realistic initial spike from Series 2000 simulator with HT-10 Adapter and DT-4 Tip (C is 100 pfd, R is 500 ohms).

Closely approximates hand with metal object.

Peak current = 21A
Risetime <.9ns

Scope scales:
2.5A/half cm
2ns/half cm

*All photos taken using Tektronix 7834 oscilloscope with 7A19 vertical amplifier. This combination has a 400 MHz bandwidth, and a 0.9 nanosecond risetime. Initial spikes in Figs. (1) and (3) will be apparently reduced by 2:1 if viewed on a 100 MHz, 3.5 nanosecond scope. (But the initial spikes will still be there, and will still cause equipment failures, whether a limited-bandwidth, 100 MHz scope "sees" them or not.) All waves shown are for a 5kV initial charge-voltage level.

SECTION 2

2. Operating Instructions

2.1 Assembly and Basic Operation

2.1.1 Assembly

1. Connect a Discharge Network (DN) to the gun assembly.
2. Connect a tip (DT or FT) to the Discharge Network.
3. Connect the low voltage interconnect cable between the gun handle and the power supply unit. (Lock it in place at both ends.)
4. Connect the ac power cable from the Power Supply to an appropriate ac outlet. Units shipped within the U.S. are set for operation at 120V ac 60Hz; units shipped outside the U.S. are generally set for 220V ac 50Hz operation. (See Section 2.1.2 for details if it is necessary to change from 120V to 220V operation, or vice versa.)

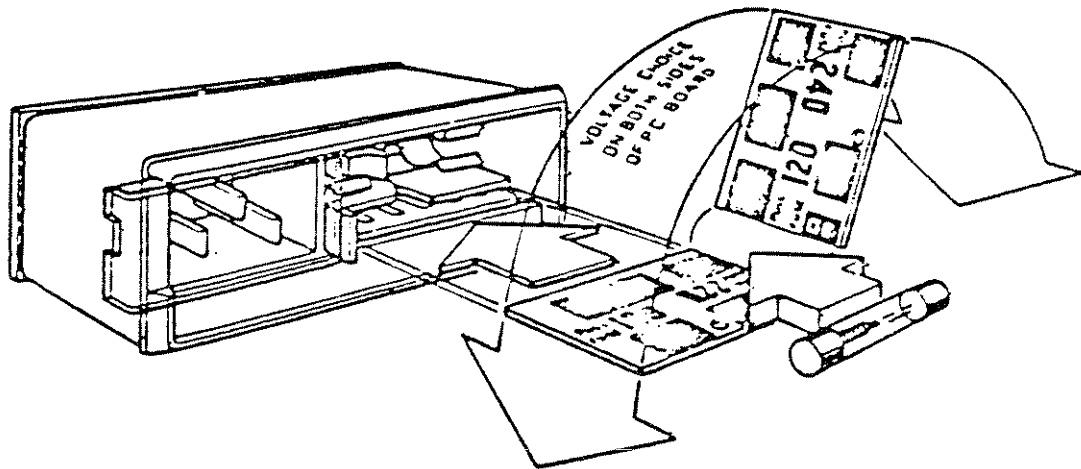
WARNING

The outlet to be used must have the third wire "safety" ground in place! Operating Series 2000 equipment without the third wire ground in place will allow any exposed metal on the gun or power supply to be elevated to as much as 25kV.

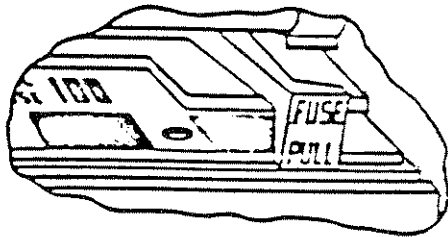
5. Connect the ground return cable ("ground strap") to the Discharge Network (DN). The other end is connected in one of the following ways:
 - A. "Green ground" (i.e., the power-line third wire) at the EUT (Equipment Under Test),
 - B. "Green ground" at the same wall socket into which the EUT is connected, but not to any other wall socket,
 - C. EUT chassis or panel (after checking it is grounded), or
 - D. A ground plane under the EUT, itself connected to one of the grounds identified in A., B. or C. above.

2.1.2 Power Requirements and Setup: Different Line Voltages

The 2000 Series Equipment may be operated from an ac power source of 100, 120, 220 or 240 volts (+10%), 50-60 Hertz. The selection of the desired voltage is made prior to connecting the instrument to the power source in the following way:



Operating voltage is shown in module window.



SELECTION OF OPERATING VOLTAGE

1. Open cover door and rotate fuse-pull to left.
2. Select operating voltage by orienting PC board to position desired voltage on top-left side. Push board firmly into module slot.
3. Rotate fuse-pull back into normal position and re-insert fuse in holders, using caution to select correct fuse value.

Fig. 2-1

Selecting Different AC Line Voltages

1. Make sure line cord is removed from rear panel.
2. Slide clear plastic protector cover from right to left, covering the line receptacle and uncovering the fuse.
3. Pull fuse ejector out and all the way to the left, ejecting the fuse and providing access to the voltage selector board.

4. Using a pair of pliers, remove the voltage selector board, replacing it in one of the four possible positions with desired voltage designation showing after it is re-installed.
5. Install the fuse: .5A Slow-Blow for 100 and 120V operation, .25A Slow-Blow for 220 and 240V operation.
6. Push fuse ejector to the right and all the way back in, slide the clear plastic protector plate back in place over the fuse, and install the line cord in the now-uncovered receptacle.

2.1.3 Operation

2.1.3.1 Power Supply/Control Unit, Model PSC-1

1. Repetition Rate Selector:

There is a five position mode switch located on the power supply unit which provides the following control:

- A. 10s - If the trigger on the ESD gun is held depressed, or if the trigger is in the lock position, and the gun is mounted on its power supply or an appropriate tripod, a single discharge will occur at a rate of approximately once per ten seconds. (The exact rate will vary depending on tip-to-discharge point spacing, voltage setting, air conditions, etc.) Use this position for "single-shot".
- B. 3s - Same as (A) above, except discharges will occur at a rate of about 1 per 3 seconds.
- C. 1s - Same as (A) above, except discharges will occur at a rate of about 1 per second.
- D. Off - Prevents high voltage generation. (Program voltage is displayed.)
- E. .05s - If the trigger on the ESD-1 is held depressed, discharges will occur at a rate of about one per .05 seconds.* This mode is not operational with the trigger in the lock position (i.e., in tripod mode) except when using an extender cable such as EC-1. In this case, the .05s mode can be actuated on a manual basis only by using the remote trigger on the discharge network (ESD-1 trigger must be in lock on mode).

*.05 seconds for human body simulation capacitor to 150pf; proportionately slower for higher capacitor values in other Discharge Networks. The rate is also strongly dependent on tip-to-target spacing versus Programmed Voltage.

2. Normal/Slow Ramp Selector:

A two position switch allows selection of NORMAL or SLOW charge ramp. In the NORMAL position, voltage will appear at the tip as soon as the trigger is depressed. In the SLOW position, activating the trigger will cause the voltage to ramp up slowly from zero to the set aiming voltage. If the aiming voltage is greater than the distance required for a discharge to occur, watching the DVM will allow the operator to determine the approximate breakdown voltage.

3. Burst/Normal Selector

A two position switch allows selection of NORMAL and BURST mode. In the NORMAL position, the charging of the discharge network is stopped immediately upon sensing a discharge from the discharge tip. This position is used for the normal discharge networks such as DN-1, DN-2, DN-5, DN-6, etc. In the BURST mode, the charging of the discharge network continues for a short time after a discharge occurs. This position is used with multiple discharge networks such as the DN-3, DN-4, etc.

2.1.3.2 Discharger or Gun, Model ESD-1

1. Voltage Control - A thumbwheel knob is provided to increase or decrease the set discharge voltage.
2. Trigger - The trigger is a three position switch. In the center off position, no voltage is transferred to the gun tip. When normally depressed (momentary contact), the high voltage will appear at the gun tip until a discharge occurs. If the trigger is held depressed, the voltage at the tip will ramp up to the Program Voltage, in a manner determined by the Repetition Rate Selector and the Normal/Slow Ramp Selector.

The lock, or upper trigger position, is operational only when the gun is mounted on a tripod or the PSC-1 power supply, and the interlock in the gun handle is satisfied. The lock trigger position is generally only used for repetitive testing at slow discharge rates (the trigger lock will not operate in the .05s mode).

3. DVM - Monitors the charge circuitry to read the voltage to which the capacitor will be charged when the trigger is depressed, and measures actual tip voltage before and during the discharge after the trigger is depressed. The DVM will continue to measure the tip voltage after the discharge EVEN IF THE TRIGGER IS RELEASED, until the tip voltage falls below a few hundred volts. Two small LED's located on either side of the DVM, annunciate the DVM mode: programmed voltage (left light) or actual tip voltage (right light).
4. Polarity Selection - Polarity selection is accomplished by removing the rear barrel of the gun approximately one and a half inches by rotating the ejector ring. Then rotate the rear barrel to the desired polarity, and re-insert it firmly into the gun. CAUTION - before changing polarity, remove all power to the gun by first turning the power supply to the off position, and then touching the tip to the return point of the ground cable, to insure that the discharge capacitor is completely discharged.

2.1.3.3 Discharge Network, Model DN-1, 2, etc.

Each Discharge Network comes with an auxiliary handle, for use with the optional Extender Cable, EC-1.

The momentary switch on this handle is used to switch to high voltage mode when the EC-1 is in use; and it operates only with the basic ESD-1 trigger switch in UP, or LOCK-ON mode. This in turn implies that the ESD-1 is mounted on the PSC-1 Power Supply Unit or the T-1 Tripod; otherwise system interlocks will prevent operation. (The purpose of these interlocks is to minimize possibilities for personnel hazard.)

2.2 Self-Discharge Proximity Tip and Tip Spacer, Model FT-10

A single assembly, the FT-10, is used both for self-discharge proximity testing, and as a spacer or "depth-gauge" in normal air discharge testing. In this latter case, the FT-10 provides a fixed distance between the discharge tip and the surface to which the discharge will be made.

The FT-10 assembly fits over the discharge network (DN) with any tip (DT-1, 2, or 3) in place.

2.2.1 Fixed Distance Testing

To perform air discharge testing to a surface, and maintain a fixed distance from the discharge tip to the surface, the FT-10 is used as a tip spacer .

The Tip Spacer is obtained by simply removing the end cap containing the discharge ball from the FT-10 assembly. Distance from the tip to the discharge surface can be adjusted by sliding the assembly forward to the desired location, and then locking the FT-10 in position via the knurled knob on the bottom of the FT-10 collar. Note: no discharge will occur unless the tip voltage is high enough to break down the gap. Too great a distance setting will prevent a discharge from occurring. (Too close a setting may generate multiple discharges.)

2.2.2 Proximity Discharge Testing

For proximity discharge testing, the end cap of the FT-10, which contains the discharge ball, must be in place; and the return wire connected to the end cap must be connected to the discharge network (DN).

2.3 Current Injection Adapters, Models CIA-5, 7.5, etc.

Several current injection adapters are available to provide the capability of directly injecting a current pulse into the equipment under test, and to insure repeatability in H and E field simulations.

The current injection adapter (CIA) mounts on the front of the discharge network (DN). At the front of the CIA are two high voltage connectors, one above the other, and two ground pins (used as locators and shield ground connectors with the FT-21 and FT-11). For Current Injection testing, the discharge tip (DT1, DT2, DT3) is connected to the lower high voltage socket.

The impulse occurs when the Discharger's voltage exceeds the current injection adapter's nominal voltage +10%. Thus the programmed voltage should be set 20 to 30% over the nominal CIA voltage to insure firing. To provide current injection over a range of different voltages, CIA's are available with nominal switching (or breakover) voltages from 5kV to 20kV: specifically at 5, 7.5, 10, 15 and 20kV.

Current injection testing is then performed by placing the tip in direct contact with the surface into which the current impulse is to be injected.

Note: If the tip is not in direct contact with a conducting surface, an extraneous beep may be heard from the gun when the trigger is pulled. This is normal and is not an indication of improper operation.

A schematic of the CIA, connected to a typical Discharge network (DN), is given in Figure 2-2.

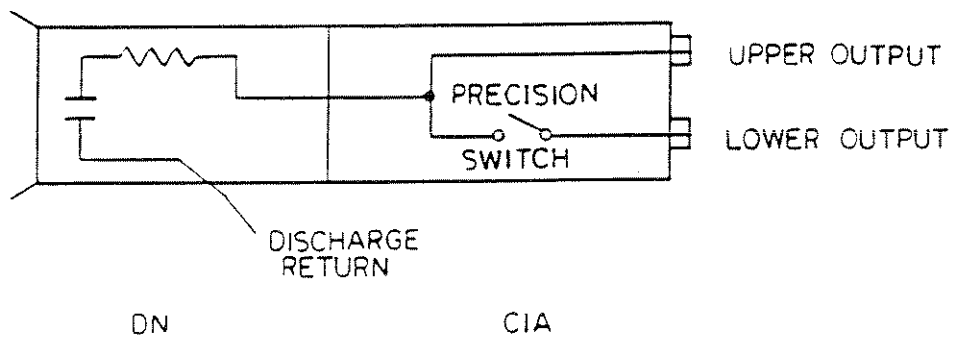


Fig. 2-2
 Typical CIA Schematic
 (Connected to Discharge Network)



The following diagram shows application of Current Injector Adapter to all three modes in which it is useful: Current Injection, Magnetic Field Simulation and Electric Field Collapse Simulation.

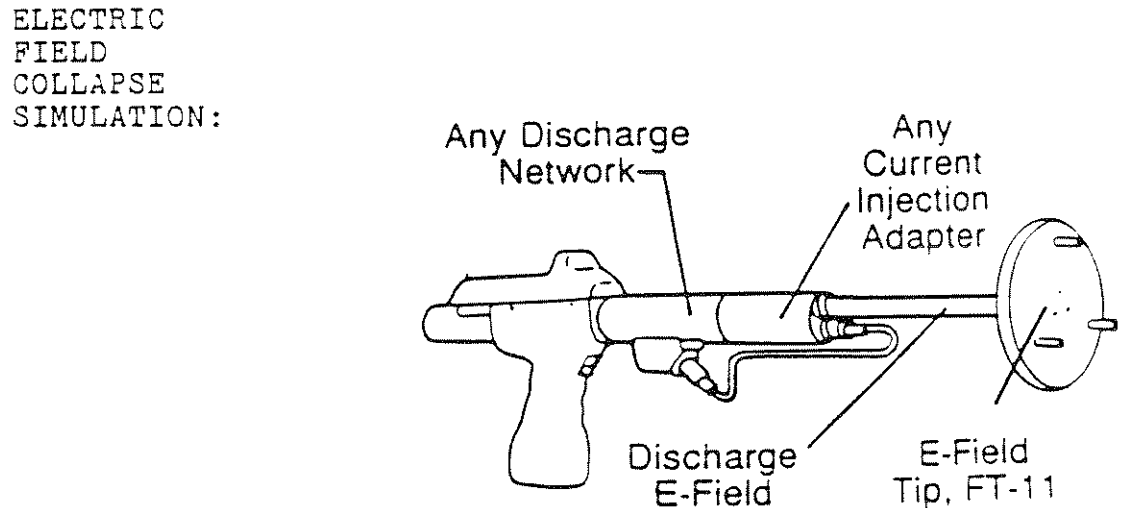
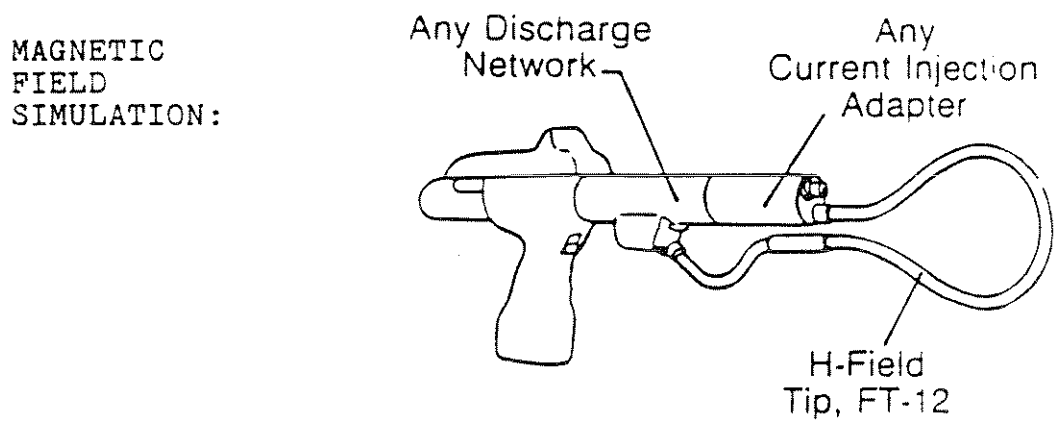
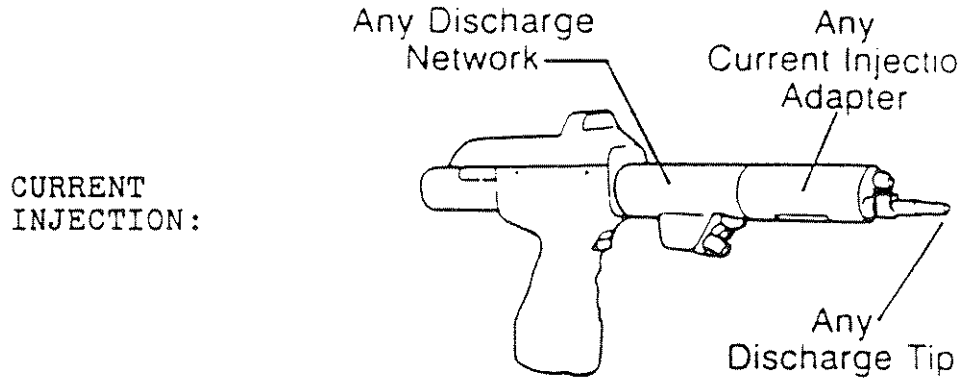


Fig. 2-3 Adapter-FT-21

Use of Current Injection Adapter for Current Injection, Magnetic Field Simulation and Electric Field Collapse Simulation

2.4 Extender Cable, Model EC-1

The EC-1 extender cable allows remoting the Discharge Network (DN) and tip. A separate handle and auxiliary trigger are provided on the discharge network.

CAUTION: Turn main power off (on the PSC-1) before connecting or disconnecting the EC-1.

When the EC-1 Extender Cable is in use, the ESD-1 gun should be firmly mounted on the power supply mounting bracket, or on a tripod.

To install the extender cable, simply remove the discharge network from the gun and connect the EC-1 between the gun and discharge network. All gun operation is the same as before, except the DN and any tips being used, are now remote from the gun. (Maximum attainable high voltage is reduced, to 20kV from 25kV, with the EC-1 in use.)

The main trigger must be in the Lock On (up) position, in order for the remote trigger to function.

2.5 Tripod and Boom, Model T-1

This section refers to the optional tripod and boom, Model T-1.

2.5.1 Unpacking

The Model T-1 Tripod is shipped inside a double box, with the inner box supported by foam end caps.

Remove the tripod and boom from the inner carton, being careful to preserve both inner and outer boxes. Boxes should be stored in the event the tripod ever has to be re-shipped.

2.5.2 Assembly

1. Loosen the lower collar on the tripod mast. Moving the collar towards the bottom of the mast will allow the legs to unfold. Tighten the lower collar with the legs spread to support the tripod.
2. The bracket, located at the center of tripod boom, has a sleeve which fits over the post on the top of the tripod mast. Attach the boom to the top of the tripod mast by placing the sleeve over the post on the mast, and tighten the clamp.
3. A bracket is provided near the bottom of the tripod mast for mounting the PSC-1 Power Supply. The power supply top bracket should be mounted to the tripod bracket provided, with the power supply push-button controls facing upward.
4. The ESD Gun is mounted on the bracket provided at the end of the tripod boom.

2.5.3 Adjustment

1. Height The two upper collars on the tripod mast can be loosened to raise or lower the tripod boom.
2. Boom Angle The boom angle can be adjusted by loosening the clutch mechanism with the handle provided.
3. Boom Length Loosening the boom collar, located just behind the ESD gun mounting bracket, will allow the length of the boom to be adjusted.

2.7 Simulating the Air Discharge and All Five Air-Discharge Components

2.7.1 Summary

Each configuration listed below must include an ESD-1, a PSC-1, and at least one Discharge Network (DN1, 2, 3, etc.)

Table 2-1

EQUIPMENT REQUIRED FOR DIFFERENT SIMULATIONS

<u>SIMULATION MODE</u>	<u>ADDITIONAL UNITS REQUIRED</u>
AIR DISCHARGE	At least one Discharge Tip DT-1, 2, or 3
1. Pre-Discharge Corona-Generated RF Interference	Point Discharge Tip DT-2
2. Pre-Discharge Electric Field	E-Field Tip FT-11
3. Discharge Electric Field Collapse	Any Current Injection Adapter, preferably CIA-20 E-Field Tip FT-11 Discharge E-Field Adapter FT-21
4. Discharge Magnetic Field	Any Current Injection Adapter, preferably CIA-20 H-Field Tip FT-12
5. Current Injection	Any Current Injection Adapter CIA-10, 20, etc. Any Discharge Tip DT-1, 2, or 3

2.7.2 Simulating the Air Discharge

2.7.2.1 Direct Air Discharge

Required are:

ESD-1	Discharger (gun)
PSC-1	Power Supply/Control Unit
DN-1, 2, 2, etc.	At least one Discharge Network
DN-1, 2, or 3	At least one Discharge Tip

Optional is:

FT-10	Spacer/Proximity Tip
HT-10 with DT-4	Hand adapter with Tool Tip

2.7.2.2 Proximity Air Discharge

Required are:

ESD-1
PSC-1
DN-1, 2, 3, etc.
DT-1, 2, or 3

Discharger (gun)
Power Supply/Control Unit
At least one Discharge Net-
work
At least one Discharge Tip

Plus:

FT-10

Spacer/Proximity Tip

2.7.3 Simulating the Five Components of the Air Discharge

2.7.3.1 Pre-Discharge Corona

Required are:

ESD-1	Discharger (gun)
PSC-1	Power Supply/Control Unit
DN-1, 2, 3, etc.	At least one Discharge Network

Plus:

DT-2	Corona Tip
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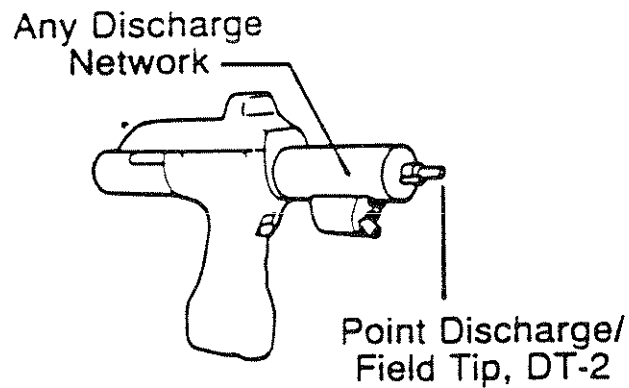


Fig. 2-5

Configuration for Simulating Pre-Discharge Corona

2.7.3.2 Pre-Discharge Electric Field

Required are:

ESD-1	Discharger (gun)
PSC-1	Power Supply/Control Unit
DN-1, 2, 3, etc.	At least one Discharge Network

Plus:

FT-11	Electric Field Tip
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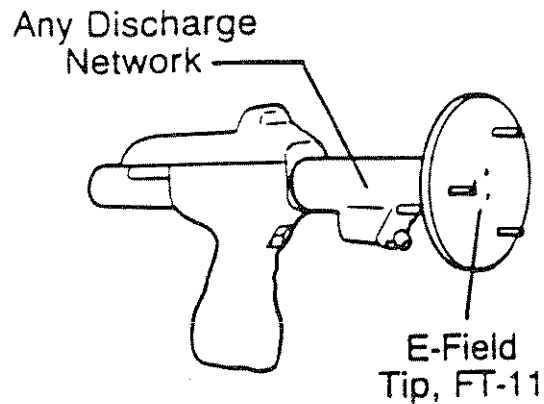


Fig. 2-6

Configuration for Simulating Pre-Discharge Electric Field

2.7.3.3 Discharge Electric Field Collapse

Required are:

ESD-1	Discharger (gun)
PSC-1	Power Supply/Control Unit
DN-1, 2, 3, etc.	At least one Discharge Network

Plus:

FT-11	Electric Field Tip
FT-21	Discharge Electric Field Adapter
CIA-20	Current-Injection Adapter, preferably 20kV as indicated. Other voltage level CIA's perfectly acceptable, but won't generate as high a field strength.

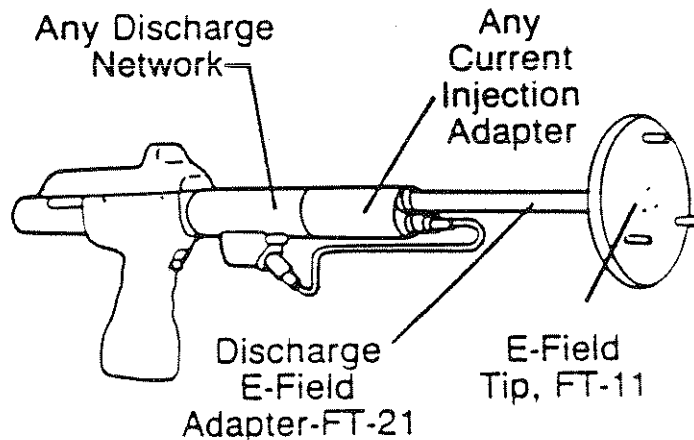


Fig. 2-7

Configuration for Simulating Discharge Electric Field Collapse

2.7.3.4 Discharge Magnetic Field

Required are:

ESD-1	Discharger (gun)
PSC-1	Power Supply/Control Unit
DN-1, 2, 3, etc.	At least one Discharge Network

Plus:

FT-12	Magnetic Field Tip
CIA-20	Current-Injection Adapter, preferably 20kV as indicated. Other voltage level CIA's perfectly acceptable, but won't generate as high a field strength.

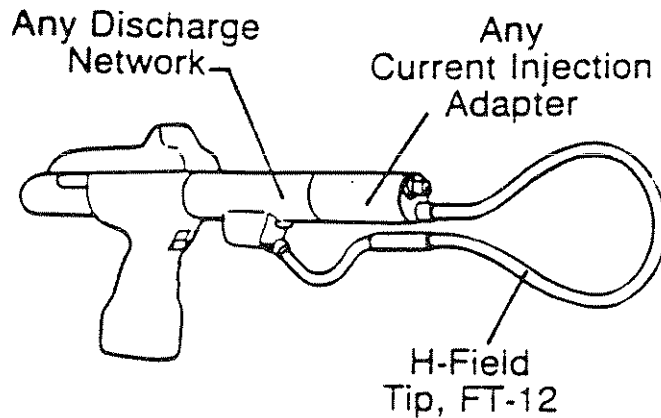


Fig. 2-8

Configuration for Simulating Discharge Magnetic Field

2.7.3.5 Discharge Current-Wave Injection

Required are:

ESD-1	Discharger (gun)
PSC-1	Power Supply/Control Unit
DN-1, 2, 3, etc.	At least one Discharge Network
DT-1, 2, or 3	At least one Discharge Tip

Plus:

CIA-5, 7.5, 10, 15 or 20	Current-Injection Adapter
-----------------------------	---------------------------

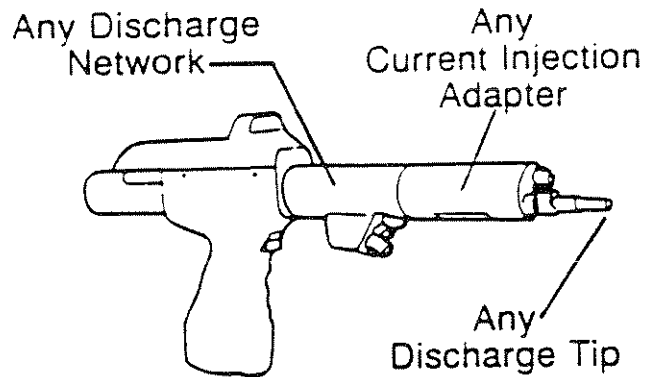


Fig. 2-9

Configuration for Simulating Discharge Current-Wave Injection

2.8 Calibrators

2.8.0 ESD Waveform Verification

Making an accurate, noise free measurement of an ESD waveform from a simulator or human source can be extremely difficult due to the wave's very fast sub-nanosecond risetimes and to the large amounts of EMI generated. We therefore strongly recommend that any calibration or re-certification be done at the KeyTek factory.

The equipment used at KeyTek consists of the following:

1. Tektronix 7104 1 GHz mainframe with EMI option
2. Faraday shield for oscilloscope
3. Tektronix 7A29 preamp
4. Tektronix 7B10 timebase
5. Tektronix 011-0068-00 20dB attenuator
6. Tektronix C-53 oscilloscope camera
7. KeyTek-manufactured IEC revised* ESD target
8. 1.5 meter square Aluminum vertical plane to mount target
9. 8' Belden 9913 coax cable with type "N" connectors

The IEC revised target is essential to obtain accurate results in a 1GHz bandwidth environment. The earlier IEC target design gives highly distorted results. The IEC revised target will be commercially available from KeyTek when the IEC finalizes its design. Plans for constructing one are available from KeyTek or the IEC.

The target is mounted in the center of the 1.5 meter square vertical plane. This plane is held vertical by a wooden stand or special mounting to a non-metallic wall.

* 25 resistors in outer ring

The oscilloscope is installed in a Faraday cage. This is a rectangular Aluminum box large enough to contain the oscilloscope and camera, and to allow air circulation around the back of the scope so it does not overheat. The power line for the oscilloscope is brought in through a filter to prevent the entry of conducted EMI. A type N feedthrough is mounted on one side near the front, to pass the ESD signal into the enclosure. The front of the enclosure is hinged at the top allowing it to be opened easily to access the camera and controls. The edges of the door are lined with spring finger stock to insure good rf integrity. The 7A29 and 7B10 occupy one plug-in slot each. The two unused slots must be filled with either blank panels or with any other plug-ins to prevent EMI leakage. It is imperative that the oscilloscope be well shielded in this way, or else the large EM field generated by the ESD event will radiate directly into the CRT and electronics of the oscilloscope, causing massive noise and distortion of the waveform.

Belden 9913 is used to connect the target to the scope because it is very low loss and has 100% shield coverage. RG55 and RG58 are too lossy and will not give accurate results.

The 20dB attenuator is needed to scale the output of the target to be within the range of the 7A29. It must be a low VSWR microwave type, such as the Tektronix part listed in #5 above.

Please contact the KeyTek Customer Service Department, if telephone assistance is required. All products in the Series 2000 ESD simulator product line are designed to maintain their calibration. Re-certification is sometimes required by customers, and that service is available at the KeyTek factory.

2.8.1 Model CTC-1 Coaxial Target Calibrator

The Model CTC-1 Coaxial Target Calibrator is built to IEC specifications.* It is used along with a storage oscilloscope of > 400 MHz bandwidth to measure discharge current waveshape.

Note, that use of an oscilloscope with 400 MHz bandwidth will permit full use of the CTC-1's ~1 nanosecond-risetime capabilities.

The schematic diagram of the calibrator is given in Figure 2-11. It includes the TC-50 balun cable supplied as standard equipment with the CTC-1.

NOTE: AS SPECIFIED BY THE IEC, ALL CALIBRATION WORK WITH THE CTC-1 SHOULD BE DONE WITH THE SHORT GROUND RETURN STRAP, THE GCS-1. IT IS SUPPLIED WITH THE CTC-1.

The long (~6 foot) ground strap (GCL-1) may be used as a check, but all Discharge Networks, following the IEC's lead in the matter, are specified "with the shortest possible ground return", i.e. the roughly 12-inch GCS-1.

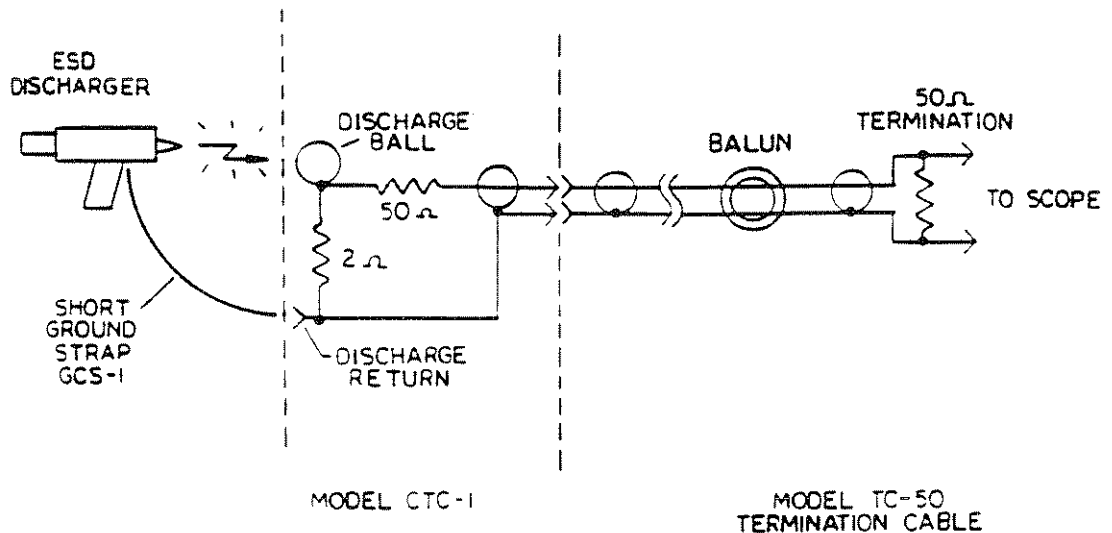


Fig. 2-11

Using the CTC-1 Coaxial Target Calibrator

* IEC Draft Standard, TC65 (Sect) 80, WG4



A balun is built into the TC-50 cable to reduce common mode effects.

When an oscilloscope with typical, 1 Megohm input impedance is used with the TC-50 terminated cable, the scale factor is 1 volt per ampere of discharge current. When using a 50 Ω scope input, the 50 Ω cable termination supplied as standard equipment with the TC-50 must be removed, to insure correct effective termination impedance and consequently correct wave shape. Scale factor remains 1 volt per ampere, since the effective termination impedance remains the same, namely 50 Ω .

If attenuation of the CTC-1 output signal is required, a suitable 50 Ω attenuator can be inserted (and indeed cascaded) between the CTC-1 rear output jack and the TC-50 cable. The following types have been found to be acceptable.

<u>Attenuation</u>	<u>Manufacturer</u>	<u>Model Number</u>
x2	Tektronix	011-0069-02
x5	Tektronix	011-0050-02
x10	Tektronix	011-0059-02

2.8.1.1 50 Ohm Measurements with the CTC-1 Coaxial Target Calibrator

The first rule to be observed when making measurements in a 50 ohm system is that you must insure that the source always "sees" a 50 ohm termination. The CTC-1 Coaxial Target Calibrator can be considered to be a 50 ohm source, which must be terminated in a 50 ohm load to produce a scale factor of 1V/A (1 volt per ampere). Anything that causes the CTC-1 to see a terminating impedance of other than 50 ohms will cause reflections and standing waves to exist, resulting in incorrect measurements.

In order to maintain the 50 ohm system, any transmission line between the source (CTC-1) and the load must have a characteristic impedance of 50 ohms. Several commercial varieties are available, including RG-58 and RG-55, (suffixes such as A, A/U, U, etc. refer to the dielectric material and do not affect the characteristic impedance). For short cables, up to a few feet, the attenuation for different varieties of cable is trivial.

The standard CTC-1 is equipped with a short length of RG-55 and a balun. This cable is terminated in 50 ohms at the balun (scope) end, for use with oscilloscopes having a 1 megohm input impedance. The combination cable, balun and termination is termed the Model TC-50. The 50 ohm coaxial termination must be removed if the CTC-output is connected to an oscilloscope having a built-in 50-ohm termination, such as a Tektronix mainframe using a 7A19 or a 7A29 vertical amplifier. (To remove the termination, slit the heat shrink tubing that holds the termination to the cable end.)

Attenuators can be used within a 50 ohm system to reduce the output scale factor. Tektronix, Hewlett Packard and others, manufacture attenuators acceptable for use in 50 ohm systems. Any attenuator used must be designed to be inserted in a 50 ohm system (with minimum loss) without changing the characteristic impedance of the line.

Attenuators are available in factors of 2, 5, 10 and others. These can be connected in series; the overall scale factor is the product of the individual scale factors. It is best to stick to the even ones for ease in scale factor calculation. Some acceptable Tektronix attenuators are listed below.

2:1 Tektronix Part #015-1001-00

5:1 Tektronix Part #015-1002-00

10:1 Tektronix Part #015-1003-00

Fig. 2-11A shows various acceptable and unacceptable configurations.

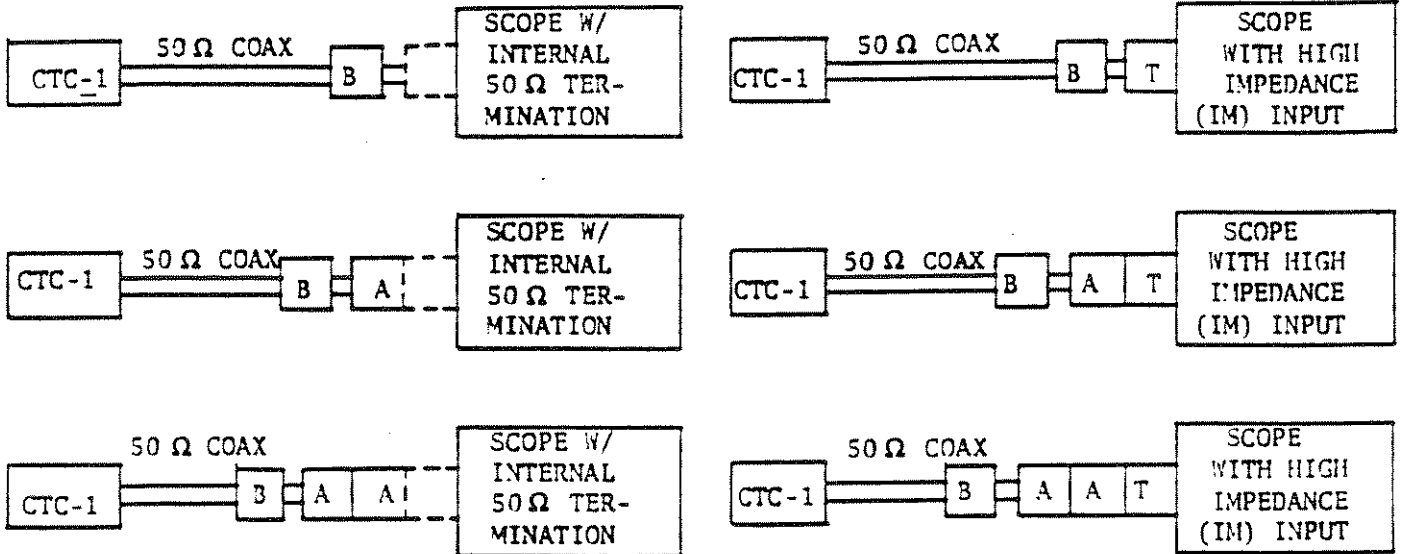
T = 50 Ω TERMINATION
(SUPPLIED BY KEYTEK)

A = 50 Ω IN-LINE ATTENUATOR
(2:1, 5:1, ETC.)

B = 50 Ω COAX BALUN
(SUPPLIED BY KEYTEK)

REMOVE KEYTEK-
SUPPLIED 50 Ω
TERMINATION

ACCEPTABLE



- NOTES: 1. THE ATTENUATOR CAN BE AT EITHER END OF 50 Ω COAXIAL CABLE; HOWEVER LOCATING THE ATTENUATOR AT LOAD END OF CABLE, FOLLOWING THE BALUN AS SHOWN, IS PREFERRED.
2. USE ONLY 50 Ω COAXIAL CABLE.
3. USE ONLY ATTENUATORS DESIGNED FOR 50 Ω SYSTEM (i.e. 75 Ω OR 300 Ω ATTENUATORS ARE UNACCEPTABLE).

UNACCEPTABLE

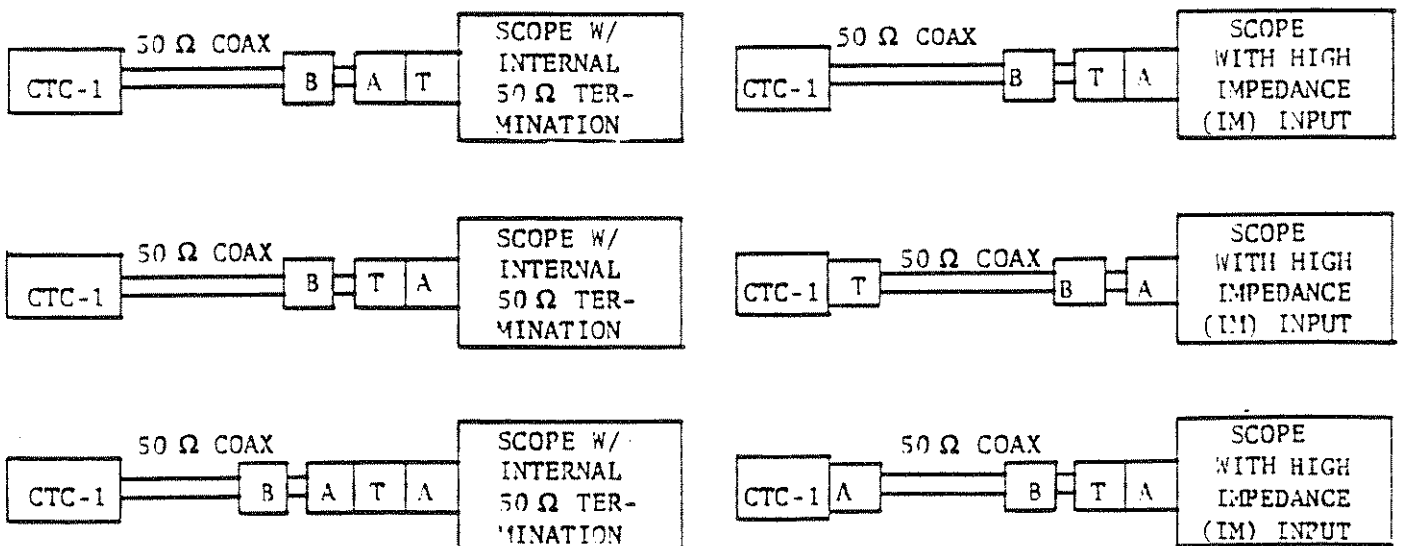


Fig. 2-11A

Acceptable and Unacceptable Coaxial Attenuator Configurations

2.8.1.2 Peak Discharge Output Current

The value of peak discharge output current available from a Discharge Network (DN) is related to the voltage stored on the DN output capacitor (V_x), and to the DN output resistance (R_x). However, peak current is not simply equal to V_x divided by R_x . This simple relation does not take into account the characteristics of the discharge arc*, nor does it take into account the not-inconsequential stray capacitances, or the very substantial inductances involved.

See section 3.1, under Applications, for further details.

*Arc resistance, in particular, may be as high as 100 to 200 ohms; and the arc will have some inductance as well.

2.8.2 Model DCA-1 DC Output Calibration Attenuator

The Model DCA-1 DC Output Calibration Attenuator is connected to any discharge network instead of a discharge tip. It has a 10,000:1 attenuation factor when driving a 10 Megohm load. This translates to an output of 1 volt for a 10kV DN output voltage. For other common loads, use the following table:

Attenuator Load	Attenuation Factor	1V Output for Input of:	25kV Yields an Output of:
∞	9,540:1	9.54kV	2.62V
10M	10,000:1	10kV	2.50V
1M	14,550:1	14.55kV	1.72V

The schematic diagram of the attenuator is as follows.

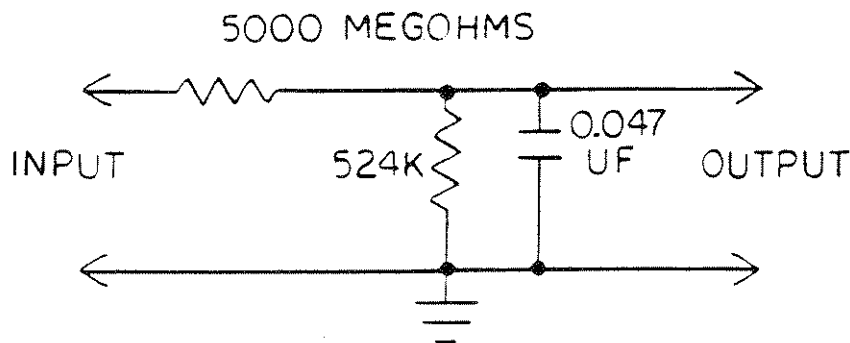


Fig. 2-12

DCA-1 DC Output Calibration Attenuator

2.8.3 Model HFS-1 H-field Sensor

The Model HFS-1 H-field Sensor consists of two parts; the HFS-1 loop antenna, and the Model HEC-1 monitor units.

To use the H-field sensor:

1. Rotate the HEC-1 unit's handle downward until it rests against the stop.
2. Attach the HFS sensor loop to the front end of the monitor.
3. Connect a TC-50 terminated cable between the storage scope and the monitor unit.

To check the relative H-field performance of the Model ESD-1:

1. Configure the ESD-1 with a CIA and a FT-12 field tip (see manual section 2.7.3.4).
2. Position the FT-12 tip in close proximity to the HFS-1 loop and pull the trigger.

Typical scope settings of 20ns/0.5cm and 50V/0.5cm should show the H-field envelope.

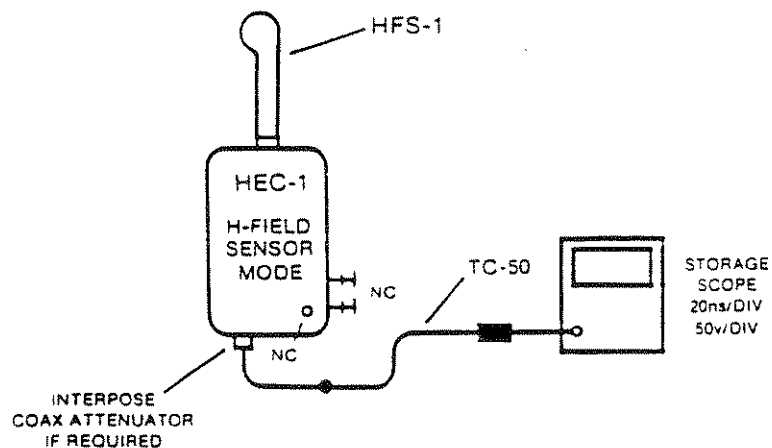


Fig. 2-13

Using the HEC-1 H-field Sensor

2.8.4 Model EFS-1 E-field Collapse* Sensor

The Model EFS-1 E-field Collapse Sensor consists of two parts; the EFS-1 E-field Collapse Antenna, and the Model HEC-1 Monitor Unit.

To operate in the E-field collapse mode:

1. Rotate the HEC-1 unit's handle downward until it rests against the stop.
2. Attach the EFS-1 sensor disk to the front end of the monitor.
3. Connect a TC-50 terminated cable between the storage scope and the monitor unit.

To check the relative E-field performance of the Model ESD-1:

1. Configure the ESD-1 with a CIA, FT-21, and FT-11 Field Tip (see manual section 2.7.3.3).
2. Position the FT-11 very close and parallel to the EFS-1 disk and pull the trigger.

Typical scope settings of 50ns/0.5cm and 5V/0.5cm should show the E-field Collapse envelope.

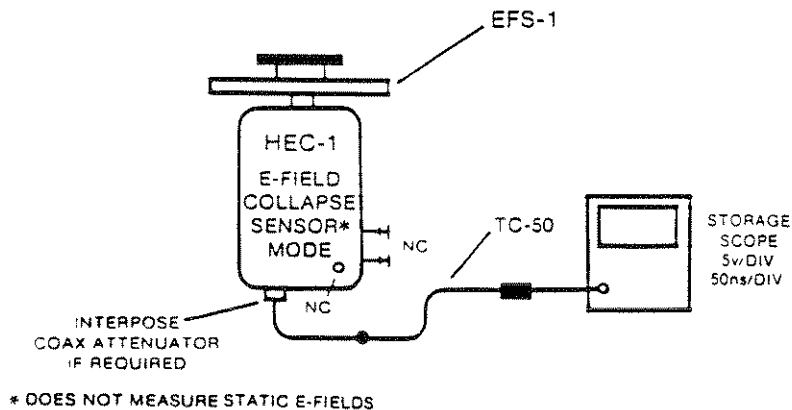


Fig. 2-14

Using the EFS-1 E-field Collapse Sensor

*Unit measures only E-field Collapse. It will not measure static E-fields.

2.8.5 Model CCS-1 Corona Sensor (Figure 2-15)

The Model CCS-1 Corona Sensor consists of two parts; the CCS-1 Antenna, and the Model HEC-1 Monitor Unit. To operate in the corona sensor mode:

1. Plug the antenna into the receptacle on the top of the monitor unit.
2. Attach a 10:1, 10M Ω scope probe to the turret terminals located on the side of the monitor unit, as indicated in the Figure.

Strong corona should show up on the oscilloscope as a series of closely spaced impulses when using the 100mV/cm and 1ms/cm ranges. The impulse decay time constant is approximately 5ms.

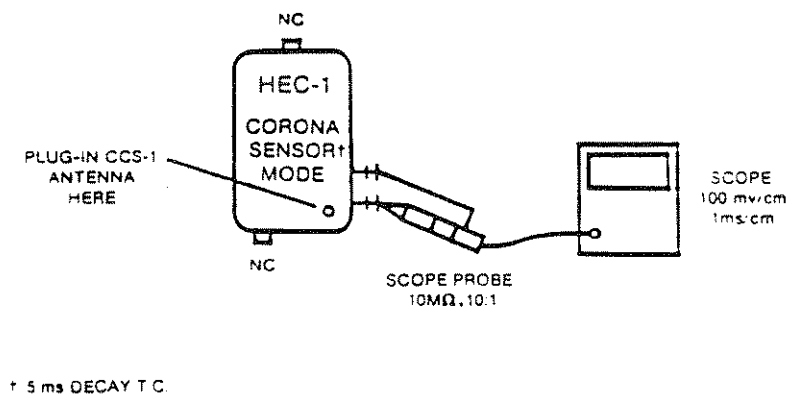


Fig. 2-15

Using the CCS-1 Corona Sensor

2.9 Dielectric Tester, Model PSC-2

2.9.1 General

The Model PSC-2 is used in conjunction with the Model 2000 and an EC-2 cable to generate a 1.2 x 50 us, 25kV impulse for the dielectric testing of materials. The output waveform, of the Model PSC-2, is taken at the OUTPUT HIGH and OUTPUT LOW rear panel connectors.

2.9.2 Specifications

Open-Circuit Voltage (OCV) waveform:

Front time: 1.2 +/- 0.36 us
Duration : 50 +/- 10 us
Vpeak : 25 kV +/- 10%

2.9.3 Power Requirements

The Model PSC-2 can only be operated from an ac power source of 105 to 130 Vrms, 50-60 Hertz. Operation of the system will be inhibited if ac is not present or the POWER switch, located on the front panel, is in the OFF position.

2.9.4 Set-up, and Operation

1. Turn Model 2000 main power OFF (on the PSC-1) and connect the cable marked EC-2 to the ESD-1 as labeled.
2. Connect the other end of the EC-2 cable to the PSC-2 as labeled.
3. PSC-1 Set-up:
 - a. Set SECONDS/PULSE switch to 10.
 - b. Set CHARGE switch to SLOW.
 - c. Set PULSE switch to NORMAL.
 - d. Turn main power switch to ON.
4. PSC-2 Set-up:
 - a. Connect main power cord to the PSC-2 and turn POWER switch to ON.
 - b. Install the PSC-2 Output Cover.
 - c. Connect the PSC-2 to the device under test, via, the OUTPUT HIGH and OUTPUT LOW rear panel connectors.

Note: Use 25kV insulated test leads for this connection. Also, two access holes for the test leads are located at the top of the PSC-2 Output Cover.

5. ESD-1 Set-up:

- a. Set the TRIGGER to LOCK (LOCK-ON) position.
- b. Adjust the VOLTAGE CONTROL knob to set the desired discharge voltage.

6. An impulse may now be initiated by:

- a. Depressing the CHARGE switch located on the PSC-2 front panel, and then
- b. Depressing the PULSE switch, also located on the PSC-2 front panel.

Note: It is recommended that there be a delay of 10-15 seconds between pulses to allow for proper operation of internal circuits.

2.9.5 Monitoring

Two BNC connectors are provided to enable oscilloscope monitoring of a replica of the voltage and current waves. These BNC connectors marked V MON (for voltage) and I MON (for current) are located on the PSC-2 rear panel and defined as follows:

1. V MON/Voltage

An attenuated version (50mV/kV) of the output Voltage is available at the V MON connector.

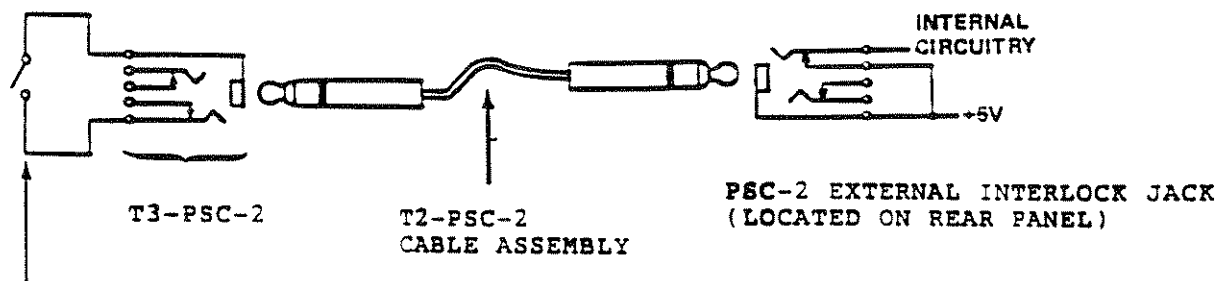
2. I MON/Current

An attenuated version (1V/A) of the output current is available at the I MON connector.

The Audible-Discharge Monitor (see section 1.2.2.2) is disconnected. A discharge is indicated by viewing the Digital Stored Voltage Monitor and noting a rapid decay of the meter reading. This signifies a charge dump.

2.9.6 External Interlock

The External Interlock jack (PSC-2 Rear Panel) is used when it is desired to extend the PSC-2 interlock circuit to include an external test fixture or equipment under test (this can be an interlock switch or interlock system which may include many switches). See Figure 2-16 for connection of T2-PSC-2 Cable Assembly and T3-PSC-2 Interlock Jack.



EXTERNAL INTERLOCK SWITCH
OR INTERLOCK SYSTEM. MUST
BE IN CLOSED POSITION FOR
PROPER OPERATION.

FIGURE 2-16

EXTERNAL INTERLOCK CONNECTION



SECTION 3

3. Applications

3.1 Peak Discharge Output Current

As indicated in section 2.8.1.2, the value of peak discharge output current available from a Discharge Network (DN) is related to the voltage stored on the DN output capacitor (V_x), and to the DN output resistance (R_x). However, peak current is not simply equal to V_x divided by R_x . This simple relation does not take into account the characteristics of the discharge arc*, nor does it take into account the not-inconsequential stray capacitances, or the very substantial inductances involved.

Typically the value of current measured using the CTC-1 lies between 10% and 95% of the value obtained by dividing V_x by R_x , depending on the value of the resistance in the particular Discharge Network. The 150 pfd/150 ohm DN-1 gives a ratio of 50 to 60%; i.e., 15 kV yields on the order of 50A peak, rather than the 100A that would flow into a simple resistor of 150 ohms. This is allowed by the IEC specification for the DN-1. It calls for current output, probably with this effect in mind, as 70% of calculated V_x/R_x , \pm 30%. Thus 70%, minus 30% of 70%, is about 50%.

For DN's with resistance values of 500 ohms to 1K, peak currents more nearly agree with calculated V_x/R_x figures.

For DN's with very much lower resistances than 150 ohms, peak output currents may even be lower than 50% of calculated V_x/R_x ; for 10 to 20 ohms, for example, peak outputs may be on the order of only 5 to 10% of calculated V_x/R_x .

Table 3-1 following, gives theoretical maxima for outputs from DN's with a wide range of C and R values, with no accounting for either arc resistance or stray capacitances. Actual values may differ by a factor of two or more, lower or higher.

*Arc resistance, in particular, may be as high as 100 to 200 ohms; and the arc will have some inductance as well.



The maxima are expressed in percent of V_x/R_x . For example the table shows that a DN-1 has a theoretical maximum of 73% at 5kV. Thus instead of getting a peak of 5kV/150 or 33.3A, it would theoretically be 73% of 33.3A, or 24.3A.* At 10kV it would be twice the figure, and so on.

The theoretical maxima have been calculated first for the inductance of a short ground strap (GCS-1), on the order of 0.7uH (including wiring within the DN itself). With a long ground strap (GCL-1), total inductance is about 1.7uH. Theoretical maxima are given for this case as well.

Note again that in almost every case, theoretical maxima are just that -- theoretical. As indicated in the IEC Draft Standard, actuals may generally deviate by up to as much as $\pm 30\%$ **

Oscilloscope bandwidth may also limit peaks. A peak occurring at 2ns will be reduced by 50 to 70% by a 100 MHz scope with its 3.5ns risetime. It will even be reduced -- 20% or so -- by a 400 MHz scope with 1 ns risetime! And a 60 MHz oscilloscope is probably just inappropriate altogether.

* Arc resistance seems to dominate for this network, so actual peak currents will be ~ 20 to 30% lower than the theoretical 24.3A.

**For the IEC-specified DN-1. As mentioned previously, deviations may even exceed 2:1 for other R-C value combinations. For really high resistances, initial overshoots, from 0.5 to 2ns in duration, due to 0.5 to 2pfd stray capacitances, may even exceed 5 or 6x the theoretical figures.

Table 3-1
Theoretical Maxima versus Vx/Rx
 For various DN C's and R's

<u>C</u> (pfd)	<u>R</u> (ohms)	<u>DN#</u>	<u>Theoretical</u> <u>Maximum</u> <u>with GCS-1*</u> <u>(% of Vx/Rx)</u>	<u>Current</u> <u>Peak</u> <u>Occurs</u> <u>at (ns)</u>	<u>Theoretical</u> <u>Maximum</u> <u>with GCL-1**</u> <u>(% of Vx/Rx)</u>	<u>Current</u> <u>Peak</u> <u>Occurs</u> <u>at (ns)</u>
60	15		13	10	8	15
60	10,000	5	100	1	100	2
100	100		60	10	7	17
100	500	6	93	5	87	10
100	1,500	2	99	3	97	6
120	1,800		99	3	98	5
125	455		93	6	87	11
150	150	1	76	10	64	18
150	2,000		99	2	99	5
200	1,000		98	4	97	8
200	2,000		100	3	99	5
250	3,000		100	2	100	4
255	80		67	15	54	25
300	500		97	7	94	13
300	1,000		99	4	98	9
300	3,000		100	2	100	4
300	5,000		100	1	100	3
330	2,000		100	3	99	6
500	5,000		100	1	100	3
700	50		68	24	55	42

*Assumes total L=0.7uH. Note actual peak current values may differ by up to 2:1, excluding possibly even higher, 1 to 2ns initial overshoots.

**Assumes total L=1.7uH. Note actual peak current values may differ by up to 2:1, excluding possibly even higher, 1 to 2ns initial overshoots.

SECTION 4

4. Calibration

4.1 Checking ESD 2000 Generator Calibration

4.1.1 Indicators & Basic Functions Test

1. Fit DN1 and DT1 (ball tip) to gun.
2. Set V Prog to zero with potentiometer on gun.
3. Press trigger (momentary)

Readout should = 00.0KV +- .1
 V/Prog led should extinguish
 V/Act led should light

Release trigger

4. Set V/Prog = 25.0KV

Press trigger (momentary)

Readout should = 25.0KV +- .1
 V/Prog led should extinguish
 V/Act led should light

Release trigger

V/Act led should remain on until readout drops
 below .3 to .5KV
 V/Prog led lights as V/Act led extinguishes

4.1.2 Calibration Check

1. Fit DCA-1^{*} to DN1 and connect DVM to DCA output
 (DVM input impedance must = 10 M)

Set + Polarity and then - Polarity

<u>Set V/Prog + & - Polarity</u>	<u>V/Act + & - Polarity</u>	<u>DCA Output + & - Polarity</u>
5.0KV	5.0KV +- 0.1KV	0.5V +- 15MV
10.0KV	10.0KV +- 0.1KV	1.0V +- 30MV
15.0KV	15.0KV +- 0.1KV	1.5V +- 45MV
20.0KV	20.0KV +- 0.1KV	2.0V +- 60MV
25.0KV	25.0KV +- 0.1KV	2.5V +- 75MV

2. If required discharge waveforms and resultant output currents can be checked in accordance with information provided in the Series 2000 operating Instruction manual.

* See page 2-25 for description.

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4.2 CALIBRATION PROCEDURE FOR ESD SERIES 2000

1. Remove outer case of the power supply unit to expose the control board (refer to figure 4.1). Connect the ESD-1 to the outer case using the mounting bracket. Attach the signal cable from the ESD-1 to the PSC-1. Connect power cord to the PSC-1.
2. Apply power to the unit. Loosen screw on top of display cover to gain access to DVM board (refer to figure 4.2). Turn set voltage knob until the display reads 0.0kV. Adjust potentiometer R1 to read 0.0kV Vprogram on display. Pull trigger of ESD-1 and adjust Vactual to 0.0kV with potentiometer R29 (refer to figure 4.5).
3. With Vprogram still set to 0.0kV, use an oscilloscope to check for 20 volts peak to peak at 1k ohm, quarter watt resistor R116, located on the control board. The amplitude adjustment is the potentiometer R67A (refer to figure 4.3).
4. With Vprogram set to 0.0kV, remove blue plugs located at J4 and J5 of the control board. Use wire jumpers to connect J5-1 to J4-3 and J4-4 to J4-1. Put oscilloscope probe to IC AD533JH, E1A pin 3 (refer to Figure 4.3), and adjust signal as close to zero volts as possible. To adjust amplitude of wave, use potentiometer R73. To adjust dc level, in respect to ground level, use potentiometer R75. Replace blue plugs to J4 and J5 and re-adjust dc level with potentiometer R75. Use potentiometer R74 to readjust amplitude to zero.
5. Set Vprogram with set voltage knob to 25.0kV. With a volt meter, measure the voltage on the DVM board from E1 pin 11 to ground (pin 8) (refer to figure 4.5). At 25.0kV the meter should read 253.0mV. Adjust this voltage level with potentiometer R5.
6. Set Vprogram with set voltage knob to 25.0kV. Pull trigger of ESD-1 and Vactual should read 25.0kV. Adjust High Voltage level with potentiometer R109 located on the Control board (refer to figure 4.3).
7. Set Vprogram with set voltage knob to 25.kV. To adjust high voltage output requires a DCA-1 attenuator or an electrostatic volt meter. Place DCA-1 to end of Discharge network and connect a volt meter to the DCA-1 terminals. Or place high voltage probe of electrostatic volt meter to output of discharge network and the ground of meter to the discharge return of the network. Pull trigger to get 25.0kV output, and adjust with potentiometer R20A located on the DVM board (refer to figure 4.5). If a DCA-1 or an electrostatic volt meter is not available, omit section 7.

8. Set Vprogram to maximum with set voltage knob it should not exceed 27.3kV. To adjust the Vprogram maximum reading requires a resistor change. This resistor is located in the handle of the ESD-1, on the handle board, as R2A (68.1K ohm 1%). To increase Vprogram, decrease the resistor value and to decrease Vprogram, increase the resistor value (refer to figures 4.2 and 4.4).
9. Set Vprogram to maximum, pull trigger and Vactual should not exceed 26.6kV. To adjust Vactual must be done in both polarities individually. Adjust the negative polarity first. This is done of the control board with the 3.3 ohm resistors R150 to R153 (refer to figure 4.3). Each resistor adds in the voltage drop of the diode it follows. Remove or add the resistors as needed. Allow unit to sit unplugged for fifteen minutes before proceeding to positive polarity adjustment. Turn unit on and check negative adjustment. Put unit in positive polarity and turn on high voltage. Again, unit should not exceed 26.6kV. Adjust the positive high voltage with R219 and R217 (330ohm and 680ohm respectively refer to figure 4.3). To increase the output increase the resistors values and to decrease the output, decrease the resistors values. Be sure that the relationship between R219 and R217 remains that R217 is twice the resistance value of R219.
10. The amount of time that the unit requires to go from Vactual back to Vprogram is called Changeover. The lowest Vactual reading should be at 0.3kV before the display switches back to the Vprogram reading. To correct the changeover time, adjust potentiometer R56 on the DVM board. This adjustment must be done separately for positive and negative polarities (refer to figure 4.5).

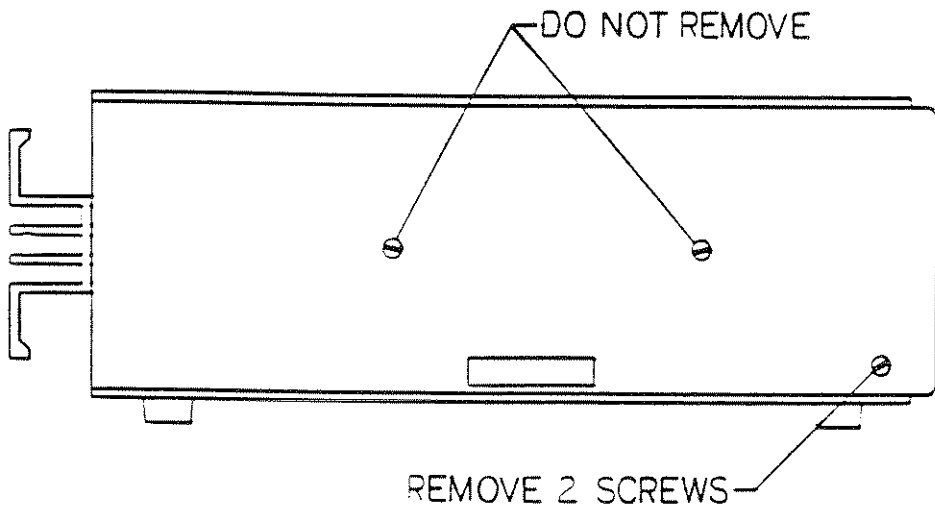
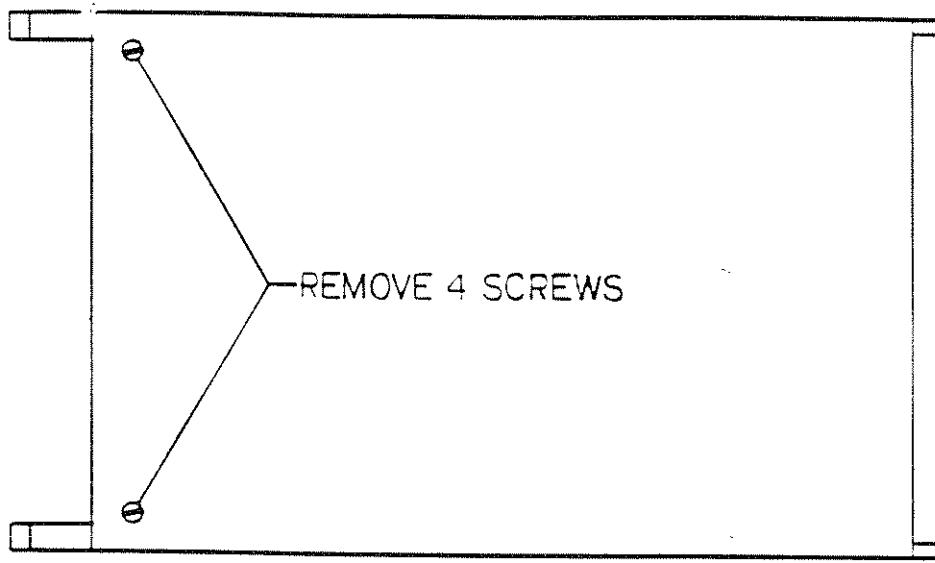


Figure 4.1

Removing outer Case of Power Supply PSC-1

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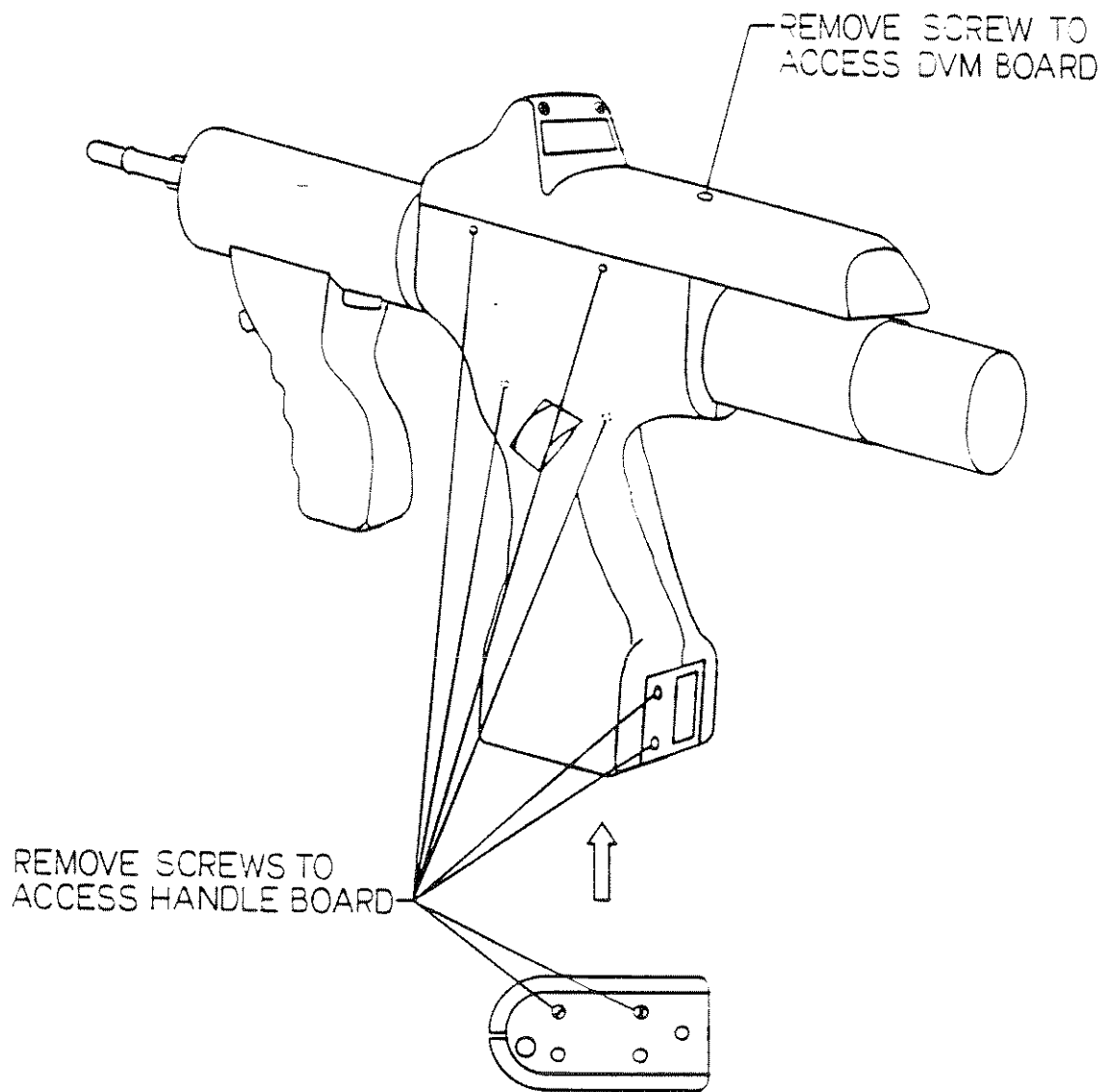


Figure 4.2

Access to DVM Processor PCB and Handle
PCB

.....

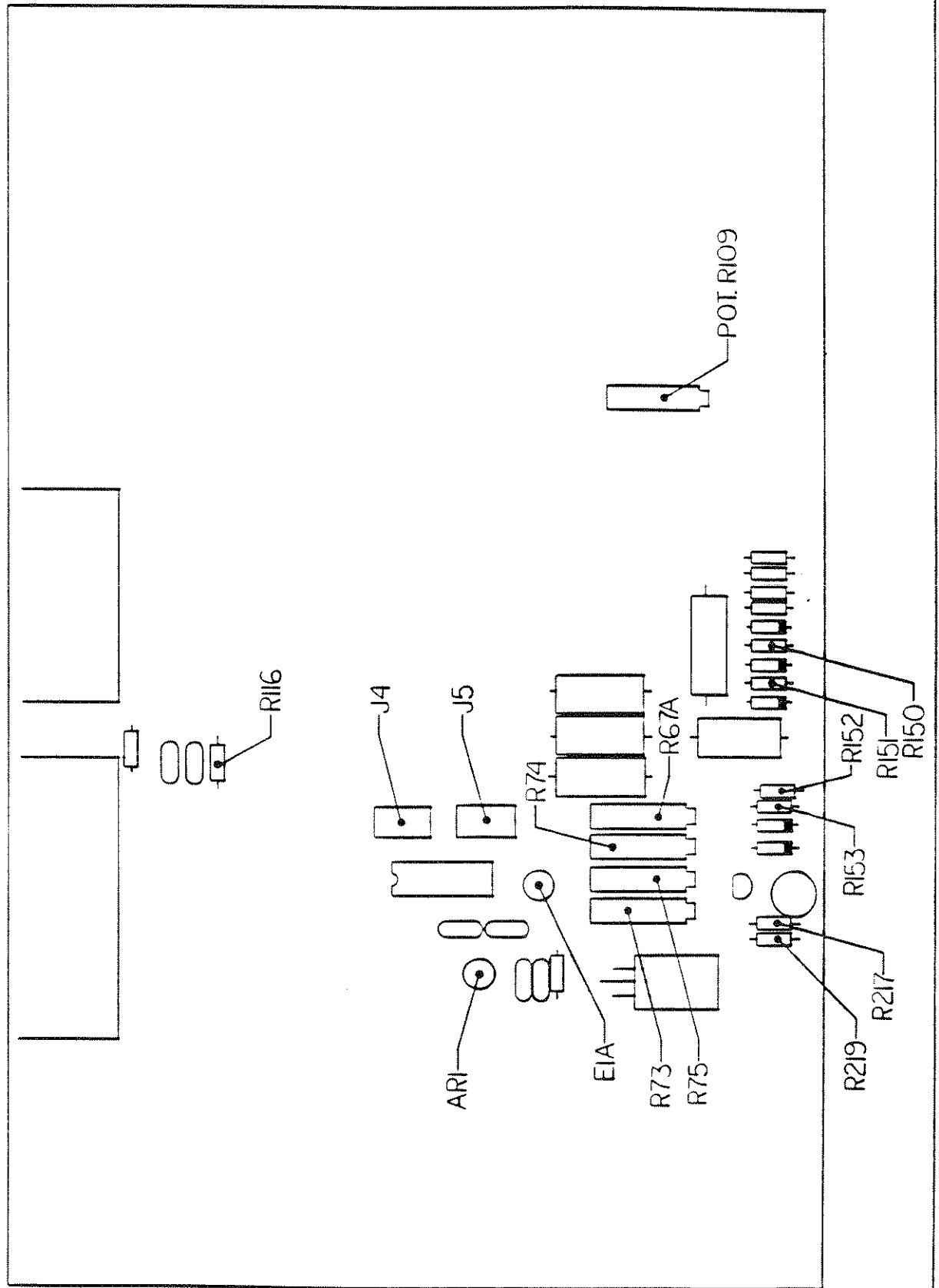


Figure 4-3
Control PCB Trim Locations

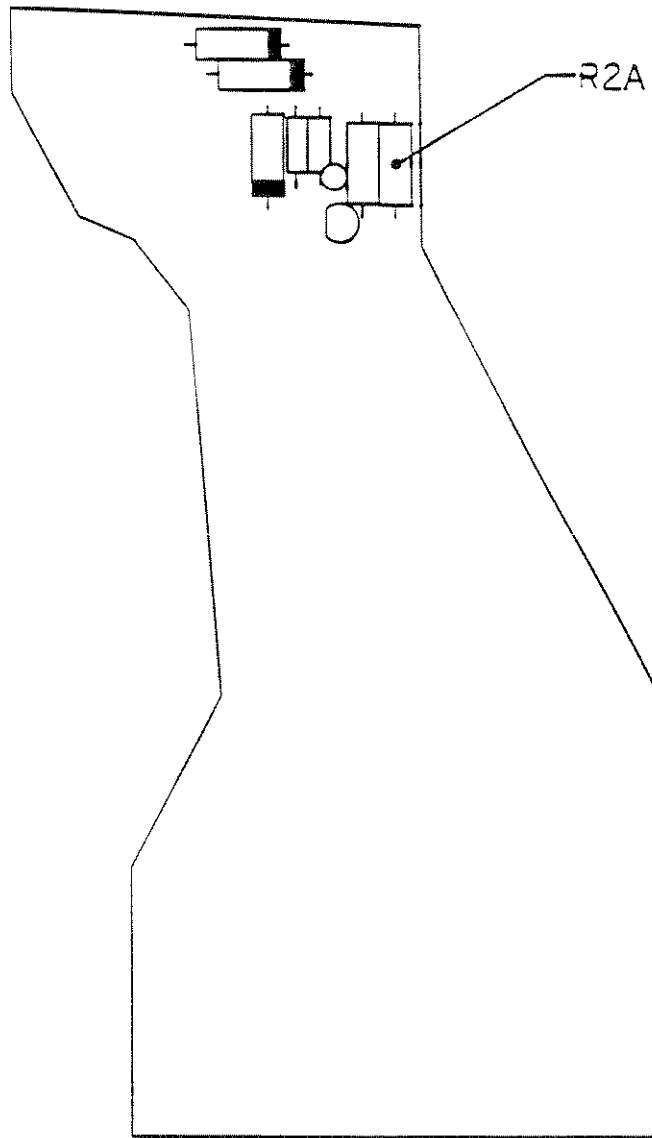


Figure 4-4
Handle PCB Trim Location



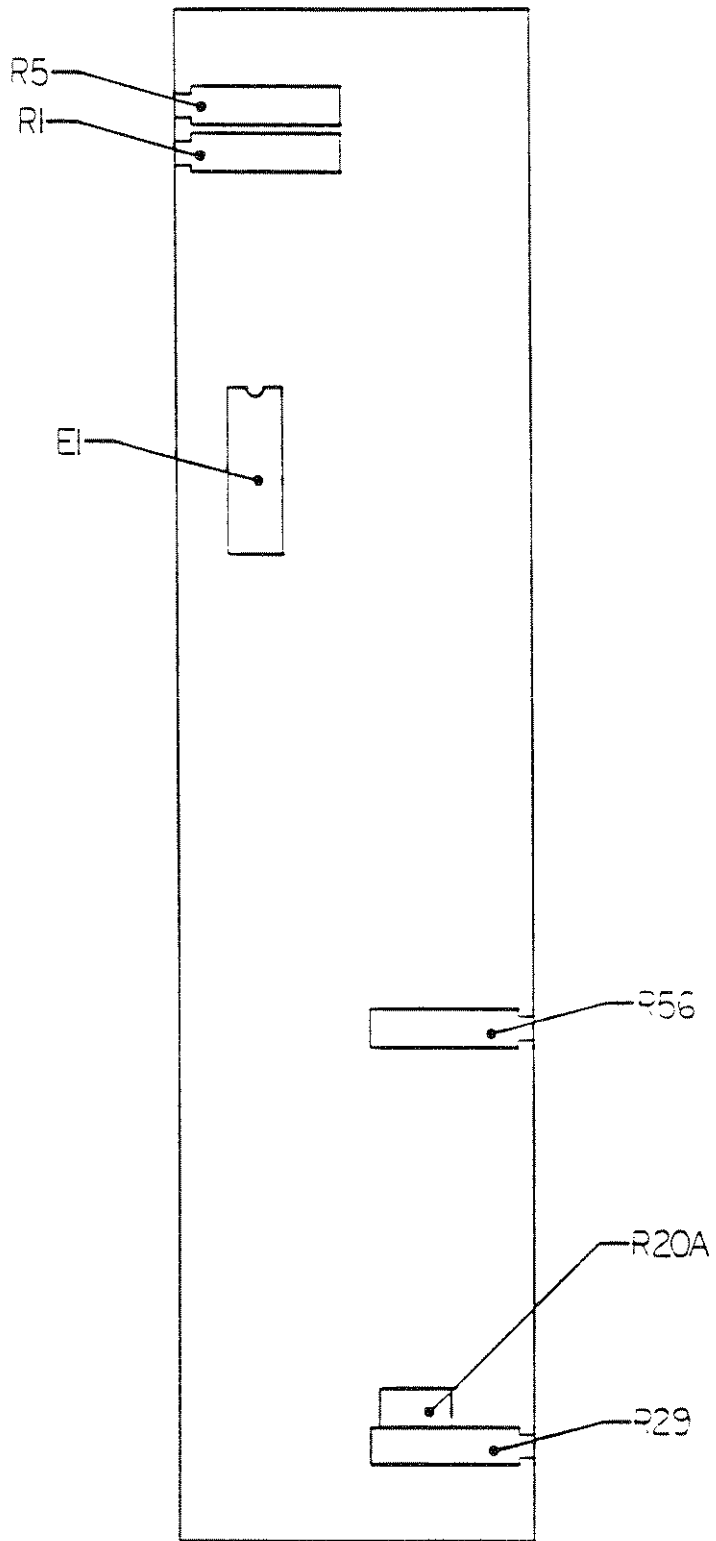


Figure 4-5

DVM Processor PCB Trim Locations

Section 5

Series 2000 Schematics

5. Schematics and Location Drawings

5.1 Symbols and Notations

5.1.1 Units and Component Assumptions








Unless otherwise indicated:

1. resistors are in ohms, inductors in microhenries
2. capacitors < 1 are in mfd
3. capacitors > 1 are in pf, except polarized units (marked with a + on one terminal) are in ufd
4. quad gates are two-input Nand gates, 74LS00; with +5 connected to pin 14, and logic ground connected to pin 7

5.1.2 Trims and Test Points

1. * Signifies trim on test.
2. Test points are numbered sequentially from top to bottom along the front of the board as viewed from the front of the instrument.

5.1.3 Terminals and Connections

-  outgoing connection to another board; see connector sheet for the board involved
-  from another point on the same board, possibly on another sheet or the same schematic (designated)
-  to another point on the same board, again possibly to another sheet of the same schematic (designated)
-  see specific schematic
-  see specific schematic
-  see specific schematic
-  analog signal ground



analog power ground



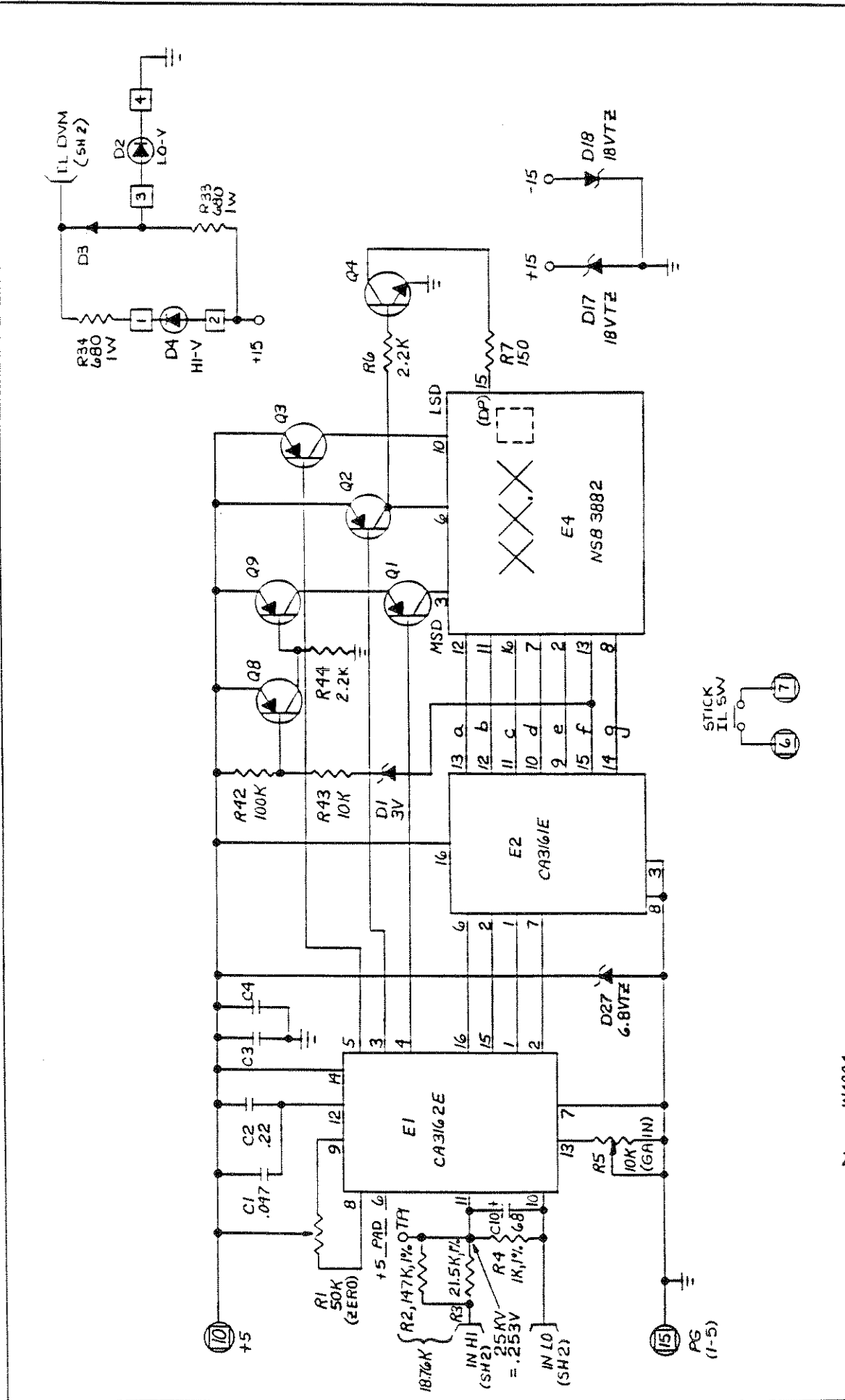
digital circuit ground, or logic ground

Chassis

or

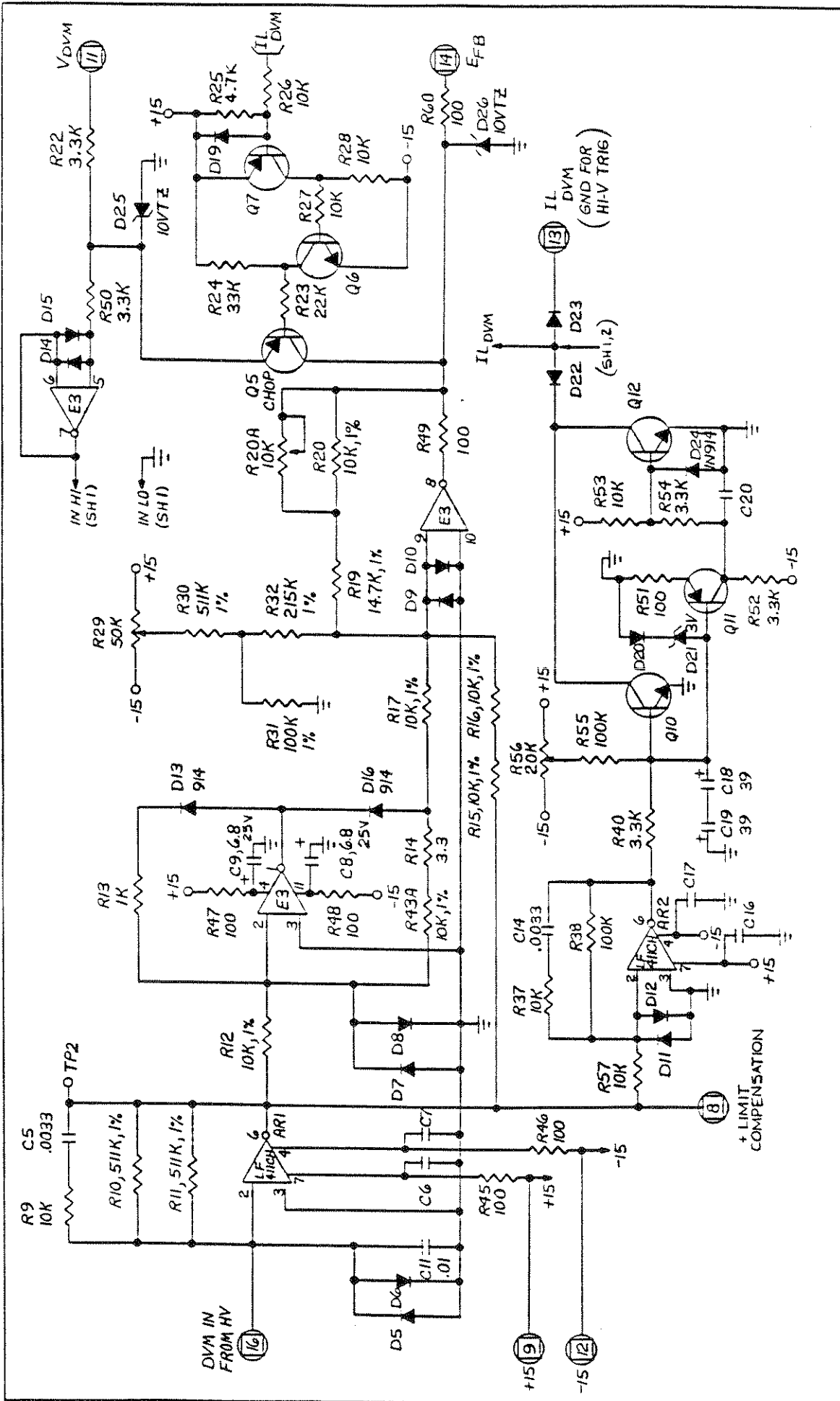
chassis ground

Ch

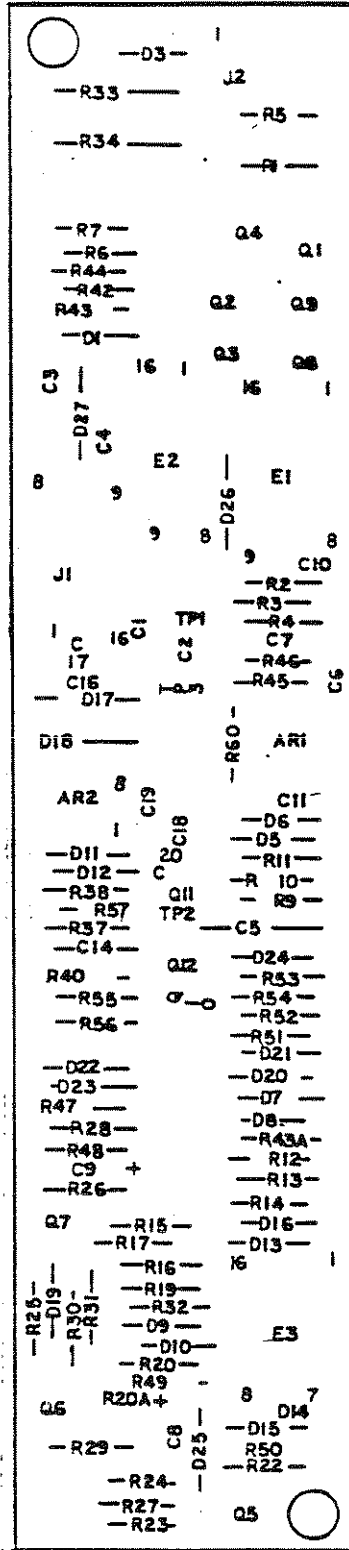
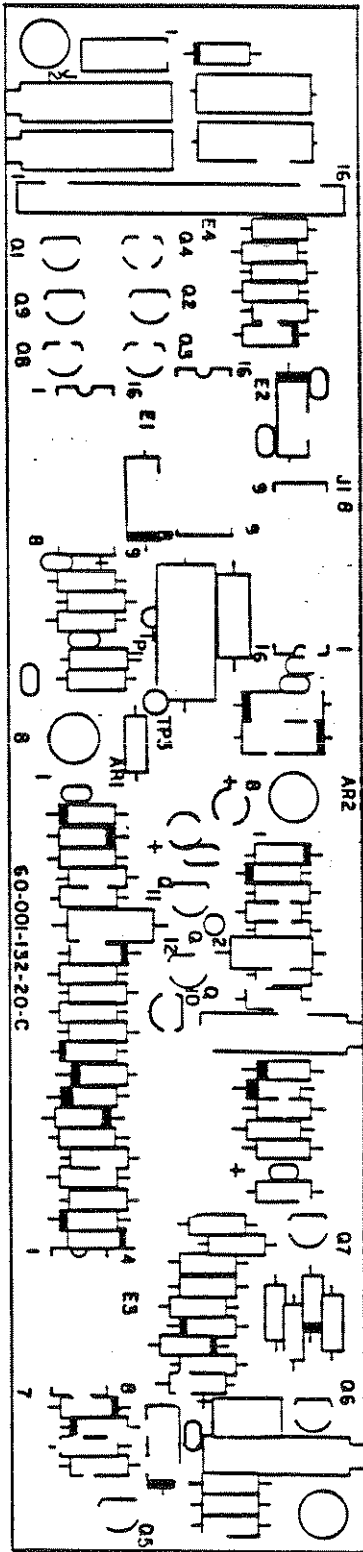


REV: 1	DESIGNED BY: EHS/DA	DATE: 2-12-85	DRN: 6108
CHK: 1	APPROVED BY: M. JESKI	SH: 1	US: 2
SCHEMATIC, DVM PROCESSOR			
KeyTek INSTRUMENT CORP		DRAWING NUMBER: 60-001-000-008	

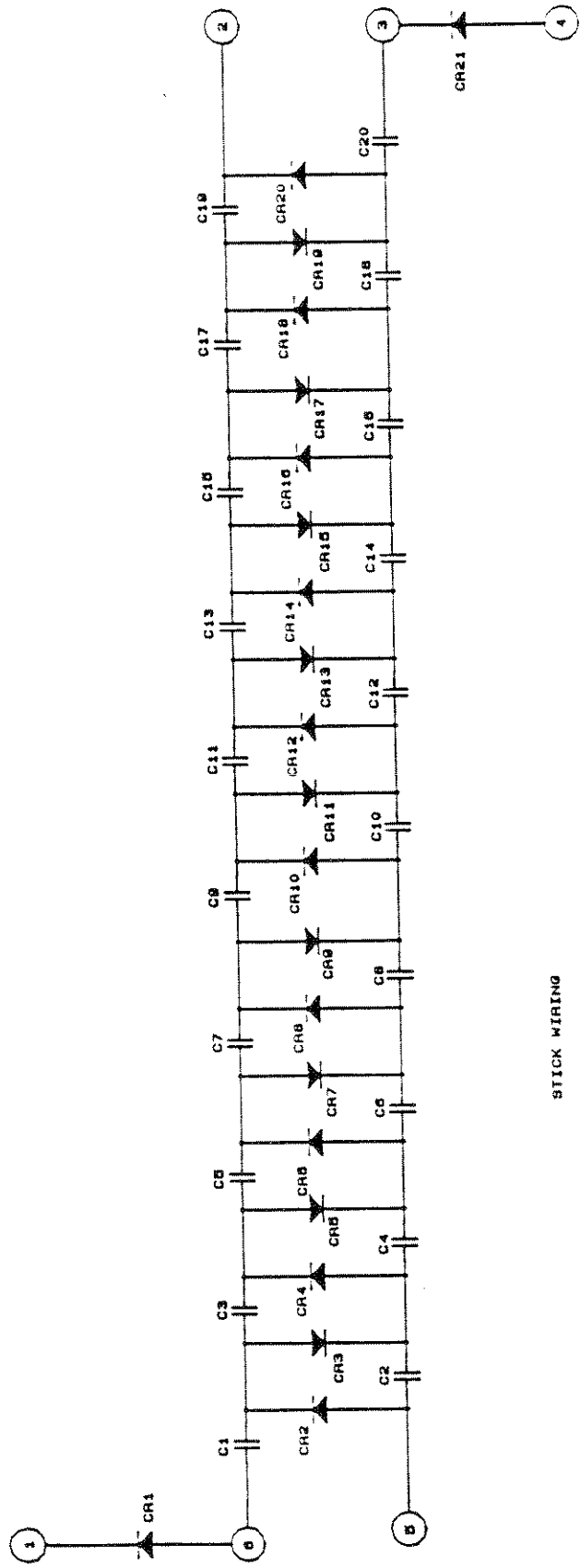
- ▶ IN4004
- || .047, 100V
- J1, 16 PIN IC CONN, DVM PCB TO HANDLE PCB
- J2, 4 PIN CONN, TO LEDS



REV	DATE	DESIGNED BY	CHKD BY	DATE	DRAWING NUMBER
1	2-12-65	W. J. JESKI	C. G.	5/30/65	20-001-000-001
SCHEMATIC, DVM PROCESSOR					
KEYTEC INSTRUMENT CORP.					

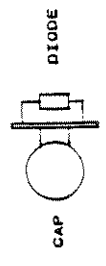
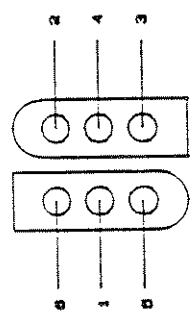


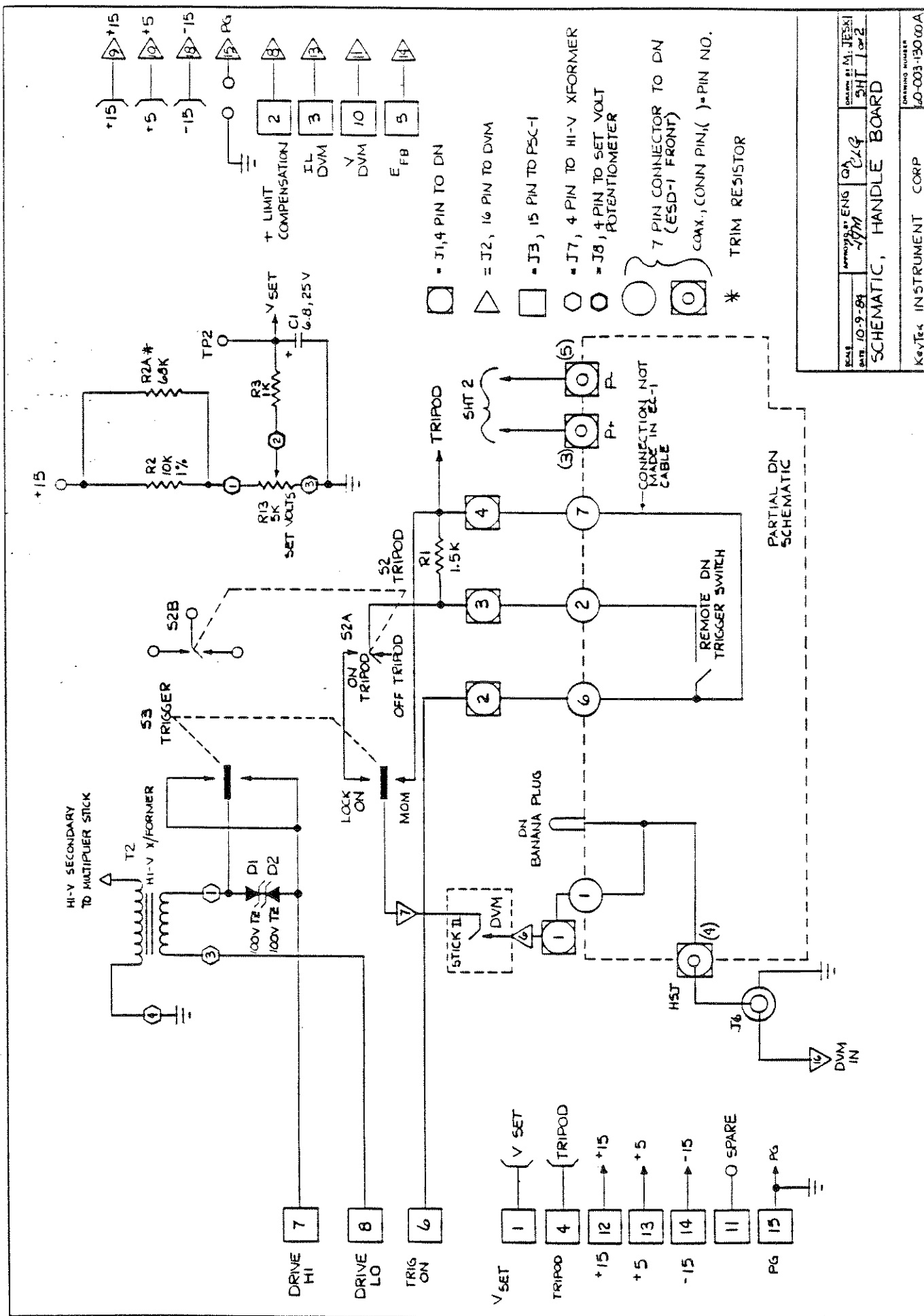
SCALE	APPROVED BY ENG	QA	DRAWN BY
DATE 2-27-85	CPH 5/30/85	122	M. JESKI
COMPONENT LOCATION, DVM PROCESSOR PC ASSEMBLY			
KeyTek INSTRUMENT CORP.	DRAWING NUMBER 60-001-132-00		



NOTES
 C1-C20 = .002 MFD, 6KV
 CR1-CR21 = RK500A

STICK WIRING



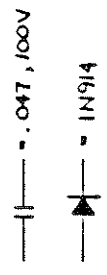
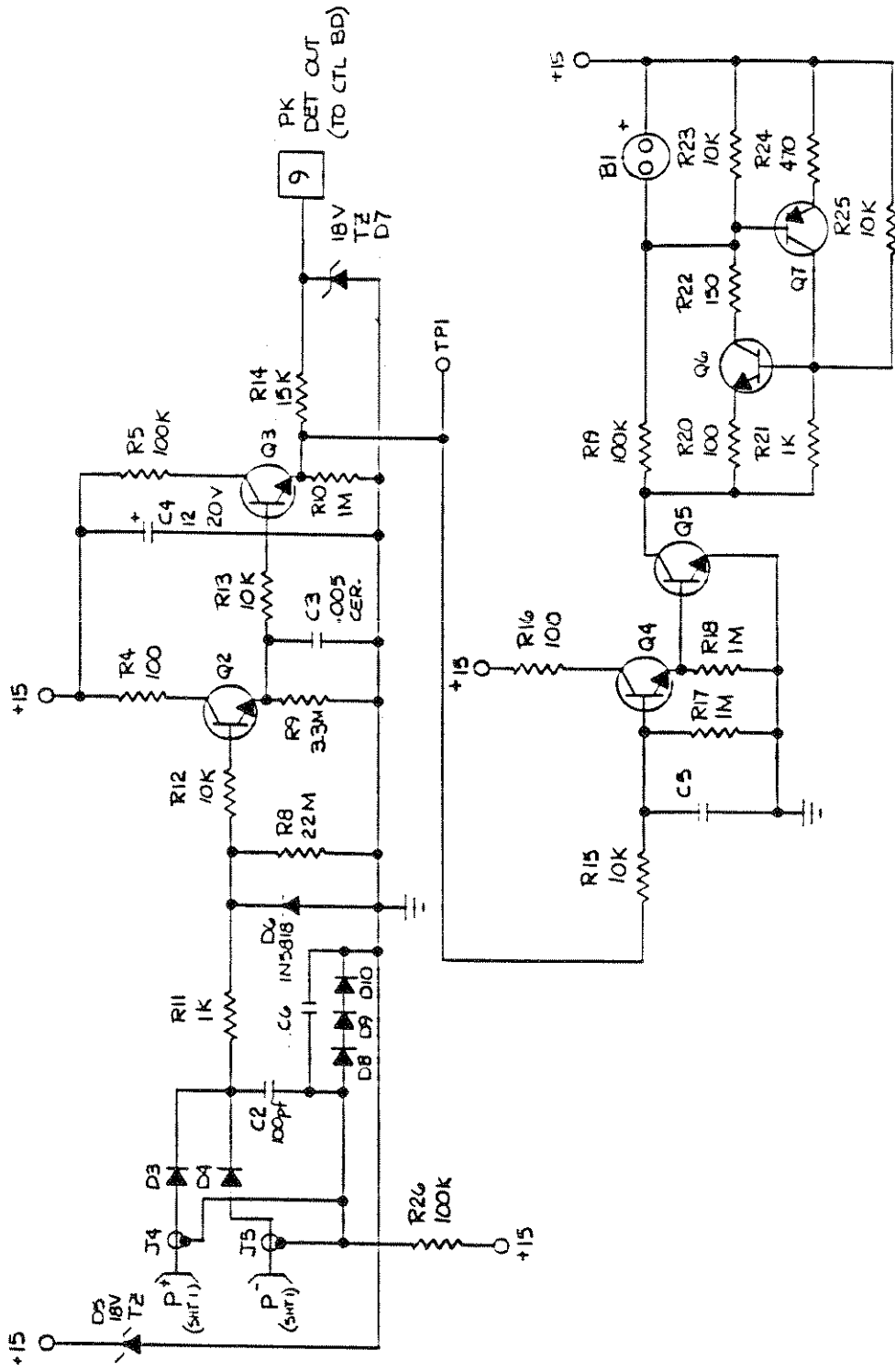


SCALE	APPROVED BY ENGR	DATE	DESIGNED BY	DRAWN BY
10-9-84	JPM	10/9/84	M. JESKI	2HT/10/2

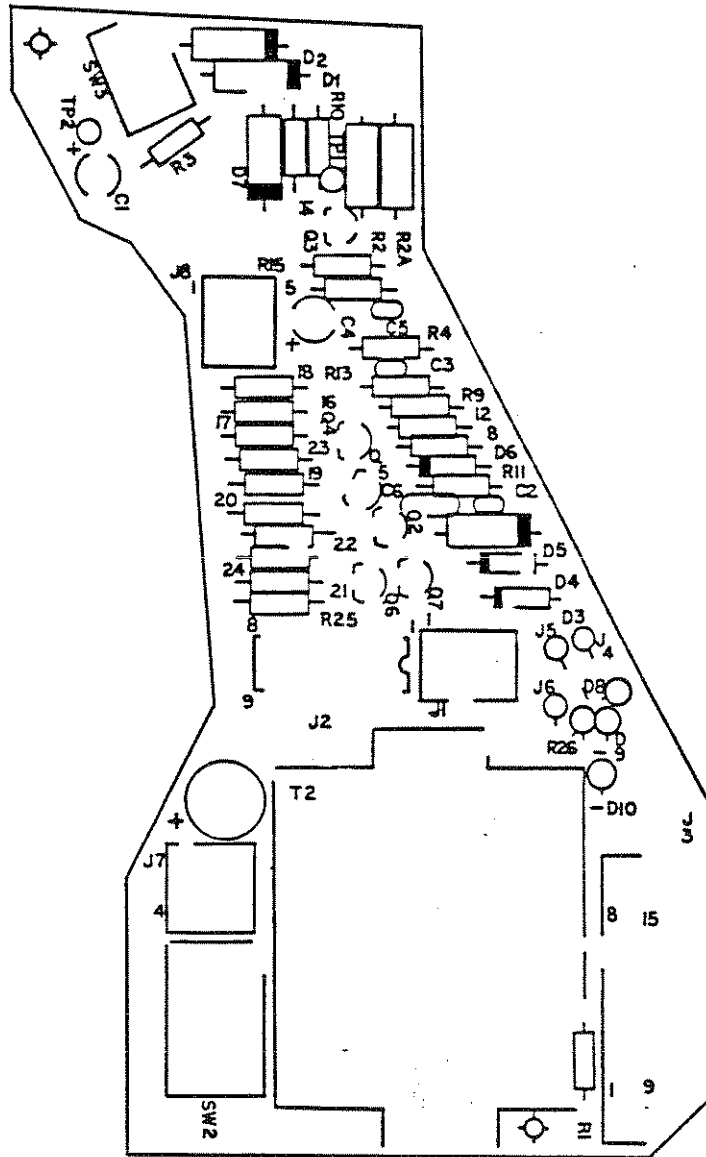
SCHEMATIC, HANDLE BOARD

KEYTEK INSTRUMENT CORP. DRAWING NUMBER: 10-003-130-00A

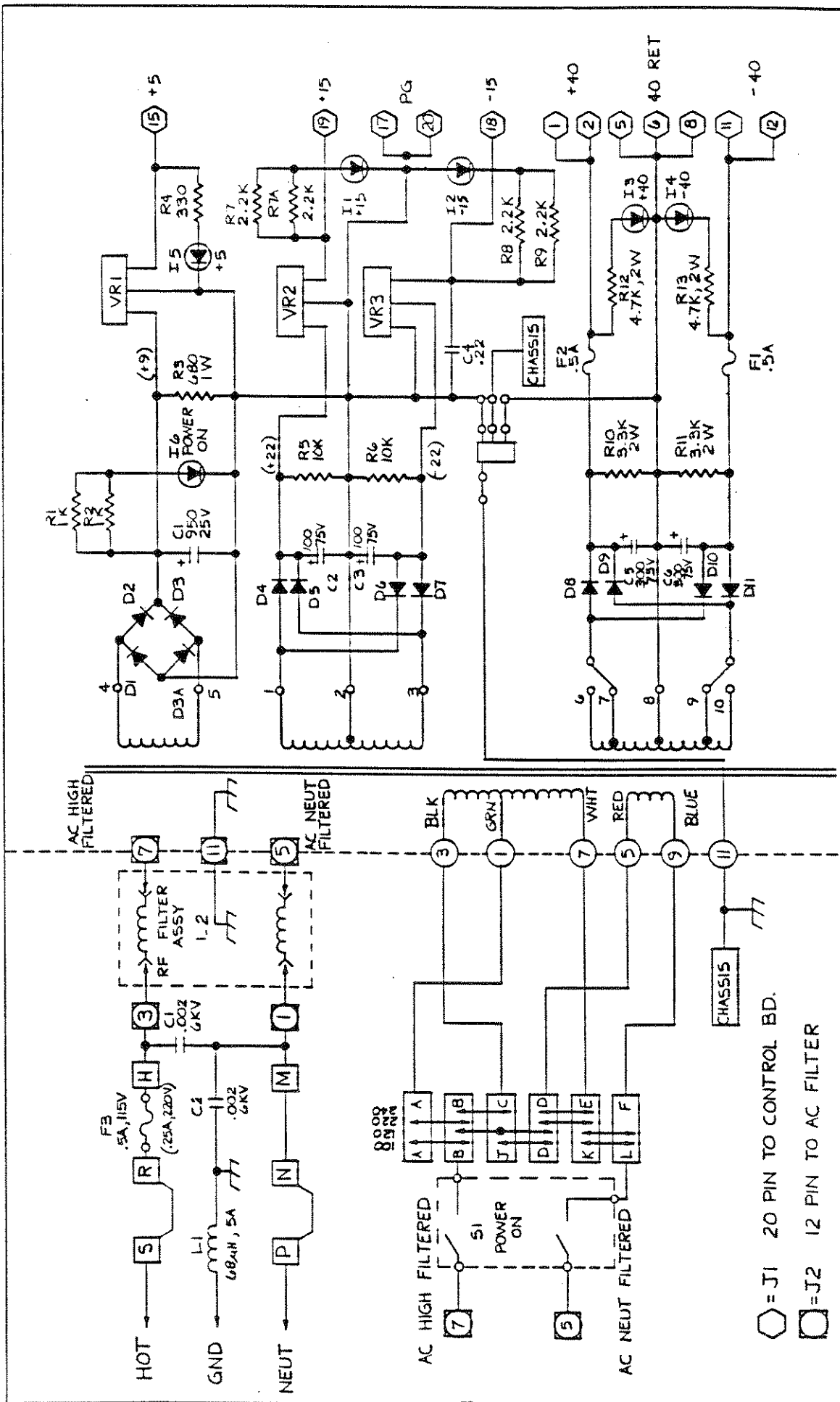




DATE	DESIGNED BY	ENGR	QA	REVISED BY	DATE
MAR 09-84	JPM			M. JESKI	3/11/84
SCHEMATIC, HANDLE BOARD					
KeyTek INSTRUMENT CORR				DRAWING NUMBER 60-003-130-00A	



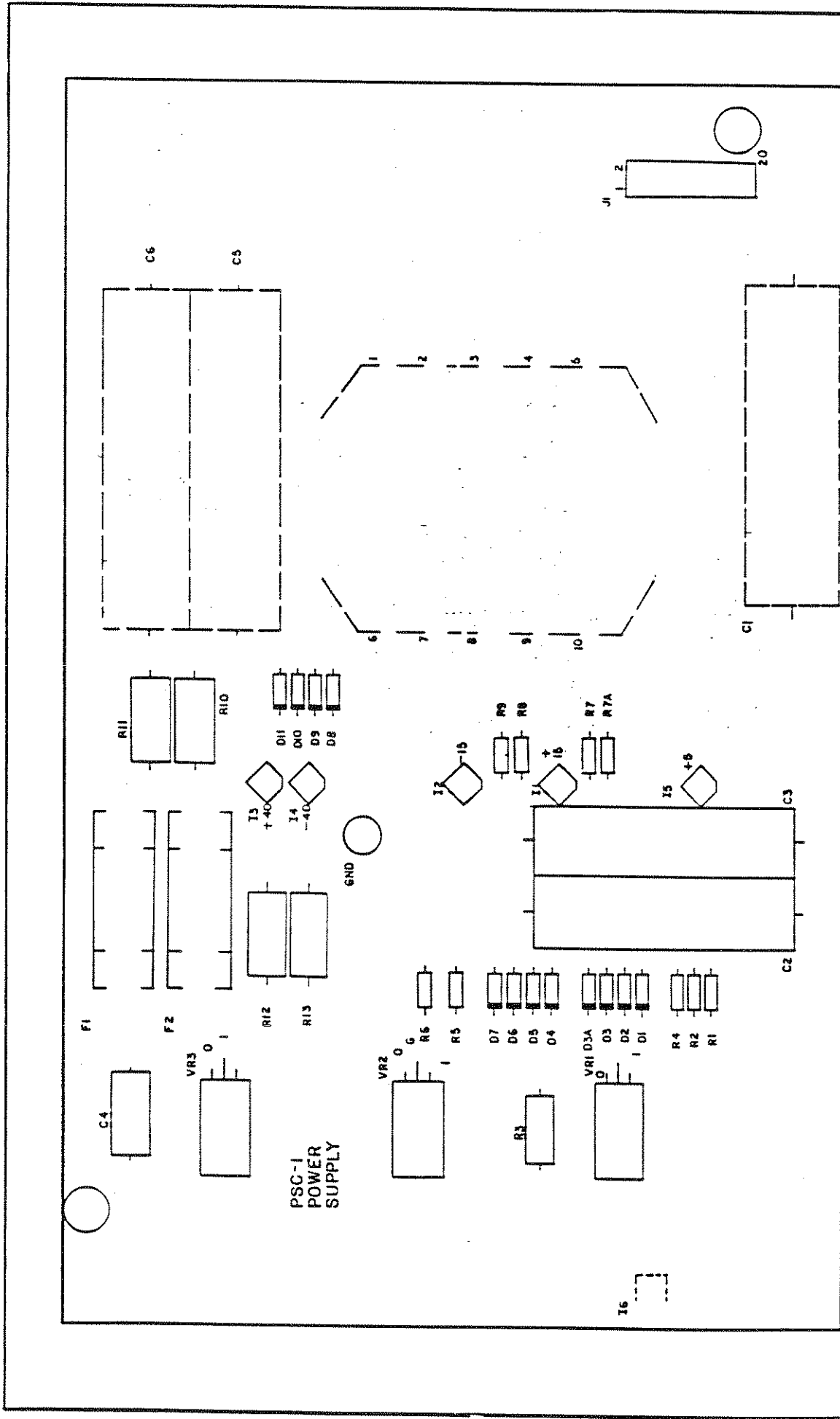
SCALE	APPROVED BY ENG	QA	DRAWN BY
DATE 2-28-89	<i>Jim Stokes</i>	<i>CRG</i>	M. JESKI
COMPONENT LOCATION, HANDLE BOARD ASSY.			
KeyTex INSTRUMENT CORP.			60-003-128-00



SCALE	APPROVED BY	DATE	DESIGNED BY
1-25-65	ENG 5/30/65	5/30/65	M. JESKI
SCHEMATIC, POWER SUPPLY, PSC-1			
KEYTEK INSTRUMENT CORP.			
60-005-000-00			

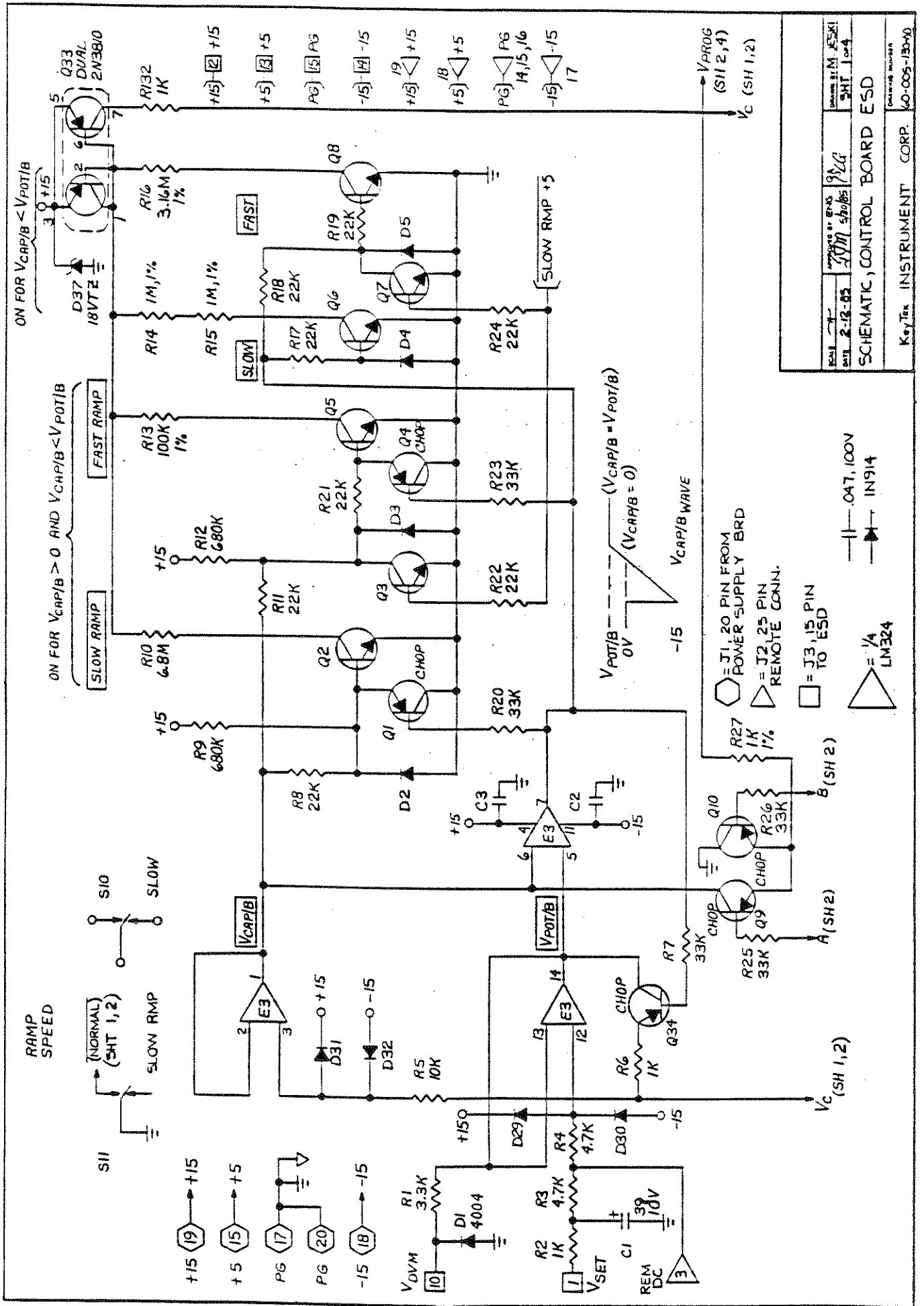
- = J1 20 PIN TO CONTROL BD.
- = J2 12 PIN TO AC FILTER
- = J3 12 PIN TO T1
- ▶ = IN4004

T1

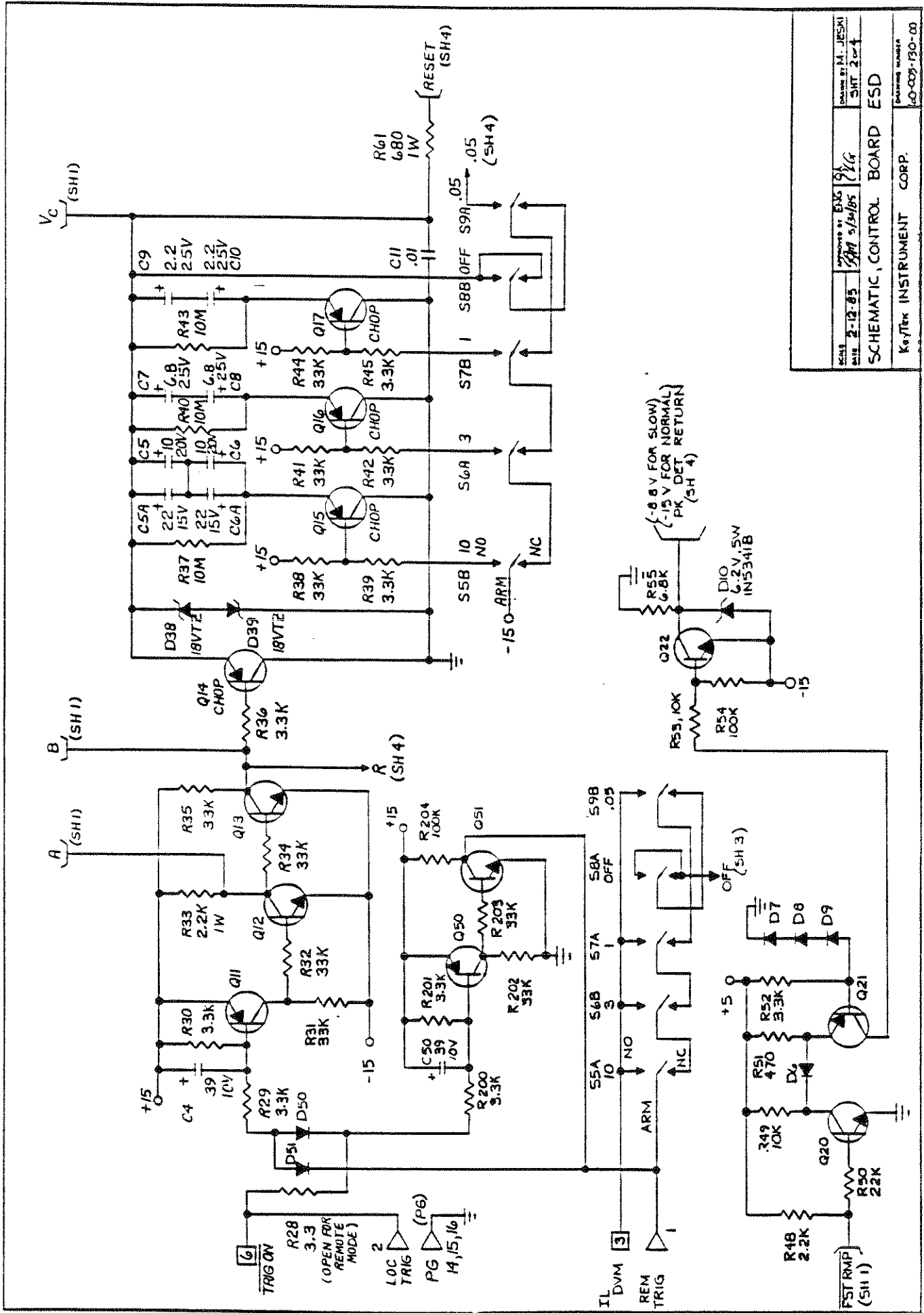


PSC-1
POWER
SUPPLY

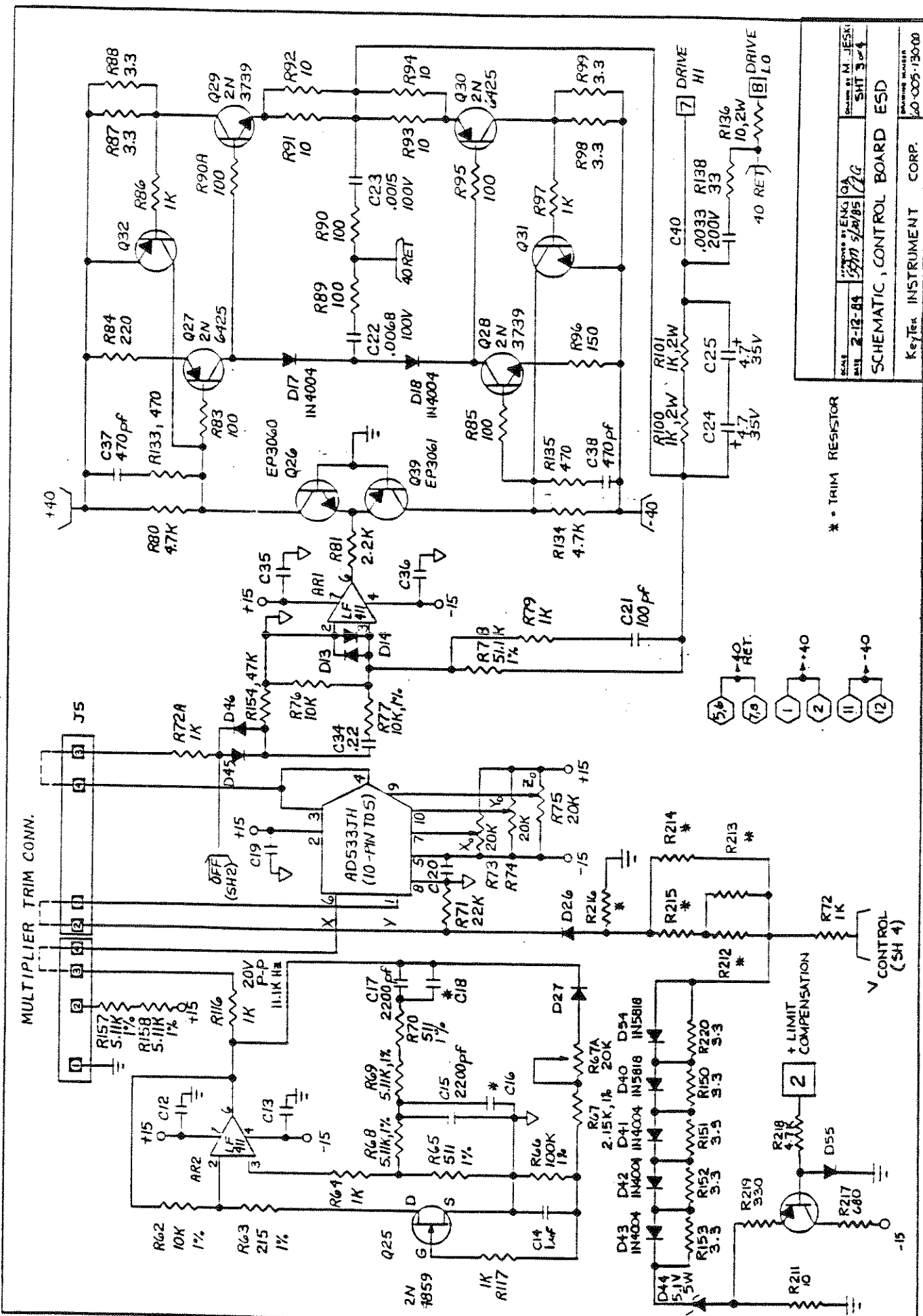
16



DATE	DESIGNED BY	CHECKED BY
2-12-83	SM/5/Bohs	PLG
SCHEMATIC, CONTROL BOARD ESD		
KEYTEK INSTRUMENT CORP. LO-005-130-0		

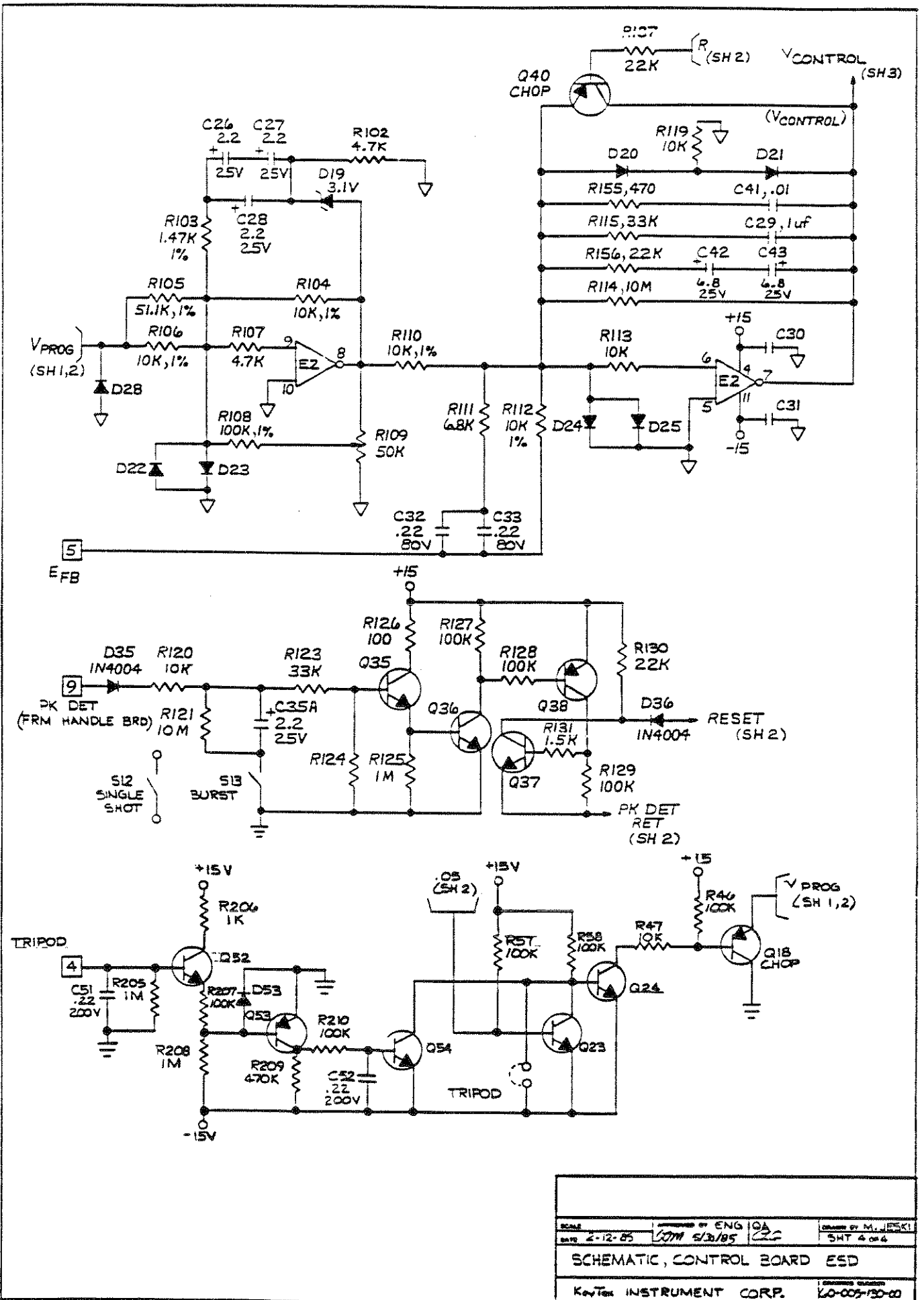


DESIGN	DESIGNED BY	ENG	9/16	DATE	2-12-85	APPROVED BY	5/24/85	CHKD BY	M. JESKI
								SHIT	2 of 4
SCHEMATIC, CONTROL BOARD ESD									
KEYTEK INSTRUMENT CORP. DRAWING NUMBER 10-008-130-00									

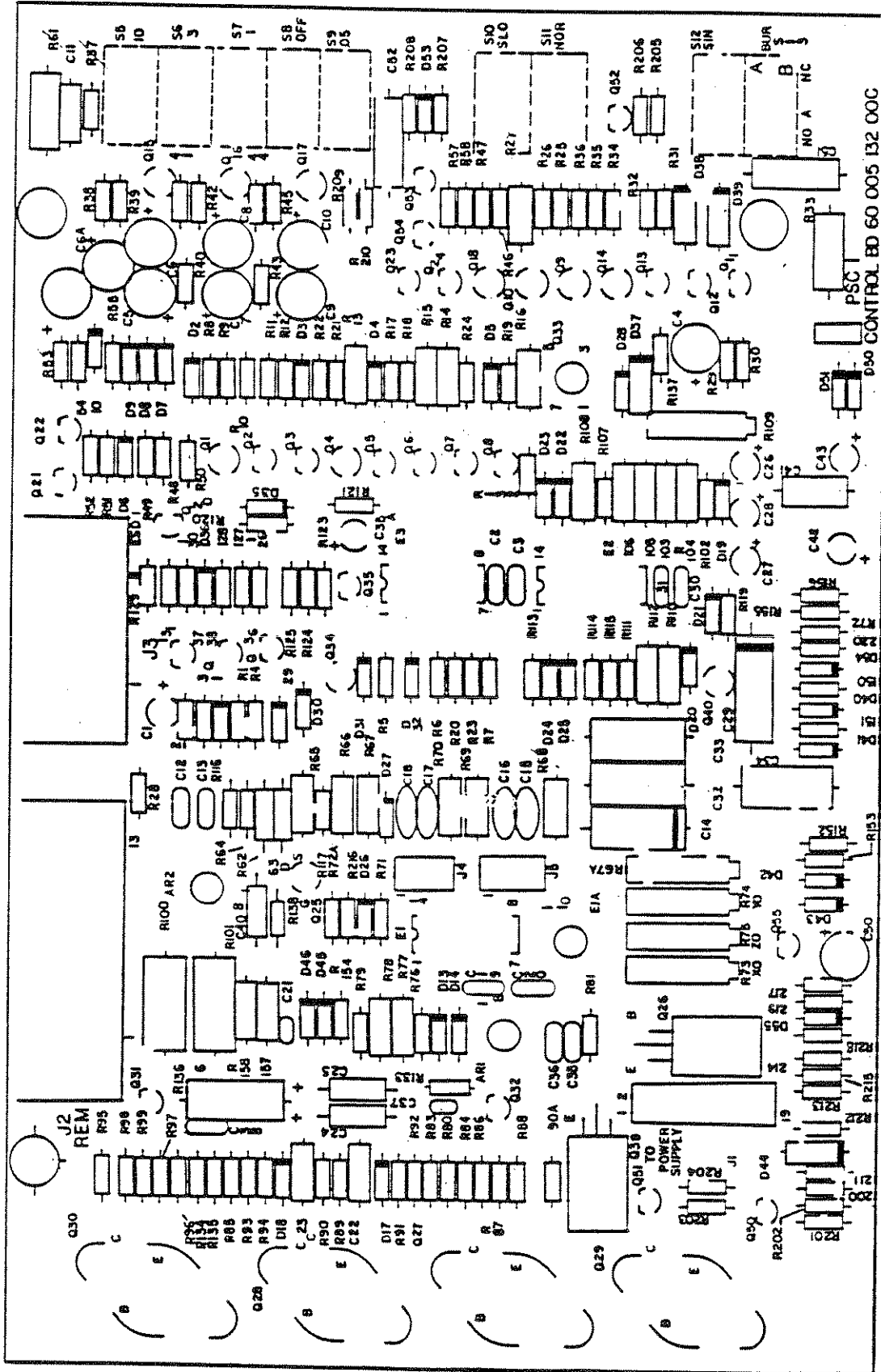


* = TRIM RESISTOR

DATE	2-12-84	DESIGNED BY	ENG 0A
DATE	5/20/85	DESIGNED BY	M. JESKI
		DRIVER	SHIT 3 or 4
SCHEMATIC, CONTROL BOARD ESD			
KeyTek INSTRUMENT CORP.		DRAWING NUMBER	
		20-005-13000	



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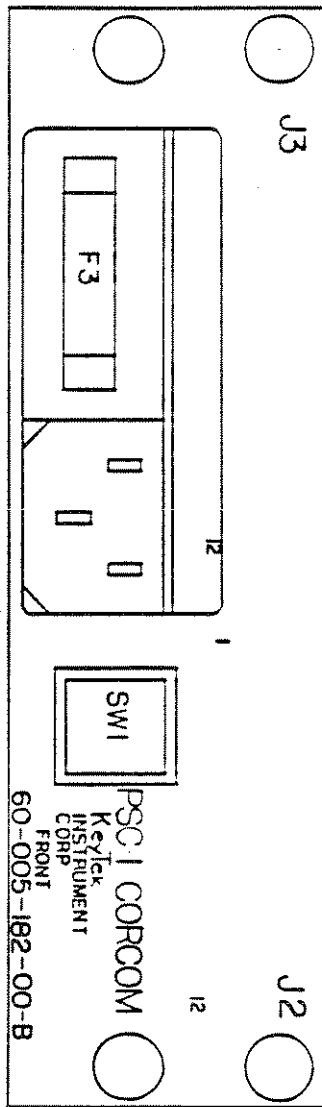
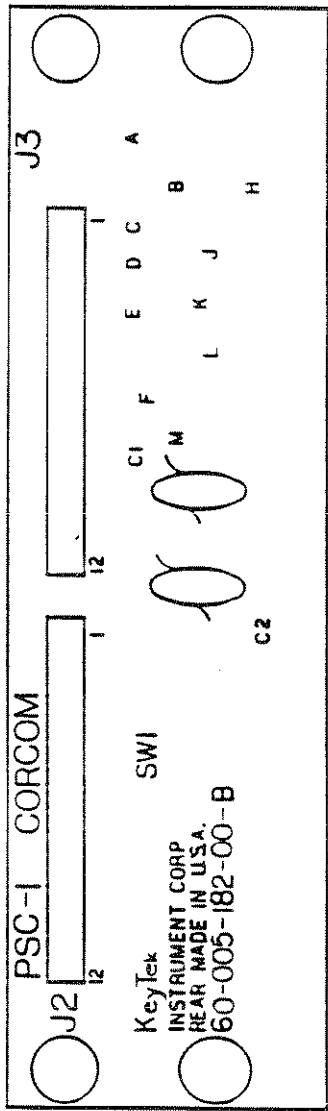


CONTROL ED 60 005 132 00C

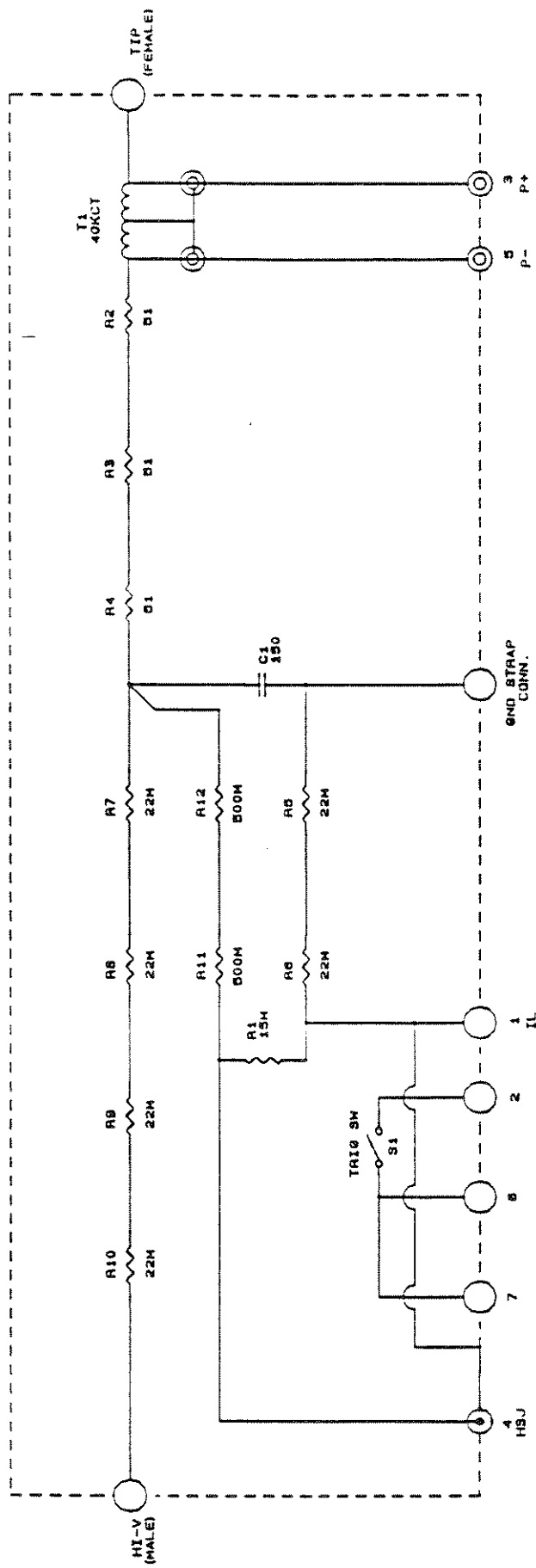
REVISED BY	DATE	APPROVED BY	DATE
M	2-27-65	5/30/65	2/4
		M. JESKI	

COMPONENT LOCATION, CONTROL
PCB A55Y

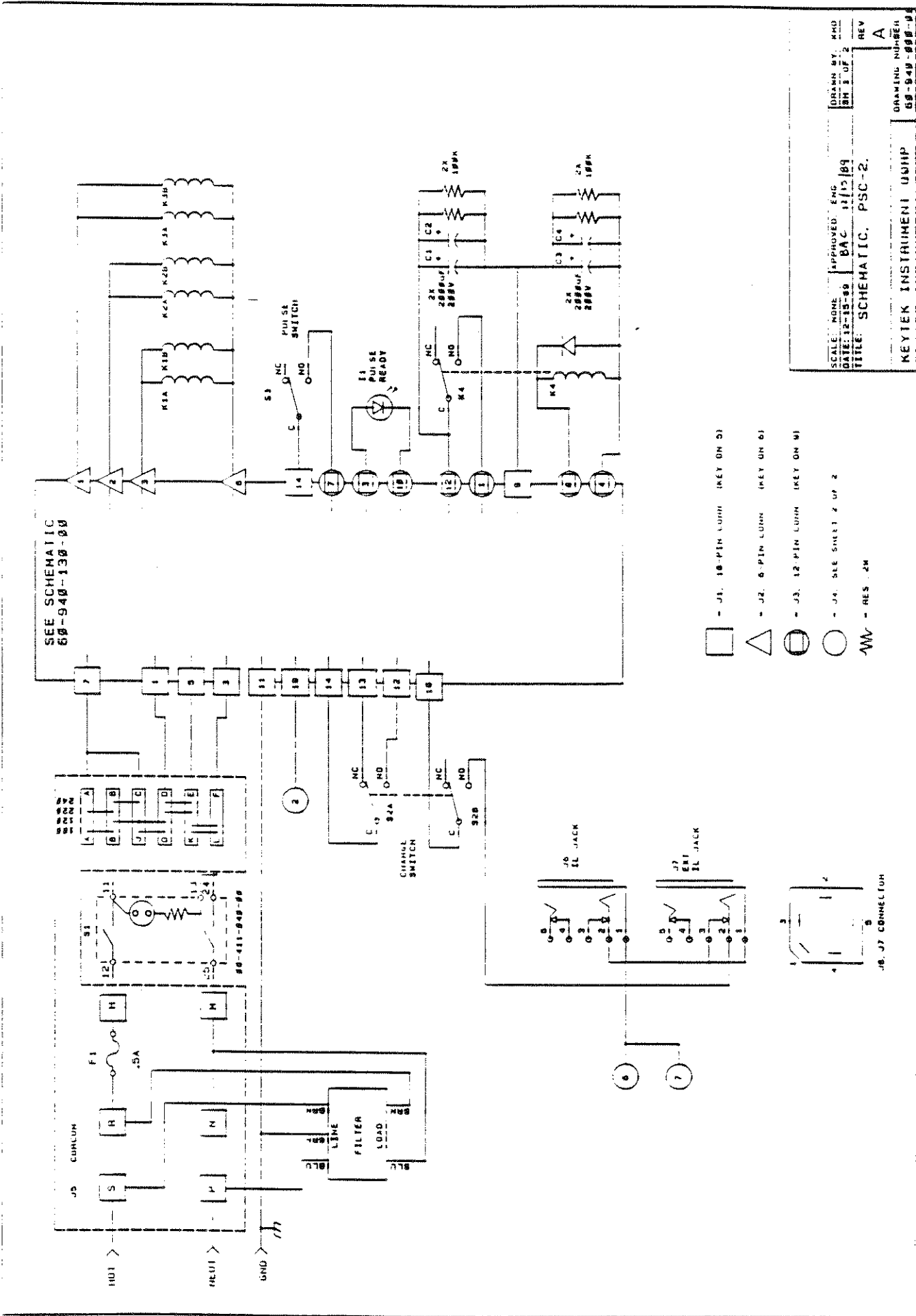
Key-Tek INSTRUMENT CORP. 40-005-138-00



SCALE	DATE	DESIGNED BY	DRAWN BY
	3-4-65	3007/2/65	CLG
COMPONENT LOCATION, PSC-1			DESIGNED BY M. JESKI
CORCOM.			DRAWING NUMBER 60-005-188-00
KeyTek INSTRUMENT CORP.			



IL PIN-1 FINDS GND VIA SCREEN CONNECTION OF HSJ ON PIN-4.



SEE SCHEMATIC
68-948-130-00

80-411-849-00

80-411-849-00

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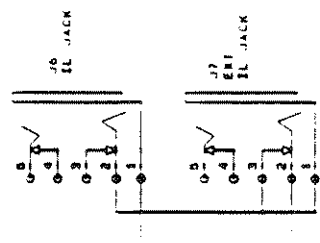
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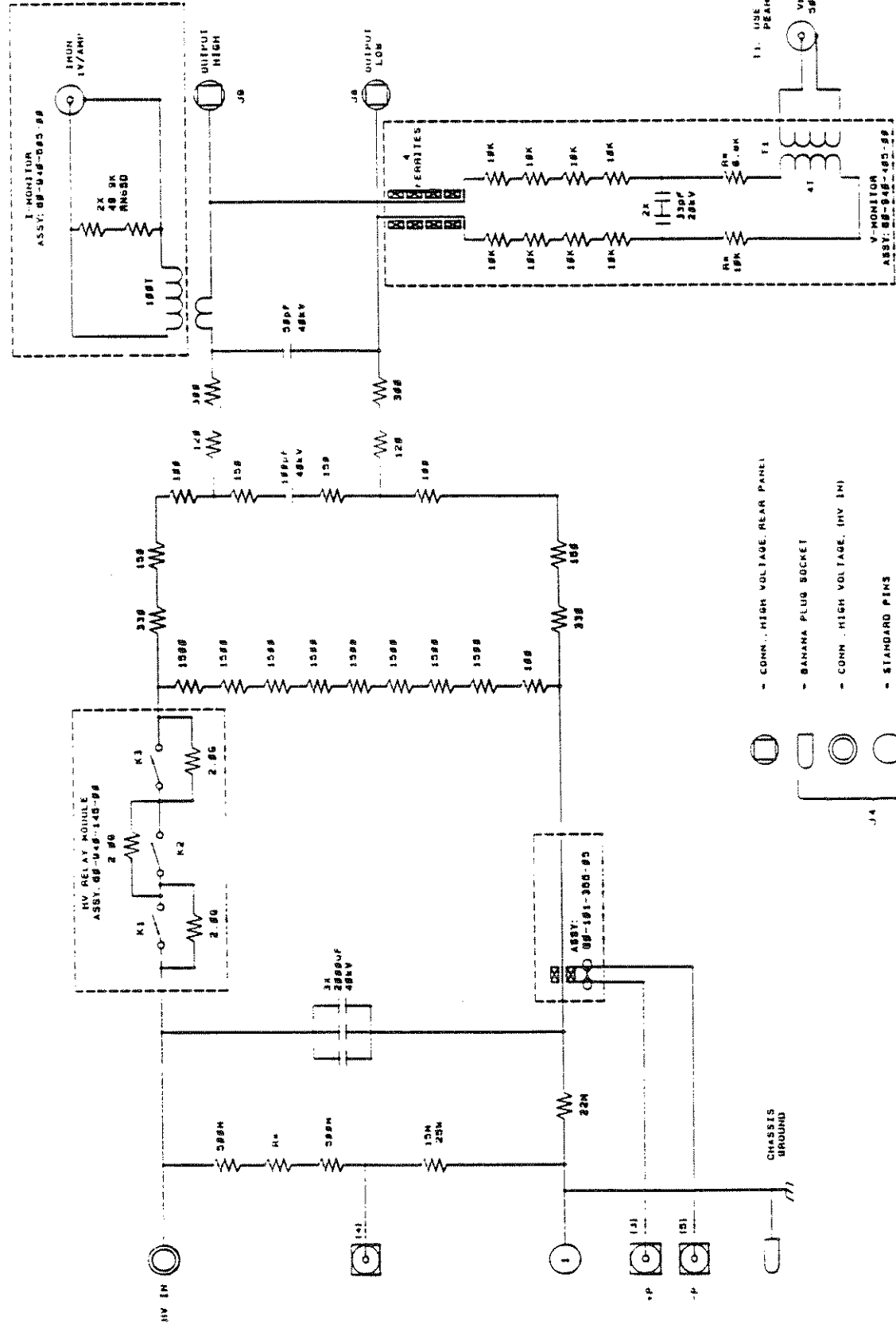
250

250

- - J1, 16-PIN LUMM (KEY ON D1)
- △ - J2, 6-PIN LUMM (KEY ON D1)
- - J3, 12-PIN LUMM (KEY ON B1)
- - J4, 5x5 SHRT 2 UP 2
- ⌋ - RES 2W

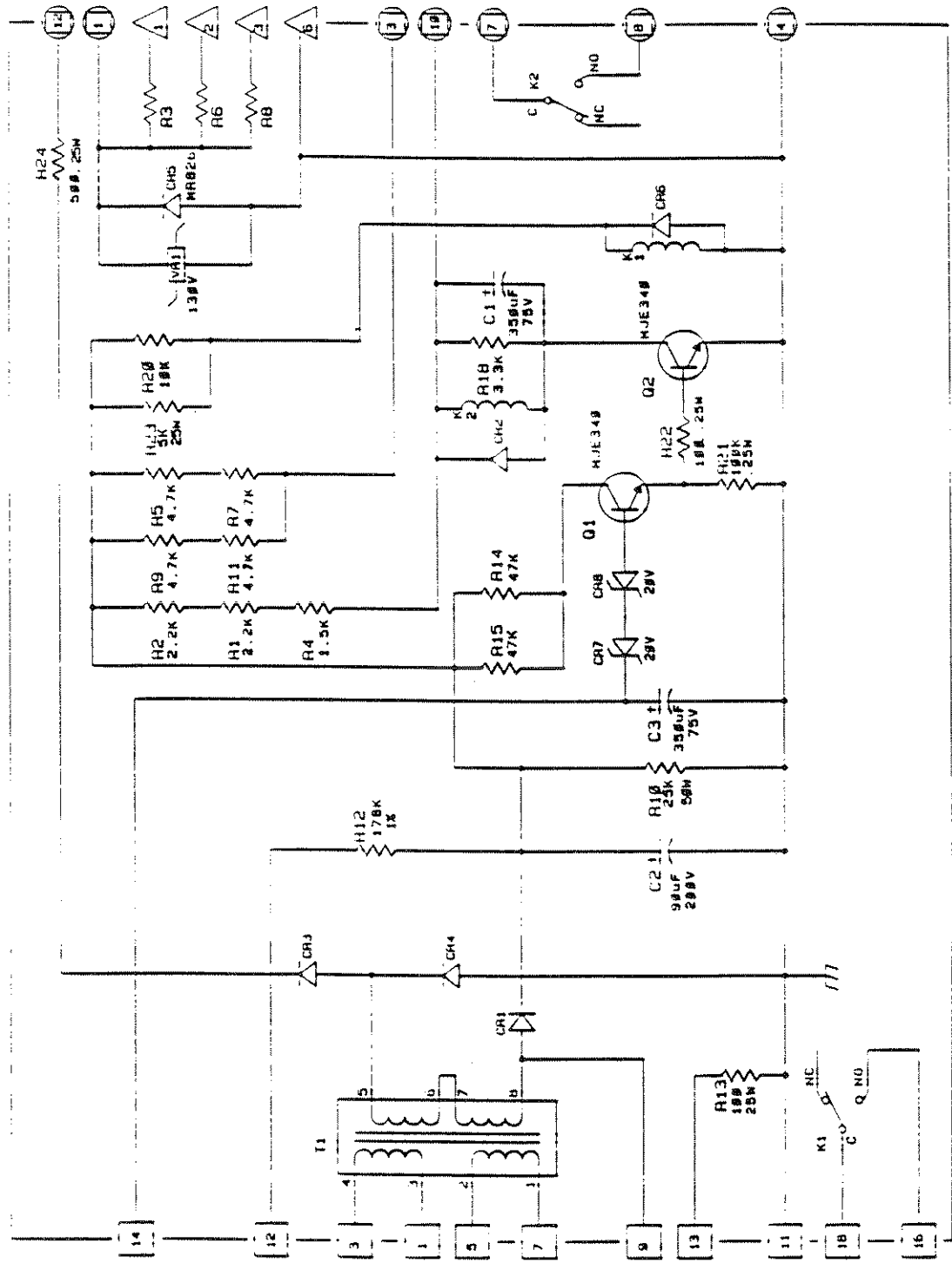


SCALE: NONE APPROVED: ENG DATE: 12-15-60 BAC 11/15/69
 TITLE: SCHEMATIC, PSC-2.
 DESIGNED BY: KMD
 DRAWN BY: J.E.P.
 REV A
 KEYTEK INSTRUMENT U0HP DRAWING NUMBER
 68-948-000-00



- CONN. HIGH VOLTAGE, REAR PANEL
- BANANA PLUG SOCKET
- CONN. HIGH VOLTAGE, (HV IN)
- STANDARD PINS
- COAXIAL PIN, 1-PIN HD
- DENOTES TRIM RESISTOR

SCALE: NONE	APPROVED: ENG	DRAWN BY: KMD
DATE: 12-18-88	BA C 11-1-89	SMT 2 OF 2
TITLE: SCHEMATIC, PSC-2		REV
		A
KEYTEK INSTRUMENT CORP		DRAWING NUMBER
88-948-883-88		88-948-883-88



- [J1] - 18 PIN PANDUIT. (KEY ON 6)
- [J2] - 6 PIN PANDUIT. (KEY ON 5)
- [J3] - 12 PIN PANDUIT. (KEY ON 8)
- ~> - 1N4584
- ~> - HES .2M
- ~> - 12 PIN PANDUIT. (KEY ON 8)

SCALE NONE	APPROVED: ENG	DA	DRAWN BY: KMD
DATE: 7-6-89	5AC	1084	INT 1 OF 1
SCHEMATIC, MAIN PCB, PSC-2			REV
KEYTEK INSTRUMENT CORP			DRAWING NUMBER
			68-948-136-89
			- 1

Section 6

6.

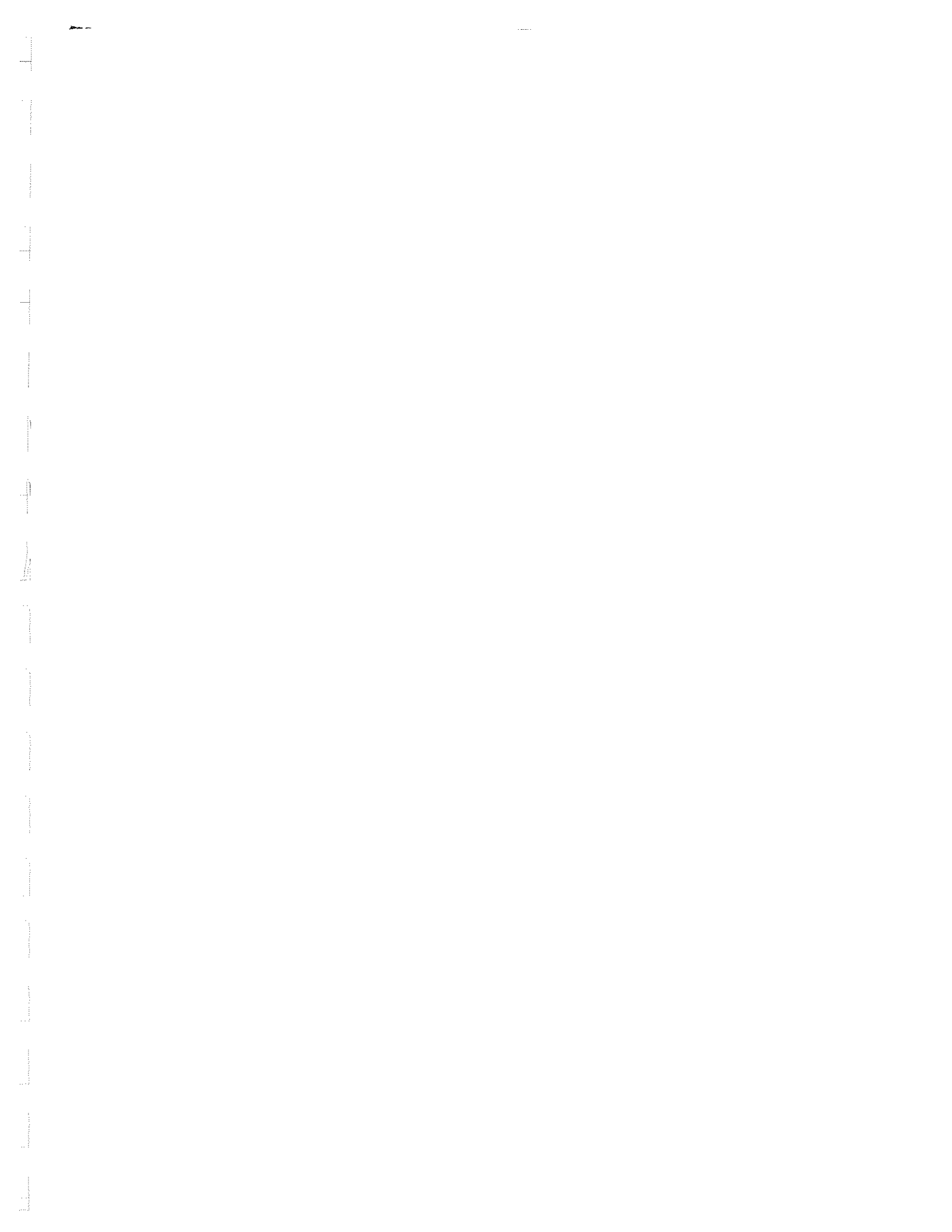
Application Notes

- AN 150 An ESD Circuit Model with Initial Spikes to Duplicate Discharges from Hands with Metal Objects
- AN 151 ESD Testing: The Interface Between Simulator and Equipment Under Test
- AN 153 Comparing Computer Models to Measured ESD Events
- AN 161 ESD Discharge Waveform Measurement, The First Step in Human ESD Simulation
- AN 162 Computer Modeling The Effects of Oscilloscope Bandwidth on ESD Waveforms, Including Arc Oscillations
- AN 172 Testing Equipment and Circuits for ESD Sensitivity

CTC-3 IEC TARGET, 1GHz
INSTRUCTIONS

August 31, 1988

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ESD Waveform Verification

Making an accurate, noise free measurement of an ESD waveform from a simulator or human source can be extremely difficult due to the wave's very fast sub-nanosecond risetimes and to the large amounts of EMI that are generated. We therefore strongly recommend that any calibration or re-certification be done at the KeyTek factory.

The equipment used at KeyTek consist of the following:

1. Tektronix 7104 1 GHz mainframe with EMI option
2. Faraday shield for oscilloscope
3. Tektronix 7A29 preamp
4. Tektronix 7B10 timebase
5. Narda Model 766-20, 20dB attenuator
6. Tektronix C-53 oscilloscope camera
7. KeyTek-manufactured IEC revised* ESD target
8. 1.5 meter square Aluminum vertical plane to mount target
9. 6' Belden 9913 coax cable with type "N" connectors

The IEC revised target is essential to obtain accurate results in a 1GHz bandwidth environment. The earlier IEC target design gives highly distorted results. The IEC revised target is now commercially available from KeyTek. (Plans for constructing one are available from KeyTek or the IEC.)

The target is mounted in the center of the 1.5 meter square vertical plane. This plane is held vertical by a wooden stand or special mounting to a non-metallic wall.

* 25 resistors in outer ring, 5 in center ring.

The oscilloscope is installed in a Faraday cage. This is a rectangular aluminum box large enough to contain the oscilloscope and camera, and to allow air circulation around the oscilloscope so it does not overheat. The power line for the oscilloscope is brought in through a filter to prevent the entry of conducted EMI. A type N feedthrough is mounted on one side near the front, to pass the ESD signal into the enclosure. The front of the enclosure is hinged at the top allowing it to be opened easily to access the camera and controls. The edges of the door are lined with spring finger stock to insure good rf integrity. The 7A29 and 7B10 occupy one plug-in slot each. The two unused slots must be filled to prevent EMI leakage. It is imperative that the oscilloscope be well shielded in this way, or else the large EM field generated by the ESD event will radiate directly into the CRT and electronics of the oscilloscope, causing massive noise and distortion of the waveform.

Belden 9913 is used to connect the target to the scope because it is very low loss and has 100% shield coverage. RG55 and RG58 are too lossy and will not give accurate results.

The 20dB attenuator is needed to scale the output of the target to be within the range of the 7A29. It must be a low VSWR microwave type, such as the Narda part listed in #5 above. (Repeated pulsing will overstress and eventually damage lower power attenuators.)

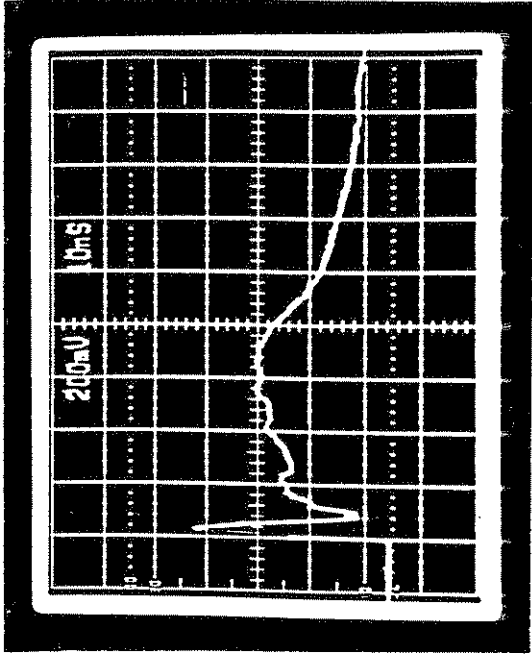
Please contact the KeyTek Customer Service Department, if telephone assistance is required.

TYPICAL

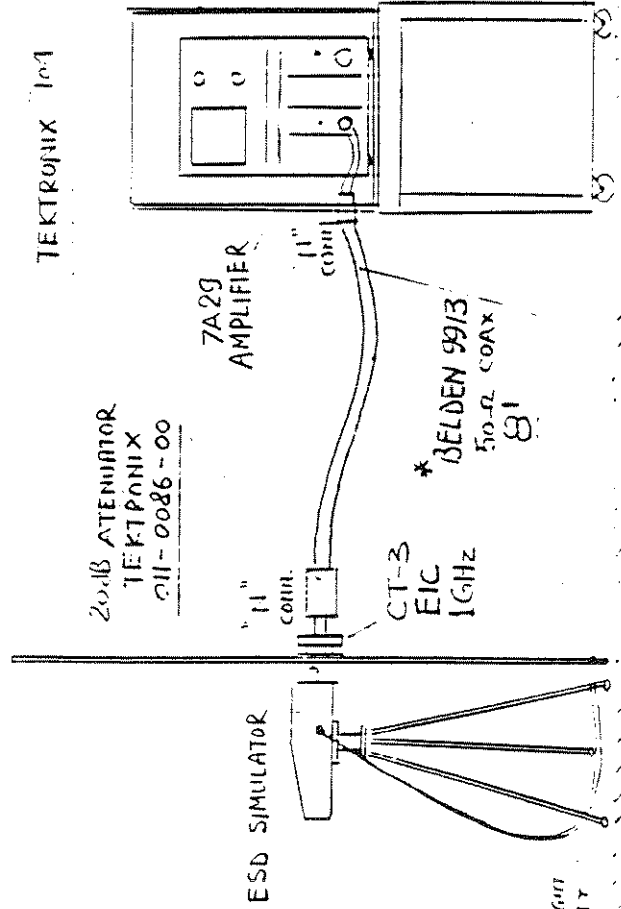
2KV

.9ns ; 3.75 V/KV

ESD GENERATOR WFM.



TARGET PLATE
1.5" SQUARE



20dB ATTENUATOR
TEKTRONIX
011-0086-00

7A29
AMPLIFIER

* BELDEN 9913
50-ohm COAXIAL

CT-3
EIC
1GHz

TEKTRONIX 7B10

FARADAY CAGE
SHOWN W. DOOR OPENED.

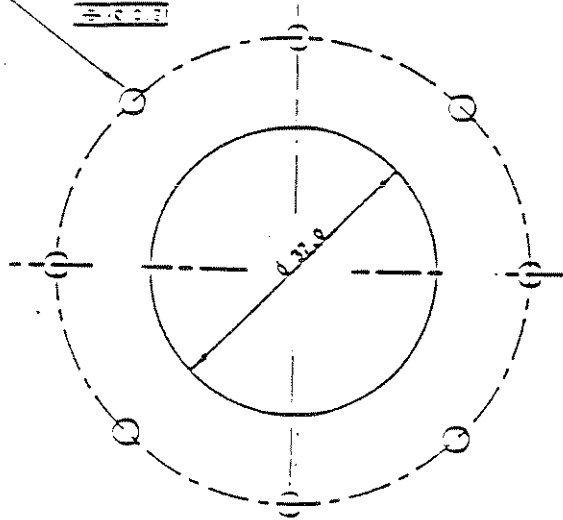
7B10
TIME BASE

GROUND STRIP
CONNECTED AT THE RIGHT
LOW END OF TARGET

Typical setup for verification of ESD generator performance

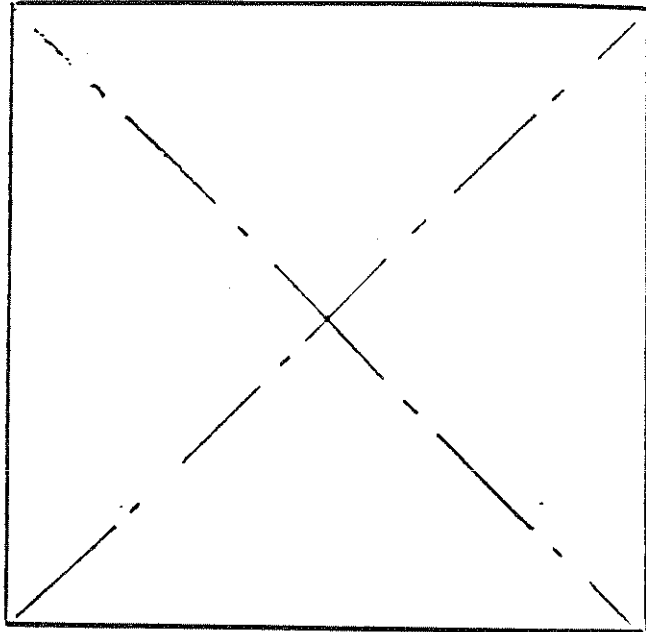
NOTE: - Use BELDEN 9913 coax cable.

3.4
8 HOLES 0.2 EQUISPACED
REG. OF POS POSITION AS SHOWN
[REDACTED]



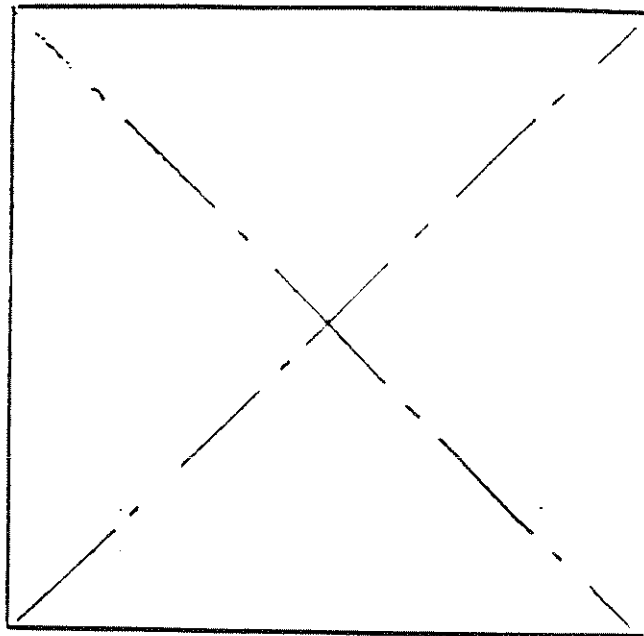
DRILLING TEMPLATE FOR ALUMINUM TARGET PLATE

ALUMINUM
TARGET PLATE
(1500 x 1500 x 1.5) mm.



The CTC-3 IEC Target
is installed on the center
of the target plate.

ALUMINUM
TARGET PLATE
(1500 x 1500 x 1.5) MM.



The CTC-3 IEC Target
is installed on the center
of the target plate.



An ESD Circuit Model with Initial Spikes to Duplicate Discharges from Hands with Metal Objects*

P. Richman

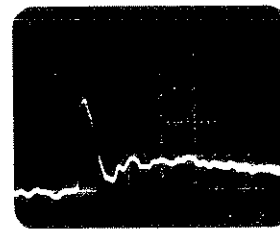
Equipment that passes electrostatic discharge (ESD) testing can and often does malfunction during actual use in mysterious yet apparently ESD-related ways. Many factors can be involved, but real explanations are not easily determined. The highly variable nature of ESD in the air makes almost any explanation seem believable.*

The differences between upsets (malfunctions) caused by ESD simulators on the one hand, and by actual personnel discharge on the other, seriously limit attempts to standardize ESD test techniques and equipment. At least part of the problem can be attributed to steep initial spikes due to human ESD. A new, dual resistance-inductance-capacitance (RLC) circuit model can account for these initial spikes in human-discharge waves.[1]

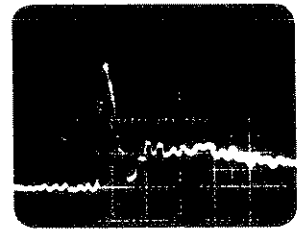
ESD WAVES GENERATED BY PERSONNEL VS. SIMULATORS

Discharges from a metal object such as a key, tool, bracelet or ring, held by or worn on the hands of charged individuals, are increasingly recognized as reasonable *worst-case* situations. They generate current waves into victim equipment that often include high-amplitude initial spikes. These range from 10 to 30 A peak, with rise times less than 1 nsec and durations of 1 to 4 nsec, when viewed with 400 MHz instrumentation (i.e., approximately 0.9 nsec rise time).[1,2,3] Two typical waves are shown in Fig. 1 for discharges from individuals charged to 5 kV.

Discharges from typical ESD simulators using a simple series RC network human-body model do not show this kind of spike performance. Many ESD simulators do, however, often put out a



(a)



(b)

NOTE: Apparent anticipation of discharge by arc oscillations seems due to EMI caused by the discharge, received into the scope via paths other than the Y-amplifier input cable — in fact, by-passing the input amplifier's 9-10 nsec delay.

Figure 1

TWO REPRESENTATIVE CURRENT WAVES FROM A HAND-HELD KEY, SHOWING THE TYPICAL, STATISTICAL VARIATION OF THE AIR DISCHARGE. (BOTH WERE MADE UNDER APPARENTLY IDENTICAL CIRCUMSTANCES.)

PEAKS AND RISE TIMES ARE REPRESENTATIVE OF WAVES FROM A RING, BRACELET, TOOL OR AN ACTUAL KEY.

(STEEP EDGES BRIGHTENED FOR READABILITY)

5 kV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM

*This variable character is the apparent basis for one ESD-simulation approach that is based on ignoring air discharge entirely. That's a lot like looking under a street light for a dropped key, instead of in the dark where it was dropped, because at least you can see under the light.

It's unlikely the key will be found there. It's just as unlikely that an effective ESD test standard can totally ignore air discharge. Both current injection and air discharge are necessary.

sharp, partial step to start the discharge current wave. Fig. 2a shows the current from a typical, International Electrotechnical Commission (IEC) specified 150 pF-150 ohm simulator, with IEC-specified *shortest possible* ground return, used for calibration.[4] Fig. 2b shows a similar discharge, but it includes the typical 30-50% initial step that results from the 2-meter ground return of *any* typical IEC simulator. Both waves are shown for the same 5 kV charge voltage used in Fig. 1.

The initial step in Fig. 2b almost makes the simulator's output seem to be *trying* to generate the initial personnel spike of Fig. 1. Two experiments tend to confirm this. First, Fig. 3a shows the discharge current wave from a single-RC ESD simulator using the Electronic Industry Association (EIA) values of 100 pF and 500 ohms.[5] Ground return is two meters; charge voltage is 5 kV. The simulator's output now has almost a 100% initial step.

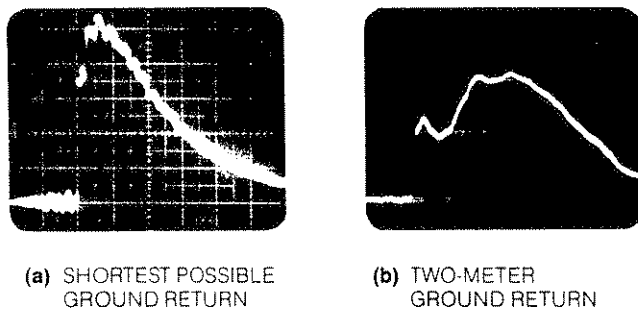


Figure 2

TYPICAL DISCHARGES FROM AN IEC-SPECIFIED ESD SIMULATOR.
 C=150 pF; R=150 ohms (SEE REF 4)
 5 kV INITIAL CHARGE VOLTAGE
 2.5 A/HALF CM, 5 ns/HALF CM.

The second experiment shows the step's probable cause. Figure 3b repeats the test of Fig. 3a, but with the ESD simulator's ground return completely disconnected. Current seems to flow in a one-wire circuit! The short, fast rise time spike of Fig. 3b is clearly related to the initial steps of Figs. 2b and 3a. Just as clearly, it cannot be generated by the simple RC model.



Figure 3

DISCHARGES FROM AN EIA-SPECIFIED ESD SIMULATOR,
 WITH GROUND RETURN FIRST CONNECTED (a)
 AND THEN DISCONNECTED (b)
 C=100 pF, R=500 OHMS (SEE REF. 5)
 5 kV INITIAL CHARGE VOLTAGE
 2.5 A/HALF CM, 5 ns/HALF CM

Conclusions to be drawn from the two experiments just described — increasing the simulator's resistor from 150 ohms to 500 ohms and opening the ground return — are:

- A physical effect associated with the RC simulator generates a step or spike somewhat like, but smaller in peak magnitude than, the ESD spike generated by a human hand with metal object.
- Capacitance of the hand — and of the *physical* RC network (separate from the *value* of capacitance used but related to the *size* of the capacitor), even including the ground return used in the simulation — to the floor and walls is the most probable source of the spike for humans and simulators, respectively.

Capacitance to the floor and walls of any object such as a hand or a network depends on the object's physical dimensions. A hand will have higher capacitance than the physical capacitance of an RC network, since the hand is typically much larger. The same hand will have lower inductance than a ground return wire, since it is far shorter. It therefore seems reasonable for the hand's capacitance, in view of its low associated inductance, to produce a higher-amplitude, steeper rise time spike.

- Simulator capacitance to the floor and walls can also explain the discharge current wave of Fig. 3b, in which there is no apparent return path for current flow.

A BETTER MODEL TO SIMULATE PERSONNEL DISCHARGE

The above mentioned simple RC model used for most ESD simulations ignores inductance, capacitance to free space and arc resistance. These issues are examined below.

Capacitance to Free Space

Most handbooks that contain formulas for capacitance include one for the capacitance between two concentric spheres. The relation is:

$$C = .56K \frac{d_1 \times d_2}{d_2 - d_1} \quad (1)$$

where d_1 and d_2 are inner and outer sphere diameters in cm, $K=1$ for vacuum and $K \sim 1$ for air, and C is in pF.[6] For a 9-cm diameter human hand in a typical small room with 3-meter diameter, C is 5.2 pF.

If room diameter is infinite, i.e., *free space*, Eq. (1) becomes:

$$C = 0.56K d_1 \quad (2)$$

and the capacitance of a 9-cm diameter hand to free space is about 5 pF. An RC network is much smaller than a hand; one pF is a reasonable capacitance for a typical network.

Capacitance to free space of the victim equipment panel may be approximated by the capacitance of a 40 to 50-cm diameter disc. Terman gives this as 16 to 20 pF.[6] If the point of discharge to the victim equipment is removed — by a 25 to 50-cm wire —

Table 1
DIMENSIONS, INDUCTANCE AND CAPACITANCE
VALUE FOR PARTS OF THE BODY

Body Part	d (cm)	l (cm)	L (μH)	C (pf)
Hand with metal object	7.5	12	.02	5
Forearm (wrist to elbow)	9	30	.1	10
Full arm (wrist to shoulder)	9	60	.27	20
Torso	30	60	.13	20
Lower body	30	60	.13	20

from a ground plane, then the resulting spike rise time will be far slower and the peak spike current will be greatly reduced.

Inductance of the Hand, Arm and Body

Inductance of both the lower and upper arm makes most of the upper arm capacitance inaccessible to the discharge for longer than the 1 to 4 nsec duration of the initial spike. The spike must therefore come from the hand plus perhaps a portion of the forearm. Inductance calculations using a round wire as a model, from Terman,[7] give:

$$L = .002\ell \left[2.303 \log_{10} \left(\frac{4\ell}{d} \right) - 1 \right] \quad (3)$$

where ℓ and d are length and diameter, respectively, in cm; L is in μH . Table 1 gives calculated inductance and capacitance values for various parts of the body.

An Equivalent Circuit to Explain the Initial Spike

Fig. 4 shows a human discharge model, configured to explain the wave of Fig. 1, taking into account:

- Capacitances to free space of hand holding a key (C_H), forearm (C_{FA}), upper (C_{UA}) and the combination of torso and lower body (C_B).
- Capacitance to free space of the victim equipment panel (C_{VE}).

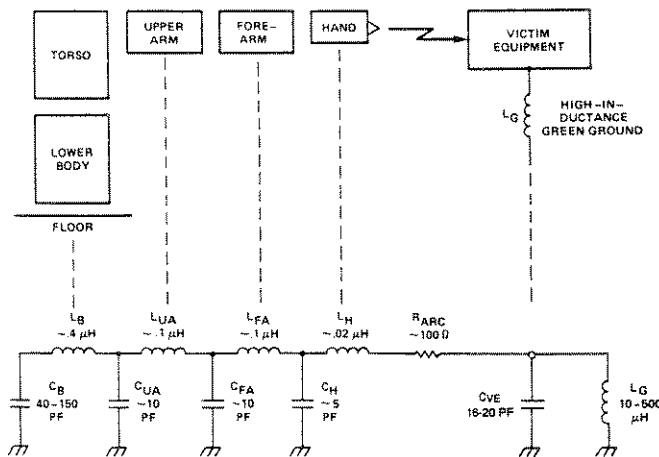


Figure 4
MULTIPLE LC NETWORK EQUIVALENT FOR PERSONNEL
DISCHARGE, IGNORING BODY RESISTANCES.

- Inductance of hand holding a key or other metal object (L_H), the parts of the arm (L_{FA} , L_{UA}) and body (L_B).
- Resistance of the arc (R_{arc}).

Solving the Single RLC Equivalent Circuit

If the simple RC circuit is expanded to be an RLC circuit, it can effectively be used to model the first part of the ESD waveform. This is because for the first few nsec the inductance, L_{FA} , effectively isolates the circuit to the left from the victim.

Solving this simplified model equation for a range of C , L and R values helps explain the initial spike. For spike duration t_d to lie below about 4 nsec, it turns out that L_H must be quite small – less, in fact, than 0.1 to 0.2 μH . From Table 1, this excludes all but the hand and possibly part of the forearm.

Table 2
TIME OF PEAK t_p , DURATION t_d , AND PEAK CURRENT i_p
FOR VARIOUS CAPACITANCES

C (pF)	R (Ω)	L (μH)	t_p (nsec)	t_d (nsec)	i_p for 5 kV (A)
1	200	.1	.4	.6	10.4
2	200	.1	.6	1.0	12.9
5	200	.1	.8	1.6	16.1
7.5	200	.1	.9	2.0	17.5
10	200	.1	1.0	3.0	18.4
60 [5]	10,000	.7	.6	417	.5
100 [5]	500	.7	5.2	40	9.0
100 [8,9]	1,500	.7	2.7	107	3.3
150 [4]	150	.7	9.9	27	25.0
300 [10]	5,000	.7	1.3	1042	1.0

Table 2 gives results of computer solution for C values of 1, 2, 5, 7.5 and 10 pF, for L equal to 0.1 μH , and for R of 200 ohms. Note how hopeless it is to use a 100 MHz scope, with its 3.5 nsec rise time, to examine these short, steep waves. Also listed in Table 2 are computer solutions for the RC values used in typical ESD equivalent circuit models. C ranges from 60 pF to 300 pF; R from 150 ohms to 10 K. L is taken as 0.7 μH , a typical total human body inductance.

Apparently the only way to get an initial current spike is with low inductance, and only the capacitance to free space of the hand and possibly the forearm can supply a low enough inductance. With 10 pF and an inductance even as low as 0.1 μH , i_p is already limited to approximately 18 A, using 200 Ω for the total resistance of the hand plus arc; the figure is approximately 27 A for 100 Ω .

In summary,

- The initial spike is generated primarily by hand and some forearm capacitance; perhaps 10 pF, accessible to the arc via a total of 0.05 to 0.2 μH .
- Net capacitance in the equivalent circuit is, therefore, the 10 pF from above, in series with the victim equipment's typical 16 to 20 pF, for a total of perhaps 6 to 8 pF.

- Use of 7.5 pF, with 200 Ω for hand-plus-arc resistance, and 0.1 μ H as a reasonable compromise for *hand* (plus some victim equipment) inductance, gives, from Table 2, a peak current of approximately 18 A for a 5 kV initial charge voltage. Time to peak is about 1 nsec, and duration is about 2 nsec. When the hand-spike amplitude adds to the early amplitude of the main body discharge, the total peak can easily reach 20 to 25 A.

ESD Circuit Model

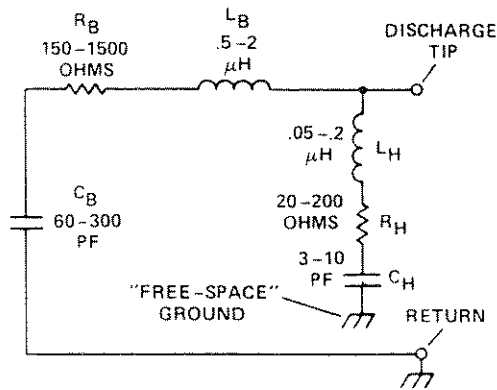


Figure 5

THE DUAL RLC MODEL FOR ESD FROM A HAND-HELD KEY, INCLUDING SIMULATION OF THE INITIAL SPIKE.

A Practical Model

Fig. 5 shows the dual RLC circuit model that results from the above analysis. It is far more realistic than the simple RC for simulating reasonable worst-case ESD: discharge from a hand-held

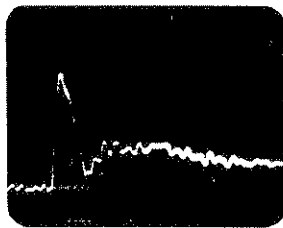


Figure 6

ACTUAL DISCHARGE CURRENT FROM AN ESD SIMULATOR USING THE DUAL-RLC™ MODEL OF FIG. 5. IT REPLICATES THE INITIAL SPIKE FROM A HUMAN HAND WITH INTERVENING METAL OBJECT

(STEEP EDGES BRIGHTENED FOR READABILITY)

5 KV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM

key. It includes two series RLC paths, each with its own realistic inductance. One path, $C_B-R_B-L_B$, simulates the body. The second, $C_H-R_H-L_H$, simulates the hand and the sharp initial spike it generates.

Finally, Fig. 6 shows an actual discharge from a Dual-RLC™ ESD simulator designed to duplicate a human discharge's initial spike. The wave of Fig. 6, too, looks remarkably like the actual discharges of Figs. 1(a) and 1(b). The simulator rise time is just as fast on the 0.9 nsec oscilloscope, and it uses a standard IEC two-meter ground return, *not the shortest possible*, 10 to 20 cm calibration ground return. The dual RLC simulator that generates this discharge should provide greatly improved realism in ESD testing.

REFERENCES

- [1] Richman, P. and A. Tasker, *ESD Testing: The Interface between Simulator and Equipment Under Test*, Proceedings of the Sixth EMC Symposium, Zurich, Switzerland, March 5-7, 1985, pp. 25-30.
- [2] King, W.M. and D. Reynolds, *Personnel Electrostatic Discharge: Impulse Waveforms Resulting from ESD of Humans Directly and Through Small Hand-Held Metallic Objects Intervening in the Discharge Path*, Proc. IEEE International Symposium on EMC, Aug. 18-20, 1981, pp. 577-590.
- [3] Daout, B. and H. Ryser, *Fast Discharge Mode in ESD-Testing*, Proceedings of the Sixth EMC symposium, Zurich, Switzerland, March 5-7, 1985, pp. 41-46.
- [4] International Electrotechnical Commission (IEC) Standard: Electrostatic Discharge (for Industrial Control), IEC Pub. 801-2.
- [5] EIA (Electronic Industries Association) Standards Project PN-1361, Environmental and Safety Considerations for Voice Telephone Terminals, Draft 6, 1985.
- [6] Terman, F.E., *Radio Engineer's Handbook*, McGraw-Hill, 1943, p. 113.
- [7] Terman, p. 48.
- [8] NEMA, Residential Controls, Environmental Testing for Electronic Controls, Part DC33, Proposed June 24-25, 1982.
- [9] MIL-STD 883B, Test Methods and Procedures for Micro Electronics.
- [10] SAE Standard Recommended Practice Information Report J-1211, June 1978, p. 20.99.



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ESD Testing: The Interface Between Simulator and Equipment Under Test*

P. Richman and A. Tasker

Crucial issues regarding the interface between the ESD simulator and the Equipment Under Test (EUT) include discharge current peaks that are vastly different from simply-calculated values, and failures of the EUT at both low and high, but not intermediate voltage levels. These phenomena can be explained and mathematically modeled in terms of circuit inductance and free-space capacitance. The more inclusive circuit model that results, gives significantly improved agreement between calculated and experimental electrostatic-discharge current waves.

The effect of oscilloscope bandwidths must also be taken fully into account. 100 MHz is far too low, for example: it can give figures for actual human-body peak discharge current that are in error by a factor of two or more.

INTRODUCTION

The peak current that flows during an electrostatic discharge (ESD) from an ESD simulator can be vastly different from the value intuition might lead one to expect. It can be at least as low as one-tenth, or at least as high as ten times the value computed by dividing stored — or test — voltage by the simulator's nominal internal resistance. In addition, the discharge current waveform in both simulator and actual human-body discharges often bears little relation to the simple, single R-C equivalent circuit in widespread use (1-5).

The two factors most responsible for these often huge discrepancies are circuit inductance and capacitance to free space.

The conventional model for personnel electrostatic discharge is given in Fig. 1. It consists of a simple capacitor C, charged to voltage V, and discharging into the victim equipment — the EUT or Equipment Under Test — through resistor R. The "low end of C is most often connected to a ground plane or to a point on the EUT, or both. A discharge tip, connected to the resistor R, is advanced toward the EUT until an arc occurs simulating the spark that leaps from a finger or from a hand-held metal object like a tool, key, bracelet or ring.

Values called for by various Standards and used by individual organizations range from 60 to 300 pfd for C, and from 10 to 10,000 ohms for R (1-5).

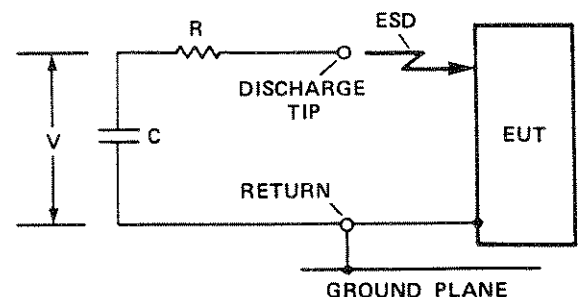


Figure 1.
CONVENTIONAL, SINGLE R-C MODEL FOR PERSONNEL ELECTROSTATIC DISCHARGE

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Fig. 2 shows discharge current due to a typical human-body discharge from a hand-held metal object. Instrumentation for converting the discharge current into a voltage suitable for oscilloscope monitoring was built as per reference (1); oscilloscope bandwidth was 400 MHz. Even though the circuit model of Fig. 1 is in common use, there is simply no way in which it can begin to account for the real-world Fig. 2 waveform, specifically for the sharp, high-amplitude initial spike. (Others have also reported initial spikes (6).)

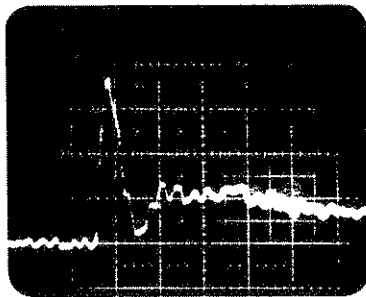


Figure 2.

TYPICAL ESD CURRENT DISCHARGE WAVE FROM A HAND-HELD METAL OBJECT. (STEEP RISE EDGES BRIGHTENED FOR READABILITY)
5kV INITIAL CHARGE LEVEL, 5A/HALF CM, 2ns/HALF CM.

This single R-C model of Fig. 1 is inadequate in that it ignores:

1. The human body and/or ESD simulator circuit inductance, which ranges from 0.5 to 2 μH .
2. The 3 to 10 pfd, almost inductance-free capacitance to free space of the human hand.
3. The typically 5 to 20 pfd, almost inductance-free capacitance to free space of the victim EUT itself.

The sections that follow deal with these parameters, all of which are ignored by the simple R-C circuit. The purpose is to modify the circuit model so that it can more reasonably account for characteristics of the current wave in a typical

human-body-generated, electrostatic discharge. The resulting model then suggests better ways to simulate ESD phenomena for test purposes.

CIRCUIT INDUCTANCE

Reference (1), an IEC draft ESD standard for Process Control, specifies a two-meter long ground return of 20 mm width. However, for calibration purposes, the same draft standard calls for a discharge circuit, including the ground connection, that is "as short as possible". Calculations, confirmed by tests, give total circuit inductance including internal simulator circuitry as well as the ground return itself, of about 1.7 μH for the two-meter ground return. Similarly, a figure of 0.7 μH results for a typical R-C network with a calibration-length ground, with a length on the order of 30 to 40 cm.

Fig. 3 shows the addition of total circuit inductance L to the simpler circuit of Fig. 1.

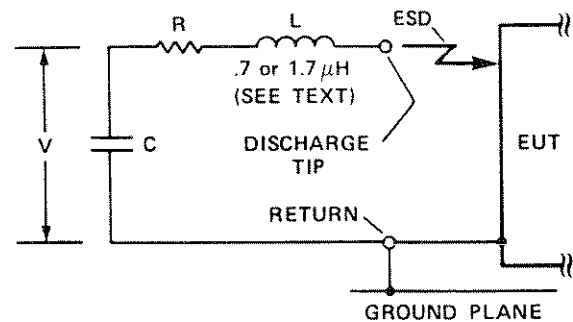


Figure 3.

ESD MODEL MODIFIED TO INCLUDE TOTAL CIRCUIT INDUCTANCE, L

Table 1 shows the large effect that L can have on network "efficiency" η , defined as the ratio of peak current I_p during

Table 1

R AND C VALUES FOR THE R-L-C EQUIVALENT CIRCUIT OF FIG. 3, WITH EFFICIENCY η GIVEN FOR REALISTIC GROUND RETURN INDUCTANCE, 1.7 μH
 I_p IS PEAK CURRENT FOR A STORED VOLTAGE OF 5kV; t_p IS TIME OF OCCURRENCE OF I_p

Organization (1 - 5)	Standard or Draft Standard	C (pfd)	R (ohms)	$\eta = 100 \frac{I_p}{V/R}$ (%)	I_p for 5kV (A)	t_p (ns)
1.	IEC (1) 65 (Secr) 80 (Draft)	150	150	64	21	18
2.	MIL (2) 883B	100	1,500	97	3.2	5.6
3.	NEMA (3) Part DC33 (Draft)	100	1,500	97	3.2	5.6
4A.	EIA (4) PN-1361 (Draft)	100	500	87	9	10
4B.	EIA (4) PN-1361 (Draft)	60	10,000	100	.5	1.4
5.	SAE (5) J1211	300	5,000	100	1.0	2.9
6.	Cart Simulation	60	10	6	28	16

discharge, to the "intuitive" peak of V/R ; multiplied by 100 to obtain per cent. (Efficiency without L must be 100%.) Calculated values of I_p were computer-derived from appropriate solutions to the series R-L-C circuit of Fig. 3, and were spot-checked via experiment. I_p was calculated for a stored voltage of 5kV, but for different voltages the values of I_p can be scaled proportionately; ignoring pre-ionization and other effects (see Appendix).

R and C values come from representative ESD test Standards, as listed in Table 1. Inductance L was taken as $1.7 \mu\text{H}$, representative of a typical simulator including a 20 mm wide ground return of about two meters, the length recommended by the IEC draft standard.

The largest effects of inductance naturally occur for lower values of R , including the IEC's 150 ohms and the 10 to 20 ohm value being used by some organizations for simulating discharges from wheeled carts and/or cabinets.

Note the vast differences, particularly for the IEC 150 pf/150Ω network, between V/R (33A for 5kV) and the calculated value, 21A, for peak current I_p for $1.7 \mu\text{H}$ circuit inductance. For the "calibration" circuit inductance of $0.7 \mu\text{H}$, the same 150 pf/150Ω IEC network gives a calculated peak current of 25A. Typically, arc and corona effects reduce this still further, by as much as 20 to 30%. Thus a 5kV stored voltage with a 150 ohm resistor will typically result in a peak current of only 16 to 18A. "Calibration" in test laboratories may report defective simulators, with only one-half required output! (The IEC specifies a peak current of 50% to 90% of stored voltage divided by resistance, thereby covering the situation quite completely. Unfortunately many calibration laboratories simply calculate V/R , and either ignore the IEC specification or neglect to calculate the effects of even the $0.7 \mu\text{H}$ "calibration" inductance).

Table 1 also includes a column giving computer solutions for the time t_p , in nanoseconds, at which the peak I_p occurs. Again ignoring effects such as pre-ionization due to partial discharge, t_p is independent of stored voltage.

Neither peak current I_p nor peak time t_p respond to network differences in a simply proportional way. The effect of changing from 150 pf/150 ohms to 60 pf/10 ohms, for example, is rather small: current peak increases from 21 to 28A, time to peak decreases from 18 to 16 ns. Yet the nominal "efficiencies" of the two networks differ by over an order of magnitude. The explanation is that inductance is the controlling factor. Until the simulation circuit resistance gets large — 500 to 1500 ohms — or more accurately until network efficiency exceeds 90 or 95%, circuit inductance dominates performance.

The control that inductance exercises over discharge current is demonstrated by the fact that rate of rise of current, di/dt , is wholly independent of both R and C for $t = 0$. This holds true whether the circuit is over-damped, critically damped or oscillatory. That is, as the current wave makes its initial rise, di/dt is equal to stored voltage divided by inductance, or (V/L) . R and C simply don't matter at this point. They do, of course, as the wave progresses, but maximum rate of rise occurs at $t = 0$, and it is entirely circuit-inductance limited. Thus for 5kV and $1.7 \mu\text{H}$, the fastest di/dt for the circuit of Fig. 3 will be $5000 / (1.7 \times 10^{-6})$, or just under 3 amperes per nanosecond. Even with the shortest ground return, with its $-0.7 \mu\text{H}$

for total circuit inductance, maximum di/dt for 5kV will be $5000 / (.7 \times 10^{-6})$, or about 7 amperes per nanosecond.

CAPACITANCE TO FREE SPACE; INTERACTION WITH INDUCTANCE

Every object has capacitance to free space — or to the walls, floor and ceiling of the room in which it is located. For a spherical object of diameter d_1 , and a room (also taken as spherical, for simplicity) of diameter d_2 , the capacitance is given by reference (7) as:

$$C = 0.556 \times K d_1 d_2 / (d_2 - d_1) \quad (1)$$

in which d_1 and d_2 are in cm. and $K \sim 1$ for air.

For a human hand or arm in a room of typical dimensions, the term $d_2 / (d_2 - d_1)$ approaches unity, so that

$$C \sim 0.556 d_1 \quad (2)$$

For a hand of approximately 9 cm "diameter", capacitance is thus on the order of 5 pfd. Note that this capacitance is almost inductance-free. The inductance of a finger, hand and/or forearm may be calculated from reference (7) as:

$$L = 0.002 \ell [2.3 \log_{10} (4\ell / d) - 1] \mu\text{H} \quad (3)$$

in which ℓ and d are length and diameter, respectively, of the finger, hand or forearm; again in cm. Table 2 gives results, along with approximate values of capacitance to free space, for all body segments involved. Use of a hand with key has been assumed, as this is rapidly becoming a de-facto standard for worst-case ESD simulation. It represents an ESD event involving a hand-held metal object such as a tool, ring, bracelet, or indeed an actual key.

Table 2

APPROXIMATE DIMENSIONS, ESTIMATED CAPACITANCE AND ESTIMATED INDUCTANCE FOR VARIOUS SECTIONS OF THE HUMAN BODY

(d = DIAMETER, ℓ = LENGTH)

	<u>d</u> (cm)	<u>ℓ</u> (cm)	<u>C</u> (pf)	<u>L</u> (μH)
Fingers holding key	2	6	2	.02
Entire hand holding key (to wrist)	7.5	12.5	5	.02
Forearm (wrist to elbow)	9	30	10	.1
Full arm (wrist to shoulder)	9	60	20	.27
Torso (shoulder to waist)	30	60	20	.13
Whole body (torso plus lower body)	30	120	40	.43

Table 3

COMPUTED VALUES OF PEAK CURRENT I_p AND PEAK TIME t_p
 I_p COMPUTED FOR 5KV: SIMPLY SCALE FOR OTHER VOLTAGES

(FOR VIRTUALLY ALL PARAMETER COMBINATIONS EXCEPT $R = 10K$,
 RISE TIME, t_r , LIES BETWEEN 25% AND 65% OF PEAK TIME t_p .)

C (pfd)	R (ohms)	L (μ H)	I_p (amperes) for bandwidth =				t_p (ns) for bandwidth =			
			Infinite	400 MHz	100 MHz	60 MHz	Infinite	400 MHz	100 MHz	60 MHz
.5	50	.1	10	6	2.4	1.5	.4	.6	.7	.7
2	50	.1	19	15	7.4	5.1	.7	1.0	1.2	1.3
5	200	.1	16	14	8.3	6.1	.8	1.2	1.8	2.0
7.5	200	.1	18	16	10	7.6	1.0	1.4	2.1	2.4
10	200	.1	18	17	11	8.8	1.1	1.5	2.4	2.8
60	10,000	.7	.5	.5	.5	.5	.6	3.1	9.5	15
		1.7	.5	.5	.5	.5	1.4	3.2	9.6	15
100	500	.7	9	9	9	9	5.2	5.7	8	10
		1.7	9	9	9	8	10.1	10.6	12	14
100	1,500	.7	3.3	3.3	3.2	3.1	2.7	3.5	7.9	11
		1.7	3.2	3.2	3.2	3.1	5.6	6.1	9.1	12
150	150	.7	25	25	25	24	10	10	12	13
		1.7	21	21	21	21	18	18	20	21
300	5,000	.7	1.0	1.0	1.0	1.0	1.3	3.5	11	17
		1.7	1.0	1.0	1.0	1.0	2.9	4.0	11	17

Computer solutions are given in Table 3 for peak current I_p and peak time t_p , from the differential equations that describe performance of the circuit of Fig. 3 (see Appendix). Solutions are given for values representative of appropriate combinations of the hand and arm from Table 2, using a compromise inductance value of 0.1 μ H. Solutions are also given in Table 3 for the R-C values specified in various standards as set forth in Table 1, for both "calibration" (0.7 μ H) and normal 2-meter (1.7 μ H) inductances. A resistance of 200 ohms is used for the small capacitance values that simulate the hand and arm, but is not a major determinant in I_p or t_p , over a wide range of resistance values.

It is assumed that the victim EUT has significant capacitance to free space in the surface area immediately adjacent to the point of ESD application; i.e., it is another, larger, and also virtually inductance-free capacitance. From reference (7), for example, the capacitance of a 30 to 40 cm diameter disc to free space can be calculated as 12 to 15 pfd. This might represent that portion of a victim EUT panel or keyboard at whose center the ESD was applied. Without such a "ground plane," free-space capacitance effects due to finger, hand and arm will be very much lower, due to the lower total circuit capacitance that will result. (EUT "ground plane" capacitance is effectively in series with hand capacitance).

In this connection, it is worth noting that the IEC-designed

coaxial "target" (1) performs far better in making current-spikes measurements when it is mounted to a ground plane on the order of 40 x 40 cm.

In addition to the "infinite bandwidth" theoretical values given in Table 3 for I_p and t_p , computer solutions are also included in the table for the same waveforms viewed with oscilloscopes of finite bandwidths: specifically 400 MHz, 100 MHz and 60 MHz.

Data in Table 3 go a long way towards explaining differences between measurements made by different investigators. Simulations with 60 pfd and 10K, for example, will be vastly different depending on the simulation capacitor's physical size, and on whether the simulation resistor is 12 cm long — hence *not* simulating a finger/hand combination — or short, and contained within a metal enclosure to which it might have, for example, .5 pfd stray capacitance. For 60 pfd/10K, I_p is .5A at 5kV. But if stray capacitance — or capacitance of the simulating 60 pfd to free space — is considered and a 400 MHz scope used, then from Table 3, I_p will be 6A for an arc resistance of 50 Ω ; and 10A with infinite oscilloscope bandwidth. Yet the value shown with 60 to 100 MHz instrumentation will range from only 1.5 to 2.4A. And after all, the 0.5 pfd stray is only 10% of the 5 pfd representative of the human hand — which at 400 MHz gives 14A for 200 Ω , as shown in the table.

Thus all of the simulation circuits in references (1) through (5) miss the point: the hand/forearm combination has a 5 to 15 pfd capacitance to free space, and it is coupled to the discharge arc with only 0.05 to 0.1 μ H. The result is a super-fast edged, short-duration (1 to 4 ns) spike of 15 to 30A, for a stored voltage of only 5kV. Experience shows this spike can be *crucial* in causing EUT malfunction, but it is neglected by all existing standards. And if it is accidentally viewed on an oscilloscope, its amplitude is typically underestimated by a factor between 2 and 4 by the 60 to 100 MHz instrumentation in common use.

Any saving grace that a simple R-C ESD simulator may have is that the simulation network can itself have a capacitance to free space! This accounts for the sharp wave-start so frequently seen in simulator current waves. Fig. 4 shows a typical case, for the EIA values of 100 pfd and 500 ohms (4). But this is a far cry from the sharp, 1 to 4 ns spike of 25 to 50A peak (for a stored voltage of 5kV) that is generated by a hand-held key, as shown in Fig. 2.

In the typical ESD simulator's discharge current output, the amplitude of the sharp initial edge generated by the simulator network's own capacitance to free space, is usually less than peak current due to the simulator's basic R-C. For this reason it has been seen as merely an unpleasant anomaly in the wave, due to "parasitics." In point of fact, it provides whatever inadequate sharp-risetime "punch" such simulator waves do have.

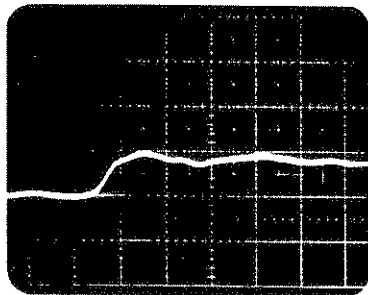


Figure 4.

TYPICAL ESD CURRENT WAVE FROM A SINGLE R-C ESD SIMULATOR (100 pfd, 500 Ω) (4). SHARP WAVE-START IS DUE TO THE SIMULATOR NETWORK'S OWN CAPACITANCE TO FREE SPACE. 5kV INITIAL CHARGE VOLTAGE, 5A/HALF CM; 2NS/HALF CM

THE NEW, DUAL RLC CIRCUIT MODEL

Fig. 5 shows the new, Dual RLC Circuit Module that seems to best replicate the effects of circuit inductance, plus hand capacitance, in an electrostatic discharge.

Two parallel R-L-C paths are provided; one for the body (C_B , R_B , L_B), the other for the hand (C_H , R_H , L_H). Since the impedance from Discharge Tip to ground during the discharge is generally low – due to the victim EUT's own capacitance to free space – the two R-L-C paths functions as almost independent current sources. Thus the waves they generate are superimposed. $C_H/R_H/L_H$ generates either the steep-rise initial spike, or for higher voltages at which corona effects cause pre-ionization, a large initial step. $C_B/R_B/L_B$ then generates the longer wave that follows, carrying the often less-damaging energy stored on whole-body capacitance.

Corona effects at higher voltages – above 3 to 6 kV, depending on discharge tip geometry – reduce the sharpness of the initial spike or step. This effect most likely accounts for the fact that many equipments that can pass ESD tests at 10 kV, say, at which level corona has seriously reduced risetime, will fail at only 5 kV, due to the steep initial rise of the spike or step. At voltages of 15 to 20 kV, failures may start again, as the sheer magnitude of the di/dt, even with heavy corona, once again becomes high enough to cause equipment malfunctions.

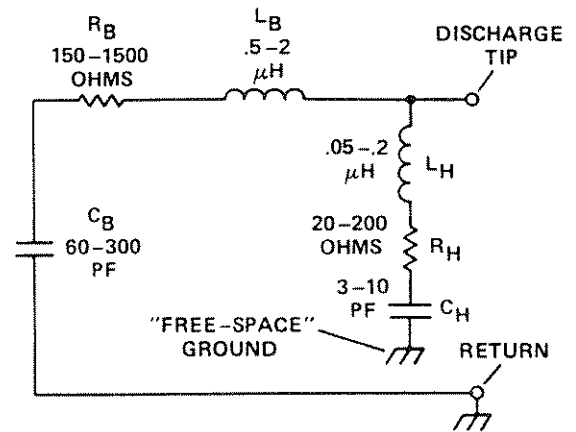


Figure 5.

THE DUAL RLC CIRCUIT MODULE FOR ESD: INCORPORATING SEPARATE PARALLEL PATHS FOR BODY AND HAND DISCHARGE.

Fig. 6 shows computer-generated current discharge waves for the Dual RLC circuit of Fig. 5, both without (6a) and with (6b) simulated arc oscillations. Hand-simulation values are 7.5 p 200 Ω and 0.1 μ H. Body-simulation values are 100 pfd, 500 and 0.7 μ H. Fig. 6b corresponds well with the human-discharge current of Fig. 2; i.e., the Dual RLC model works.

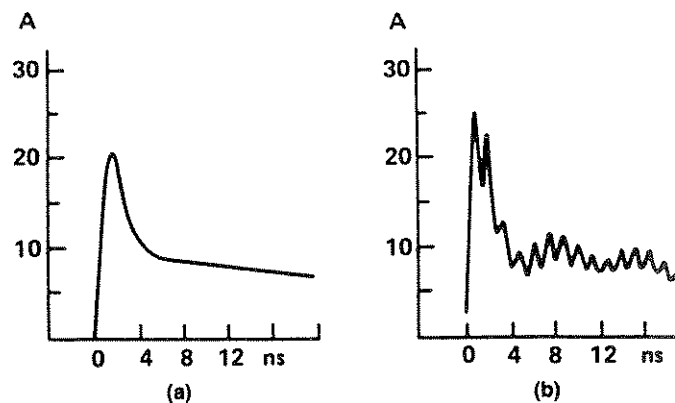


Figure 6.

COMPUTER SOLUTION FOR DISCHARGE CURRENT FROM THE DUAL RLC CIRCUIT OF FIG. 5; (a) WITHOUT AND (b) WITH SUPERIMPOSED SIMULATED ARC OSCILLATIONS (400 MHz BANDWIDTH).

$$C_H = 7.5 \text{ pfd} \quad R_H = 200 \Omega \quad L_H = 0.1 \mu\text{H}$$

$$C_B = 100 \text{ pfd} \quad R_B = 500 \Omega \quad L_B = 1.7 \mu\text{H}$$

5kV INITIAL CHARGE. VOLTAGE, 5A/DIVISION, 4ns/DIVISION

Fig. 7 shows a typical current-discharge wave from a practical ESD simulator that was designed to reproduce the Dual RLC model of Fig. 5. It agrees well with both Figs. 2 and 6b.

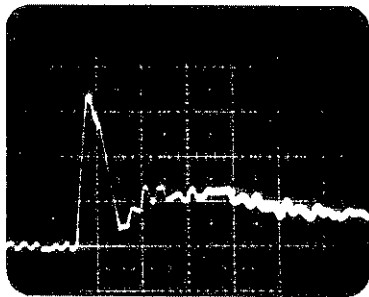


Figure 7.

ACTUAL DISCHARGE CURRENT FROM A PRACTICAL ESD SIMULATOR EMBODYING THE DUAL RLC CIRCUIT OF FIG. 5 (STEEP-RISE EDGES BRIGHTENED FOR READABILITY).

5kV INITIAL CHARGE VOLTAGE, 5A/HALF CM, 2ns/HALF CM.

CONCLUSIONS

1. Any ESD circuit model that doesn't include inductance can't simulate reality well enough for test purposes.
2. Capacitance of the hand to free space causes a spike at voltages to 5 kV, and an initial fast edge at higher voltages. Both are grossly under-estimated by 60 to 100 MHz instrumentation, while measured adequately with instrumentation of 400 MHz and above.
3. The inevitable 0.25 to 2 pfd capacitance to free space of the simulator's own network — including ground return — is the only tie to fast-edge reality that many simulators have; and it is too small by a factor of perhaps ten. Nevertheless it probably *still* causes a large proportion of ESD-simulation failures.

Thus any limited effectivity enjoyed by many ESD simulators may be provided by sharp spikes due to the unplanned, essentially inductance-free capacitance inherent in the physical dimensions of the model, including its ground return. (Some energy representing voltage stored on the whole body capacitance is assuredly necessary. However, disagreements among standards for R and C values are possibly as unimportant as they appear; i.e., most standards seem to work some of the time.)

Doubts about the matter can be resolved by testing first with, and then without, the connection to ground of the simulator's ground return. (But leave the ground return connected at the simulator end! Its capacitance to free space adds to the waveform.) EUT failures — or the lack thereof — will sometimes be identical for the two cases. Opening the ground return de-emphasizes the C_B - R_B - L_B , body-simulating path in Fig. 5. In the typical simulator, the C_H - R_H - L_H hand-simulating path will remain, via parasitics; although the strays that make up C_H are still far too small to properly simulate the human hand and forearm.

4. A parallel RLC/RLC circuit model (the "Dual RLC" model) gives excellent general agreement with initial edge and initial spike experimental data.

5. It is quite practical to simulate the Dual RLC model with physical components, while nevertheless retaining the convenient two-meter ground return. Data from such simulators agree well with both calculations and data from actual personnel electrostatic discharge. The Dual RLC model represents the situation well: C_H discharges through a low inductance to give the initial spike simulating the human hand; C_B discharges through a higher inductance, to simulate the longer wave that conveys energy stored on the entire body.
6. Simulators not incorporating the C_H - R_H - L_H hand-spike simulation path may well not be able to induce failures at 3 to 6 kV in the same way that actual personnel discharges can do. Thus ESD-testing with such instrumentation may not represent the reality the equipment under test will face when placed in service.

REFERENCES

- [1] International Electrotechnical Commission IEC 65(Secr)80 Draft Standard: Electrostatic Discharge (for Industrial Process Control). (Now IEC Pub. 801-2.)
- [2] MIL STD 883B, Test Methods and Procedures for Micro Electronics.
- [3] NEMA, Residential Controls, Environmental Testing for Electronic Controls, Part DC33, Proposed June 24-25, 1982.
- [4] EIA (Electronic Industries Association) Standards Project PN-1361, Environmental and Safety Considerations for Voice Telephone Terminals, Draft 5, Nov. 24, 1981.
- [5] SAE Standard Recommended Practice Information Report J-1211, June 1978, p 20.99.
- [6] King, W.M. and Reynolds, D., Personnel Electrostatic Discharge: Impulse Waveforms Resulting from ESD of Humans Directly and Through Small Hand-Held Metallic Objects Intervening in the Discharge Path, Proc. IEEE Int'l Symposium on EMC, Aug. 18-20, 1981, pp. 577-590.
- [7] Terman, F.E., Radio Engineer's Handbook, McGraw-Hill, 1943, pp48,113.

APPENDIX

Solution for Parameters of the Series R-L-C Circuit of Fig. 3

The differential equation that describes Fig. 3 for a short-circuit load is:

$$R i(t) + L di(t)/dt + \frac{1}{C} \int i(t) dt = V \quad (1)$$

For critical damping,

$$L < R^2 C / 4 \quad (2)$$

$$\text{and } i(t) = (V/L)te^{-Rt/2L} \quad (3)$$

For overdamping,

$$L = R^2 C / 4 \quad (4)$$

$$\text{and } i(t) = (V/2LA)te^{-Rt/2L} (e^{At} - e^{-At}) \quad (5)$$

in which

$$A = 1/2 \sqrt{(R/L)^2 - 4/LC} \quad (6)$$

For underdamping

$$L > R^2 C / 4 \quad (7)$$

$$\text{and } i(t) = (V/LB) e^{-Rt/2L} \sin Bt \quad (8)$$

in which

$$B = 1/2 \sqrt{4/LC - (R/L)^2} \quad (9)$$

For the critically damped case of equation (3), time of occurrence t_p of peak current I_p , as well as I_p itself, may be found as:

$$t_p = RC/2 = 2L/R \quad (3a)$$

$$\text{and } I_p = (2/e) (V/R) \quad (3b)$$

For the same case, di/dt from equation (3) is:

$$di/dt = (V/L)e^{-Rt/2L} (1 - Rt/2L) \quad (3c)$$

which for $t = 0$ reduces to:

$$\left. \frac{di}{dt} \right|_{t=0} = V/L \quad (3d)$$

Similar solutions for the overdamped case of equation (5) yield:

$$t_p = (1/2A) \ln \frac{(R/2L) + A}{(R/2L) - A} \quad (5a)$$

$$I_p = (V/2LA) e^{-Rt_p/2L} (e^{At_p} - e^{-At_p}) \quad (5b)$$

$$di/dt = (V/2LK) e^{-Rt/2L} [(A - R/2L)e^{At} + (A + R/2L)e^{-At}] \quad (5c)$$

Again, $di/dt = 0$ reduces to:

$$\left. \frac{di}{dt} \right|_{t=0} = V/L \quad (5d)$$

Finally, analogous solutions for the underdamped case of equation (8) give:

$$t_p = (1/B) \tan^{-1} (2LB/R) \quad (8a)$$

$$\text{with } I_p = (V/LB) e^{-Rt_p/2L} \sin Bt \quad (8b)$$

$$di/dt = (V/LB) e^{-Rt/2L} [B \cos Bt - (R/2L) \sin Bt] \quad (8c)$$

in which, for the third time, di/dt at $t = 0$ is:

$$\left. \frac{di}{dt} \right|_{t=0} = V/L \quad (8d)$$



Comparing Computer Models to Measured ESD Events*

P. Richman

ABSTRACT

A new, Dual R-L-C circuit model has been identified to explain the electrostatic discharge (ESD) waves from a human body with an intervening metal object.[1] This new circuit model has been proposed as a far more realistic replacement for the single R-C in common use. The new model accounts for the observed initial spike, risetime, peak and duration characteristics of the current discharge wave. The super-fast initial spike may well be a major cause of ESD-induced equipment failures. For this reason, modeling and then simulating the Dual R-L-C circuit can be of significant help in reducing the incidence of such failures.

Computer solutions were derived for discharge current waves based on the new Dual R-L-C circuit configuration. A library of such solutions was generated, for a wide range of circuit parameters. They were generally based on reasonable calculations for the physical parameters involved – hand and arm capacitance, inductance and so on.[1] This library was compared with current waves measured during actual human-body discharges, and results matched to obtain best estimates for all six circuit-model parameters.

Output waves are examined for an ESD simulator whose design is based on the Dual R-L-C model. They compare favorably both with actual human discharges and with the computer simulations.

INTRODUCTION

It is often difficult to associate a specific equivalent circuit or circuit model with waves resulting from actual ESD events. For one thing, neither circuit inductance nor capacitance to free space are familiar parameters; and both are crucial in determining the nature of ESD. In addition, ESD is highly statistical in character. Discharges under nominally identical circumstances can be vastly different, since arc characteristics change as a function of many variables. All of these factors must be taken into account when modeling specific circuits.

The new, Dual R-L-C model involves six components whose values must be determined. Computer simulation was therefore used to develop a library of possible current discharge waves. Matching these with waves from a given set of actual human-body discharges yields good estimates for all six circuit values. The results are in reasonable agreement with the physical quantities involved, namely the electrical parameters both of various sections of the body, and of potential victim equipments.

The use of a library of time-domain responses is preferable to progressively introducing parameter changes to improve a single computer response. This is so because even fairly large changes in network parameters can yield relatively small changes in the discharge wave, a situation typical of work in the time domain. As a result, it has been found that visually scanning a range of waves with varying parameters is the best way to select an optimum set of equivalent-circuit component values.

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THE DUAL R-L-C MODEL

Fig. 1 shows the new, Dual R-L-C ESD Circuit model.[1] The C_B , L_B , R_B path departs from the commonly used single R-C human body model in that L_B , a series body inductance, has been added. This inductance facilitates modeling observed risetime, peak current, time of peak, and pulse current duration from actual discharges. In addition, the C_H , L_H , R_H path models the capacitance, C_H , of the human hand to free space; along with its associated inductance L_H and resistance R_H . [1] The body (B) and hand (H) paths function as separate current sources.

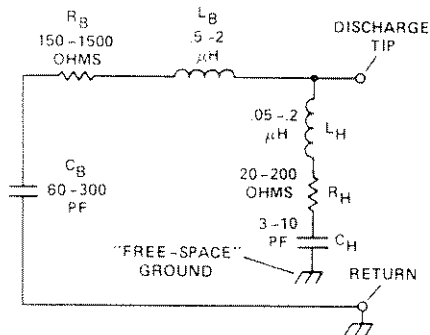


Figure 1.
NEW, DUAL R-L-C ESD
EQUIVALENT CIRCUIT MODEL

Figs. 2 (a), (b) and (c) show three typical current-discharge waves from a human body including a hand-held key. The key is representative of many possible hand-associated metal objects including a tool, bracelet, ring, or indeed an actual key. (Discharges without metal objects often have the same character, specifically the initial spike; they are just lower in amplitude.) The initial voltage level was 5kV. The oscilloscope bandwidth was 400 MHz, with a corresponding risetime of 0.9 ns. All three waves were obtained under ostensibly identical circumstances. All have spikes with risetimes from $<.9$ ns to ~ 1.5 ns, and durations of 2 to 4 ns. No simple R-C model can account for such performance, but the Dual R-L-C model can readily do so.

COMPUTER RESULTS

Fig. 3 gives a computer-generated plot for the C_B - L_B - R_B body path in Fig. 1, again for a 5kV initiation level. Results are "viewed," via computer simulation, with a 400 MHz bandwidth. L_B was 0.7

μH . [1] C_B and R_B values of 100 pfd and 500 ohms were taken from an EIA draft Standard, [2] and also seem to best represent the body portion of the typical human ESD event.

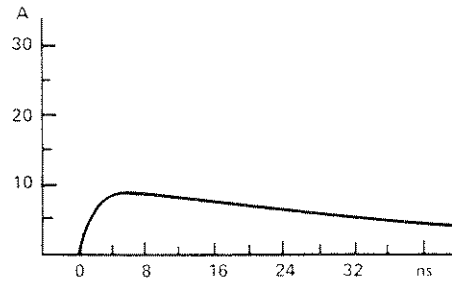
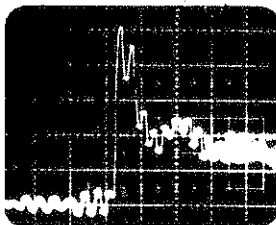


Figure 3.
COMPUTER SIMULATION FOR THE
 C_B - L_B - R_B PATH OF FIGURE 1
 $C_B = 100$ PFD. $R_B = 500$ OHMS (EIA). $L_B = 0.7 \mu H$
5KV INITIAL CHARGE VOLTAGE
5A/FULL DIVISION. 4ns/FULL DIVISION

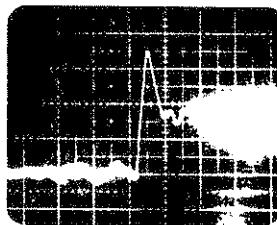
Figs. 4 (a) through (i) show computer-generated curves for the C_H - L_H - R_H hand path in Fig. 1 for a 5kV initiation level and 400 MHz "observation" bandwidth. C_H ranges from 5 to 10 pf, L_H from .05 to .2 μH and R_H from 50 to 400 ohms.

It may not be immediately apparent from Fig. 4 that any one of the hand/forearm discharge waves will combine with the body discharge wave of Fig. 3 to give results comparable with the actual discharges of Fig. 2. Each of the hand/forearm waves of Fig. 4 must first be combined with the body wave of Fig. 3 before reasonable comparisons can be made. It is also helpful to go even one step further, and simulate superimposed arc oscillations. Doing so permits still closer comparisons between computer-generated and actual waves. It also demonstrates that the phasing of arc oscillations can be a major factor in determining the character of the discharge current waveform.

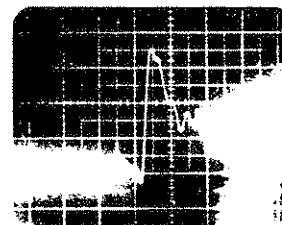
Figs. 5 (a) through (i), therefore, show the combination of the body wave of Fig. 3 with each of the hand/forearm waves of Figs. 4 (a) through (i), respectively. Several of the resulting combination waves resemble the real ones of Fig. 2 closely enough to confirm that the general approach is valid.



(a)



(b)



(c)

Figure 2.
TYPICAL ESD DISCHARGES FROM
HUMAN BODY WITH HAND-HELD KEY
(STEEP EDGES BRIGHTENED FOR READABILITY)
5KV INITIAL CHARGE VOLTAGE
2.5A/HALF CM. 2ns/HALF CM

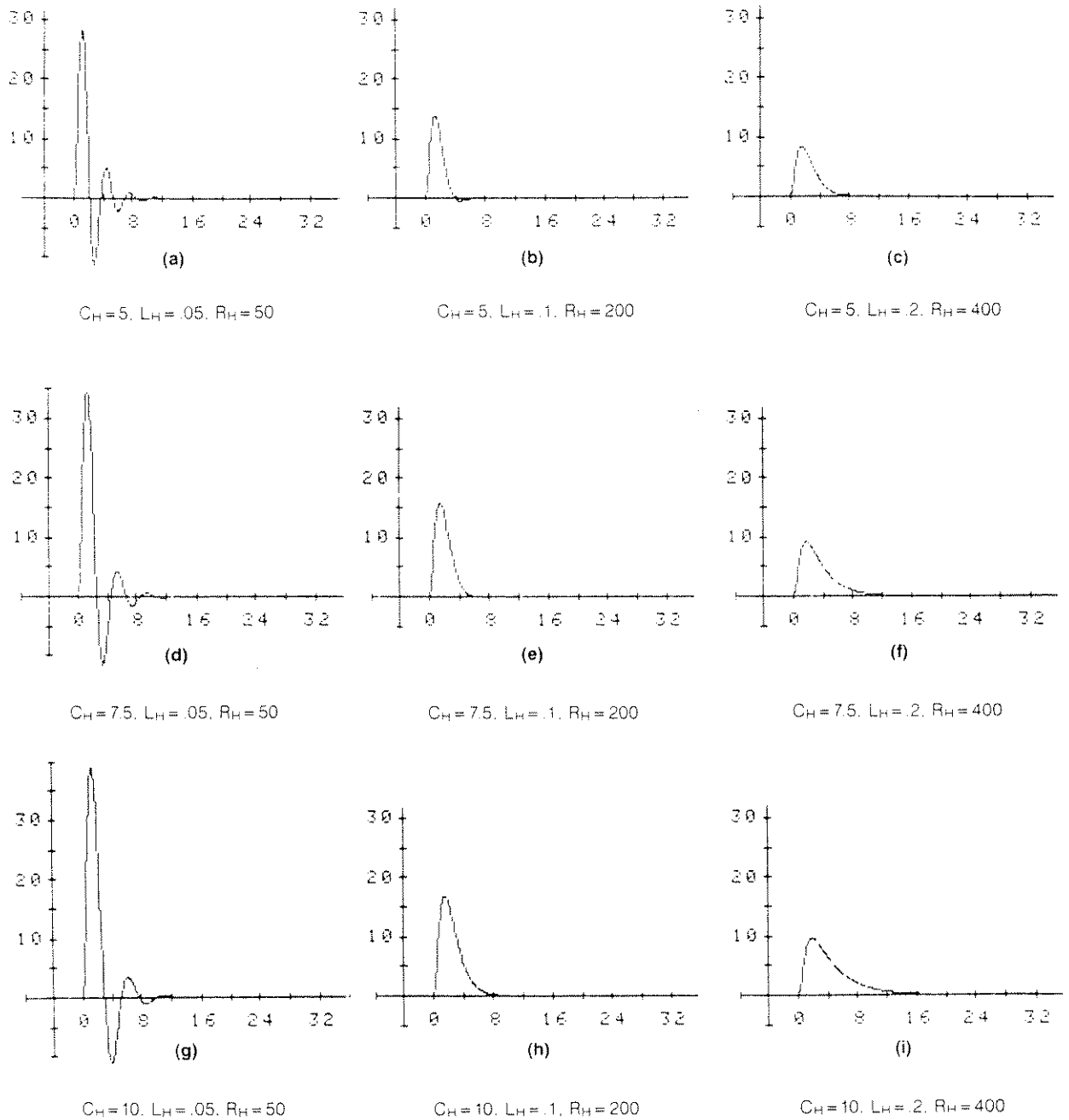


Figure 4.

COMPUTER-GENERATED CURVES FOR VARIOUS
VALUES OF C_H (PFD), L_H (μH) and R_H (OHMS)

RESPONSE DUE TO HAND/FOREARM DISCHARGE ALONE

5kV INITIATION LEVEL
5A/VERTICAL DIVISION, 4ns/HORIZONTAL DIVISION

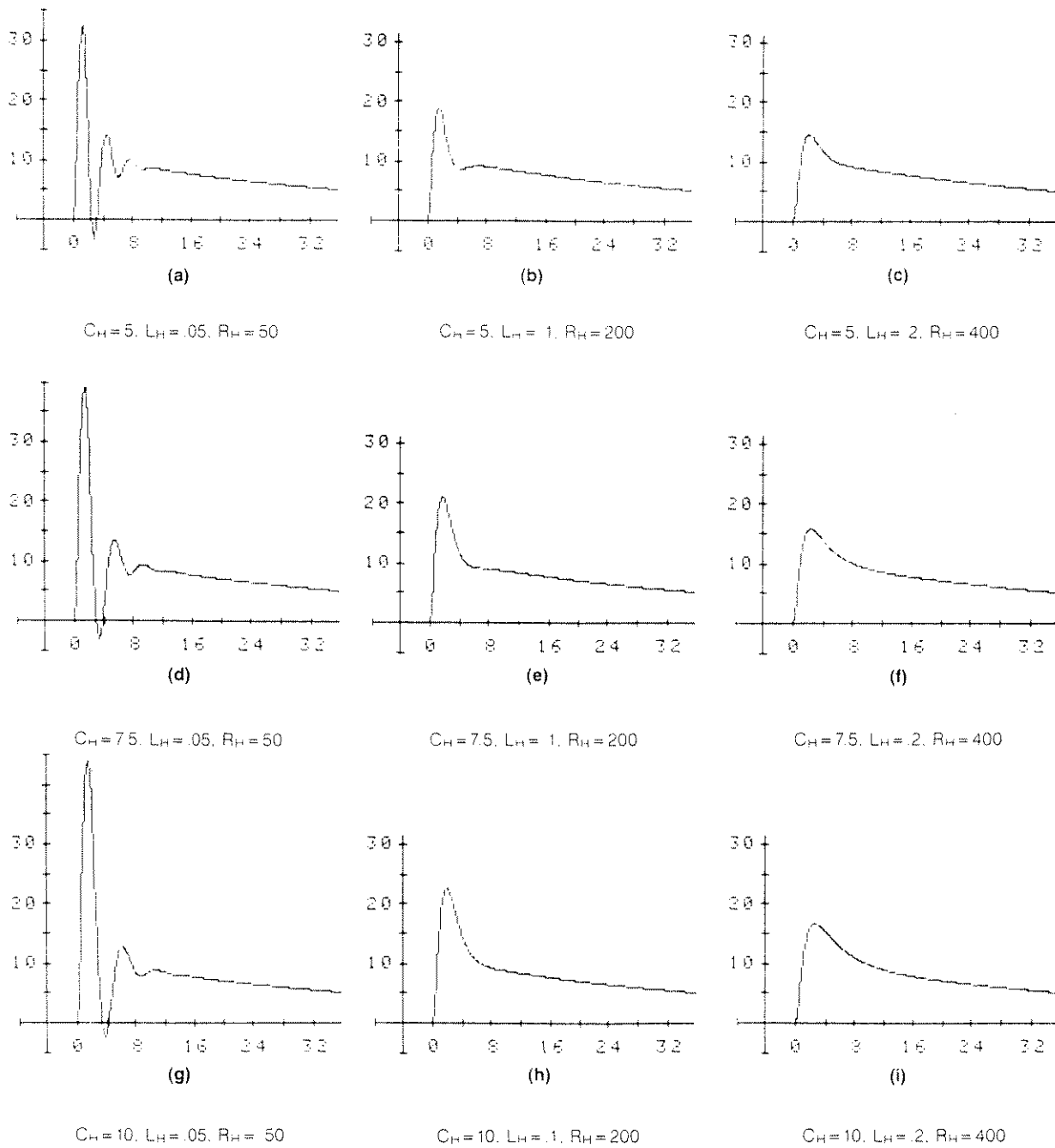


Figure 5.

COMPUTER-GENERATED CURVES FOR VARIOUS
VALUES OF C_H (PFD), L_H (μ H) and R_H (OHMS)

RESPONSE DUE TO DISCHARGE OF THE COMBINATION OF
HAND/FOREARM AND REST OF BODY

$C_B = 100$ PFD, $L_B = 0.7\mu$ H, $R_B = 500$ OHMS

5kV INITIATION LEVEL
5A/VERTICAL DIVISION, 4ns/HORIZONTAL DIVISION

Fig. 6 shows the computer simulation incorporating optimized values for all six circuit components in the Dual R-L-C model of Fig. 1. It is simply a repetition of the combination wave of Fig. 5 (e), with its optimum 7.5 pfd/0.1 μ H/200 ohm values.

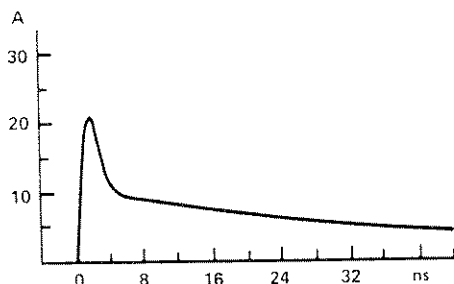


Figure 6.
COMPUTER SIMULATION
FOR COMBINED BODY AND HAND
 $C_B = 100$ PFD $C_H = 7.5$ PFD
 $C_B = 0.7$ μ H $L_H = 0.1$ μ H
 $R_B = 500$ OHMS $R_H = 200$ OHMS
5kV INITIAL CHARGE VOLTAGE
5A/FULL DIVISION, 4ns/FULL DIVISION

Figs. 7 (a) and (b) show the same computer run as Fig. 6, but with computer-simulated arc oscillations superimposed. The two waves differ *only* in regard to phasing of the arc oscillations versus the start of the electrostatic discharge. The wave of Fig. 7 (a) corresponds reasonably well with the actual discharge wave of Fig. 2 (a). The wave of Fig. 7 (b) corresponds with the actual discharge waves of Figs. 2 (b) and 2 (c). Evidently arc oscillation phasing can be a major determinant in perceived wave character. Different phasings can result in a double peak as in Figs. 2 (a) and 7 (a), or a spike as in Figs. 2 (b), 2 (c) and 7 (b).

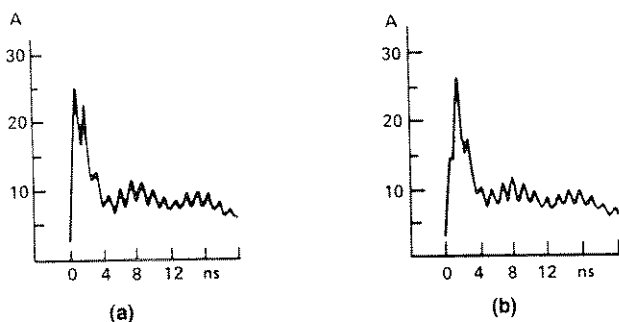


Figure 7.
COMPUTER SIMULATION OF FIGURE 6
WITH SUPERIMPOSED ARC OSCILLATIONS
AT DIFFERENT PHASINGS
5kV INITIAL CHARGE VOLTAGE
5A/FULL CM, 4ns/FULL CM

A SIMULATOR USING THE DUAL R-L-C MODEL

Figs. 8 (a) and (b) show typical outputs from a Dual R-L-C, ESD simulator incorporating the same parameters used in the computer-generated wave of Fig. 6. They also correspond, within the rather wide range of ESD statistical variation, with the human discharges of Figs. 2 (a), (b) and (c); far better than any previous ESD simulation waves.

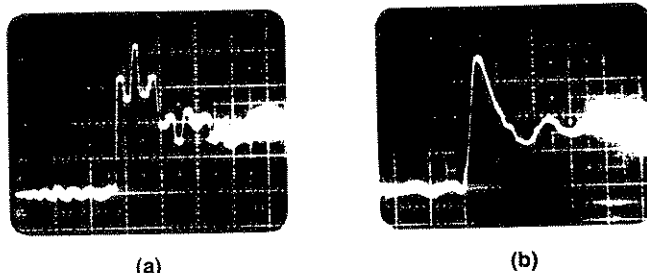


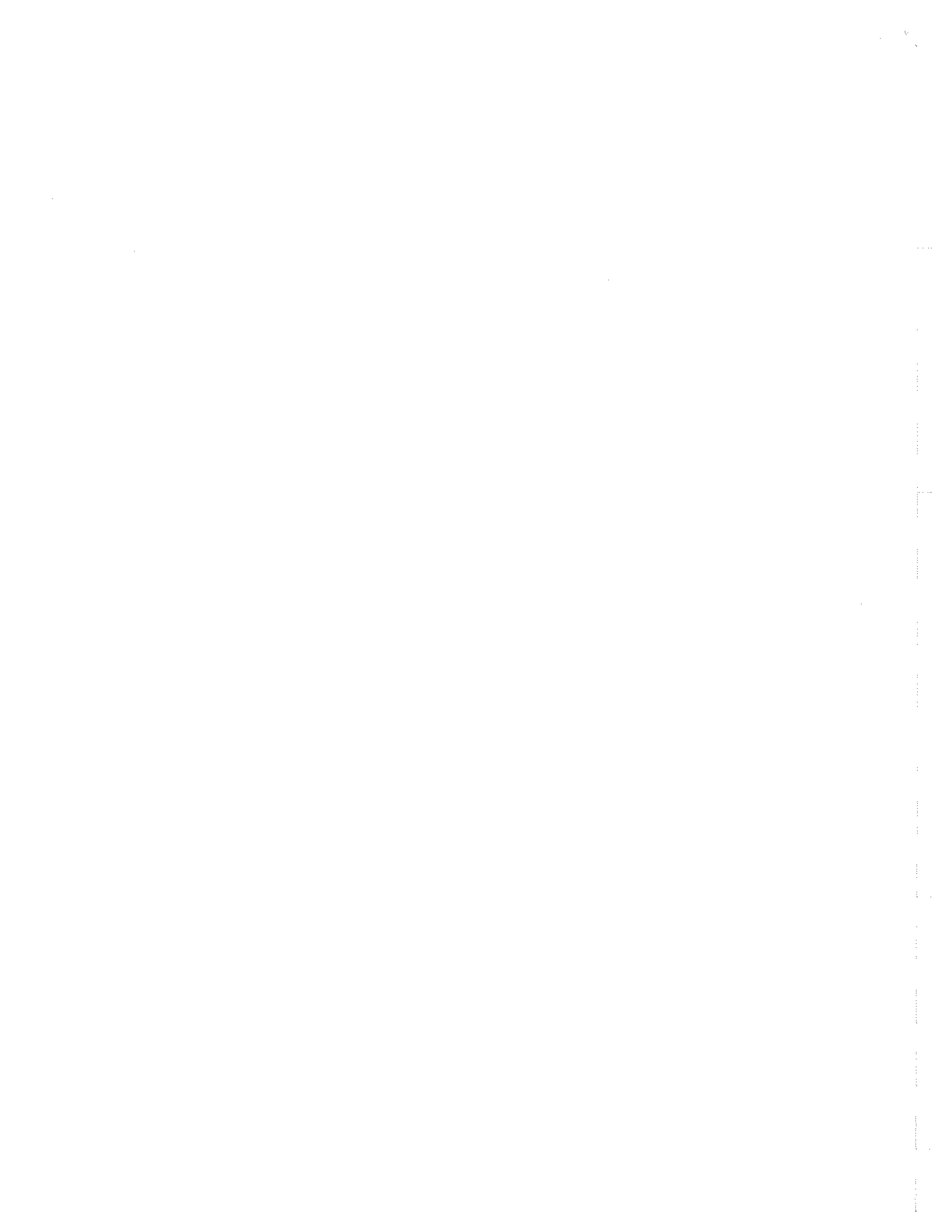
Figure 8.
TYPICAL OUTPUTS FROM AN ESD
SIMULATOR INCORPORATING THE BODY
AND HAND PARAMETERS OF FIGURE 6
 $C_B = 100$ PFD $C_H = 7.5$ PFD
 $L_B = 0.7$ μ H $L_H = 0.1$ μ H
 $R_B = 500$ OHMS $R_H = 200$ OHMS
(STEEP EDGES BRIGHTENED FOR READABILITY)
5kV INITIAL CHARGE VOLTAGE
2.5A/HALF CM, 2ns/HALF CM

CONCLUSIONS

The new Dual R-L-C circuit model for human ESD gives computed results that account for an important, previously unexplained phenomenon: the super-fast initial current discharge spike. This spike is apparently due to capacitance of the hand and forearm to free space. An ESD simulator was built using the new circuit, with optimized circuit values. It gives current discharge waves that agree well with both human discharge, and with the computer solutions designed to model it.

REFERENCES

- [1] Richman, P. and Tasker, A., "ESD Testing: The Interface Between Simulator and Equipment Under Test," *Proceedings of the Sixth EMC Symposium, Zurich, Switzerland, March 5-7, 1985*: "EMC 1985"
- [2] EIA (Electronic Industries Association) "Standards Project PN-1361, Environmental and Safety Considerations for Voice Telephone Terminals," Draft 5, Nov. 24, 1981.





ESD Discharge Waveform Measurement, the First Step in Human ESD Simulation*

A. Tasker

ABSTRACT

Until uncertainties concerning acceptable measurement techniques are resolved, there can't be real agreement on what constitutes the discharge current waveform of an actual human ESD event. The results of examining two different, commercially-available current-viewing resistor assemblies, along with two different commercially-available current transformer assemblies, verify their applicability in ESD waveform measurement.

INTRODUCTION

Recent papers[1,2] have reported striking facts about the human ESD current discharge waveform: less than one nanosecond rise times combined with large (on the order of 100 to 400%) overshoots. This brings to light questions about the measurements, i.e. can some of these phenomena be attributable to the measurement equipment and/or techniques used?[3] In order to resolve this issue, various time domain tests were conducted on the measurement instruments involved. The results of these tests follow.

THE OSCILLOSCOPE

The oscilloscope used was the Tektronix 7834 with EMI option, and a 7A19 vertical plug-in. The 7A19 has a 50 ohm input impedance. The combination yields an advertised bandwidth of 400 MHz (900 ps rise time). Figure 1 shows the oscilloscope response to a one nanosecond rise time pulse from a Tektronix PG502, 50 ohm pulse generator, implicitly terminated by the oscilloscope. It depicts a smooth transition with no tendencies toward underdamped responses (i.e., overshoots).

CURRENT VIEWING ASSEMBLIES

Two different, commercially-available current viewing resistor (CVR) assemblies along with two different commercially-available current transformer (CT) assemblies were examined for time domain response. One CVR was a two-ohm, IEC-specified

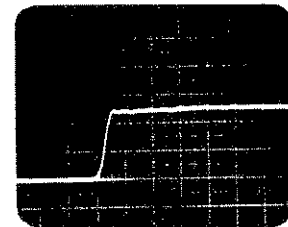


Figure 1.
PULSE GENERATOR OUTPUT
0.5 V/HALF CM, 1 ns/HALF CM

coaxial target designed specifically for ESD measurements.[4] The second CVR was a 100 milliohm unit, Model 5BNC-5-1, available from T & M Research. Its advertised bandwidth is 1200 MHz, with a risetime of 300 ps, and it is constructed very differently from the IEC coaxial target. The current transformers examined were the models CT-1 and CT-2, both manufactured by Tektronix. Advertised bandwidths and risetimes are 1 GHz and 350 ps respectively for the CT-1, and 200 MHz and 500 ps respectively for the CT-2.

The first series of tests used each CVR & CT assembly in turn, to measure the current in the terminating resistor of a coaxial line

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connected to the PG 502 pulse generator. The CVRs were connected as shown in Fig. 2, which specifically depicts use of the coax target.

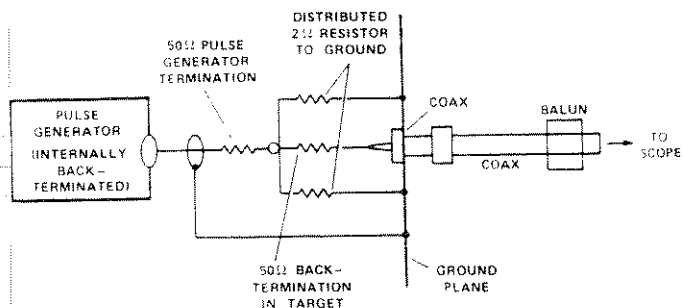


Figure 2.
CONNECTIONS FOR CHECKING THE CURRENT-VIEWING RESISTORS USING THE PULSE GENERATOR (COAXIAL TARGET AS EXAMPLE)

The CTs were connected as shown in Fig. 3. The results of these tests are shown in Figs. 4 (a), (b), (c) and (d).

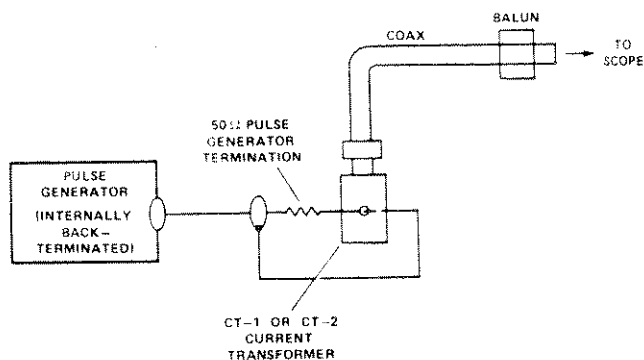
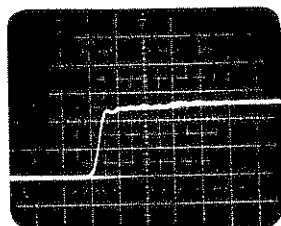
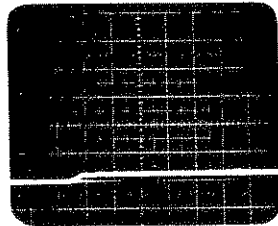


Figure 3.
CONNECTIONS FOR CHECKING THE CURRENT TRANSFORMERS USING THE PULSE GENERATOR

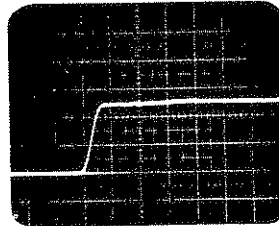
It can be seen that the response of these devices to a sharp rise time pulse is smooth, and that there is a minimum of overshoot present. Displayed rise time is about as fast as the oscilloscope can show, i.e. about 1 ns. There are some anomalies along the



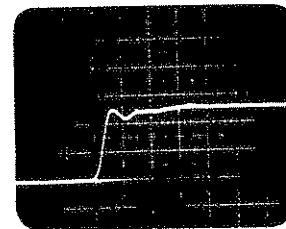
(a) IEC COAXIAL TARGET
10 mA/HALF CM,
1 ns/HALF CM



(b) T & M CVR
100 mA/HALF CM,
1 ns/HALF CM



(c) CT-1 CURRENT TRANSFORMER
10 mA/HALF CM,
1 ns/HALF CM



(d) CT-2 CURRENT TRANSFORMER
10 mA/HALF CM,
1 ns/HALF CM

Figure 4.
PULSE RESPONSES OF THE FOUR CURRENT TRANSDUCERS

tops of the waveforms, presumably due to line reflections, but they are quite small.

Based on the above data it would appear that all four current transformers are suitable for applications with risetimes at least as fast as a nanosecond.

ACTUAL ESD EVENTS

The next series of tests involved the measurement of the discharge current of actual human ESD events, using these same CVRs and CTs. A diagram of the test setup using a CVR is shown in Fig. 5, while that for a CT is shown in Fig. 6.

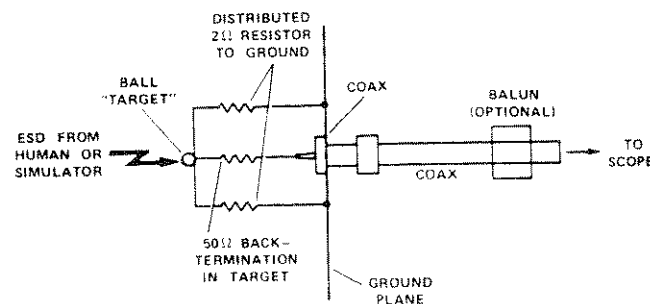


Figure 5.
ESD CURRENT MEASUREMENT USING A CVR

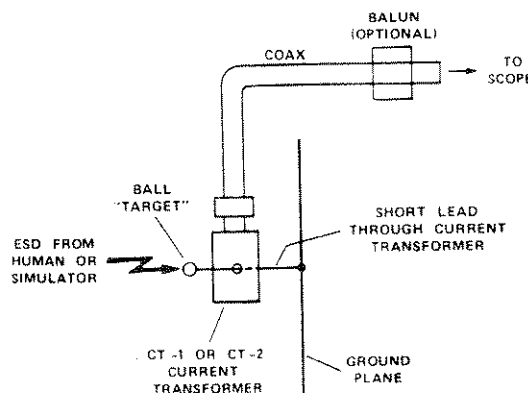


Figure 6.
ESD CURRENT MEASUREMENT USING A CT

All discharges were at the 5 kV stored voltage level, used the oscilloscope referenced above, and involved use of a hand-held

key representing any hand-associated metal object such as a ring, bracelet, tool, or an actual key. Fig. 7 shows typical ESD current waveforms for each of the four current transducers under examination.

Each of these waveforms shows a very fast rise time, in the neighborhood of one nsec. Probably the actual rise time is even faster, but the 0.9 ns oscilloscope rise time is the limiting factor here. Additionally, each shows a current overshoot, or initial spike, in the neighborhood of 20 to 30 A. The spike falls quickly to the 8-10 A level, where apparently exponential decay takes over.

SIMULTANEOUS MEASUREMENTS

Human ESD

In order to further show that a coaxial target and a CT-2 current transformer can correlate, a series target arrangement with dual oscilloscope setup was implemented. In this way, results are obtained which show how each responded to the identical human discharge. A diagram of the test setup is shown in Fig. 8. Discharges were at the 5 kV stored voltage level, used the oscilloscope referenced above, and involved the use of a hand-held key.

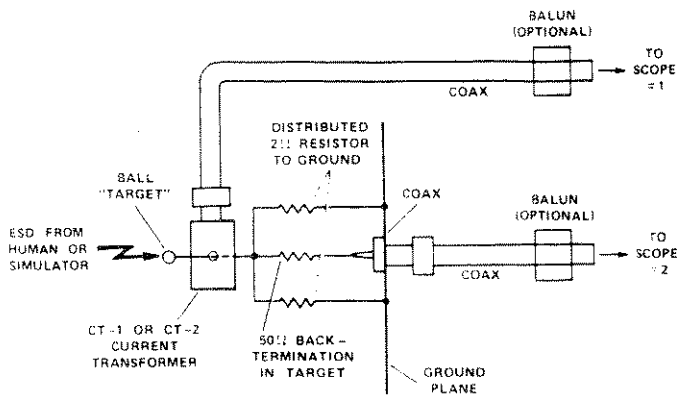
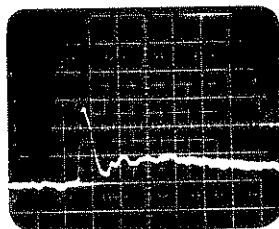
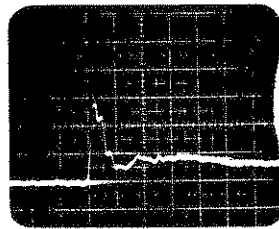


Figure 8.
MEASUREMENTS SIMULTANEOUS ESD
USING A COAXIAL TARGET AND A CT

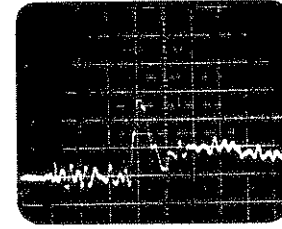
Results are shown in Figs. 9 (a) and (b) for the target and the CT-2 respectively. They show that the two measurement devices correlate remarkably well.



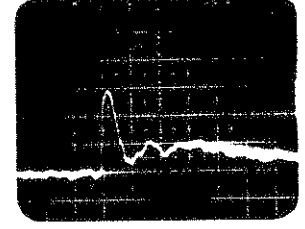
(a) IEC COAXIAL TARGET



(b) T & M CVR (CURRENT VIEWING RESISTOR)

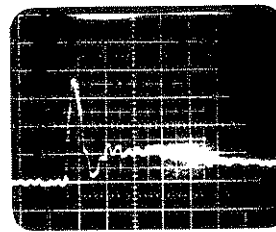


(c) TEKTRONIX CT-1
CURRENT TRANSFORMER

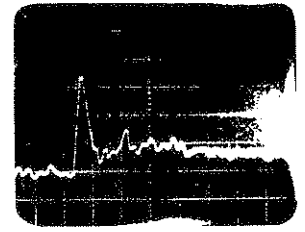


(d) TEKTRONIX CT-2
CURRENT TRANSFORMER

Figure 7.
CURRENT TRANSDUCER OUTPUTS FOR HUMAN ESD
(STEEP EDGES BRIGHTENED FOR READABILITY)
5 kV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM



(a) IEC COAXIAL TARGET



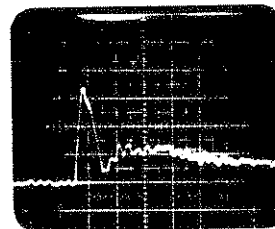
(b) TEKTRONIX CT-2
CURRENT TRANSFORMER

Figure 9.
SIMULTANEOUS HUMAN ESD CURRENT WAVEFORMS
FROM THE IEC COAXIAL TARGET AND THE TEKTRONIX CT-2
(STEEP EDGES BRIGHTENED FOR READABILITY)
5 kV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM

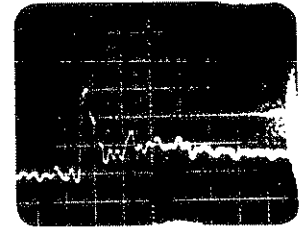
Simulator ESD

In order to further verify correspondence between these two measurement techniques, the coaxial target and the CT-2, an ESD simulator of new design was employed in a similar experiment using identical measuring equipment.

This simulator is based on the Dual-RLC™ circuit described elsewhere. [2] Results are shown in Figs. 10 (a) and 10 (b), again for coax target and CT-2 respectively. They also agree.



(a) IEC COAXIAL TARGET

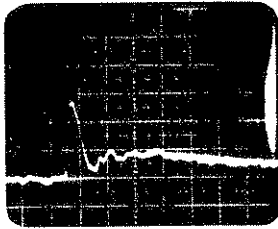


(b) TEKTRONIX CT-2
CURRENT TRANSFORMER

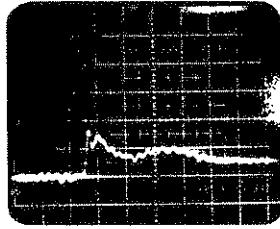
Figure 10.
SIMULTANEOUS TRUE-ESD™ SIMULATOR CURRENT WAVEFORMS
FROM THE IEC COAXIAL TARGET AND THE TEKTRONIX CT-2
(STEEP EDGES BRIGHTENED FOR READABILITY)
5 kV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM

PRECAUTIONS

Several precautions must be taken with any measurement involving fast rise times. First, use of a ground plane is mandatory. Second, impedances must be kept low. Finally, open leads must be kept as short as possible. Fig. 11 (a) shows, for reference purposes, a normal ESD current waveform as viewed on the IEC coaxial target. (It is the same as Fig. 7 (a).) Fig. 11 (b) shows the results of adding just a 15 cm (6") piece of open wire in series with the ESD current discharge path. It can be seen that the small inductance represented by this relatively short wire is enough to vastly change the viewed waveform, and indeed to effectively obliterate the initial spike.



(a) LOW INDUCTANCE.
BASIC IEC DESIGN



(b) MEDIUM INDUCTANCE:
15 CM OR 6" ADDITIONAL
WIRE LENGTH

Figure 11.
COAXIAL TARGET CURRENT WAVEFORMS
FOR HUMAN ESD, WITH (a) LOW
AND (b) MEDIUM INDUCTANCE IN
THE DISCHARGE PATH
(STEEP EDGES BRIGHTENED FOR READABILITY)
5 kV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM

CONCLUSIONS

It has been verified that properly constructed CVR (current viewing resistor) and/or CT (current transformer) assemblies can be used for ESD measurements, in connection with which rise times at least as fast as a nanosecond can be expected.

It can also be concluded that the initial ESD current "spike" or overshoot is very real. It is part of the human ESD current waveform involving a metal object intervening in the discharge path, and properly-designed ESD simulators can replicate it.

REFERENCES

- [1] W.M. King and D. Reynolds, "Personnel Electrostatic Discharge: Impulse Waveforms Resulting from ESD of Humans Directly and Through Small Hand-Held Metallic Objects Intervening in the Discharge Path," Proc. IEEE Int'l Symposium on EMC, Aug. 18-20, 1981, pp. 577-590.
- [2] P. Richman and A. Tasker, "ESD Testing: The Interface Between Simulator and Equipment Under Test," Proceedings of the Sixth EMC Symposium, Zurich, Switzerland, March 5-7, 1985.
- [3] H. Calvin, H. Hyatt, H. Millberg, and D. Pellinen, "Measurement of Fast Transients and Applications to Human ESD," EOS/ESD Symposium Proceedings, 1980, pp. 225-230.
- [4] IEC (International Electrotechnical Commission) Standard, Pub. 801-2, Electrostatic Discharge for Industrial Process Control (was IEC 65 (Secr) 80).



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Computer Modeling the Effects of Oscilloscope Bandwidth on ESD Waveforms, Including Arc Oscillations*

P. Richman

SUMMARY

It has recently been recognized that capacitance of the hand and forearm to free space can cause a potentially damaging, 1 to 4 ns initial spike, with < 1 ns risetime, in ESD current discharge waveforms. ESD simulators can now replicate the spike. Oscilloscopes in general use can often barely recognize this wave characteristic however, due to bandwidth limitations. It is the purpose of this paper quantitatively to predict what will be displayed as a result of this ESD spike input, on oscilloscopes with bandwidths ranging from 60 MHz to 1000 MHz. Also presented are computer printouts including arc oscillations at different phase angles, showing the large influence both the oscillations and their relative phasing have on the character of the ESD wave.

INTRODUCTION

Sharp initial spikes in ESD current waves have been reported for several years.[1,2,3] A recent paper [4] and a related article[5] have introduced the idea that capacitance of the hand and forearm to free space – in effect to the walls of the room – is responsible for the sharp initial spike preceding the principal

body-capacitance discharge in an ESD event. The spike's worst-case manifestation occurs for discharges from a hand with metal object such as a tool, ring, bracelet or key. For this so-called "hand/metal" situation, peak initial spike current for a 5 kV initial charge voltage ranges from 10 to 30A. (The initial spike also occurs for a hand by itself, without a metal object, except at lower current levels.)

Concerns regarding the ability of oscilloscopes in common use to accurately display this initial spike in ESD waves are far from academic. ESD testing of computers and other complex electronic equipment can often give results that are counter-intuitive. For this reason, successful tests with ESD simulators may not insure that equipment will survive a real, personnel discharge. The initial spike may help explain these problems. A credible theory has been presented to account for the spike,[4,5] but the possible limitations of many existing oscilloscopes must be explored if other investigators are to be able to duplicate the reported results. (Measurement techniques for capturing the discharge current waves must also be suited to the purpose.[6])

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HUMAN ESD WITH INTERVENING METAL OBJECTS

Figs. 1 (a) and 1 (b) show two typical discharges from a hand-held key, representative of a metal object such as a ring, bracelet, tool or indeed a key. The two discharge waves appear to have rather different characteristics, although they were made under essentially the same experimental conditions. Both were viewed on an oscilloscope of 400 MHz bandwidth, or 0.9 nsec rise time.

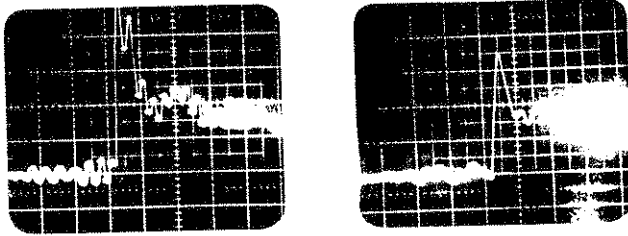


Figure 1.
TWO TYPICAL DISCHARGES FROM A
HAND WITH METAL OBJECT
(STEEP EDGES BRIGHTENED FOR READABILITY)
5 kV INITIAL CHARGE VOLTAGE
2.5 A/HALF CM, 2 ns/HALF CM

Fig. 2 shows the new, Dual-RLCTM human-body ESD equivalent circuit. It has been shown, in Refs. [4], [5] and [7] to be capable of accounting for the initial spike observed in Fig. 1. The spike is superimposed on the far slower, so-called "double-exponential" due to total body capacitance, in an electrostatic discharge current. C_B , R_B and L_B are "whole-body" parameters. C_H , R_H and L_H are parameters due to the hand and forearm. The fact that hand inductance is very low accounts for the fast risetime of the initial spike, while the low value of C_H accounts for the spike's short duration.

Differential equations for the circuit of Fig. 2 were solved by numeric integration on an HP-85 computer, whose printer provided the waveform plots that follow. The actual solutions are smooth curves: granularity in the plots is due to plotter resolution limitations.

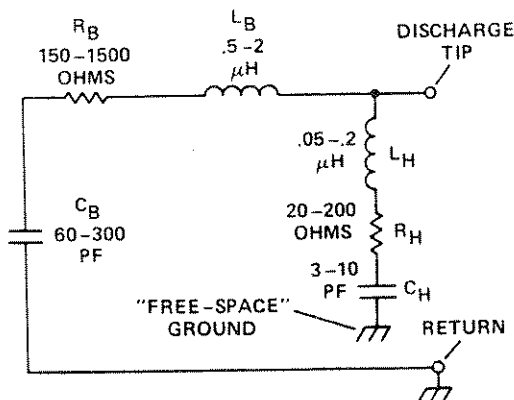


Figure 2.
NEW, DUAL-RLCTM
EQUIVALENT CIRCUIT FOR HUMAN ESD

Values for the simulation parameters in Fig. 3 were optimized for correspondence with actual discharges.[7] They are:

$$\begin{array}{ll} C_B=100 \text{ PFD} & C_H=7.5 \text{ PFD} \\ L_B=.7 \mu\text{H} & L_H=.1 \mu\text{H} \\ R_B=500 \text{ OHMS} & R_H=200 \text{ OHMS} \end{array}$$

Figs. 3 (a) and 3 (b) show computer solutions for the circuit of Fig. 2, including simulation of a single-pole, 400 MHz oscilloscope with 0.9 μs rise time, used to view the response.

Superimposed on the same solutions are simulated arc oscillations, whose principal oscillation frequency is about 1 GHz. The arc oscillations in Fig. 3 (b) differ from those in Fig. 3 (a) only in that they are phase shifted by -144° relative to those in Fig. 3 (a). Thus a relative phase shift in arc oscillations can significantly alter the perceived character of two otherwise identical ESD waves; Fig. 3 (a) is "rectangular," Fig. 3 (b) is a "spike." The waves of Figs. 3 (a) and 3 (b) correspond quite well with those of Figs. 1 (a) and 1 (b), respectively. It consequently appears that some apparent unrepeatability in the air discharge is due simply to phasing of arc discharge oscillations, which themselves only exist on occasion. Their influence on the oscilloscope display is also a function of the scope's EMI sensitivity, and its physical location versus the ESD arc.

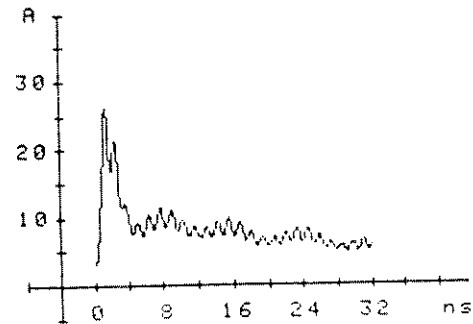


Figure 3 (a).
COMPUTER SOLUTION FOR THE
DUAL-RLCTM EQUIVALENT
CIRCUIT OF FIGURE 2, INCLUDING
SIMULATED ARC OSCILLATIONS
5 kV INITIAL CHARGE VOLTAGE
5 A/DIVISION; 4 ns/DIVISION

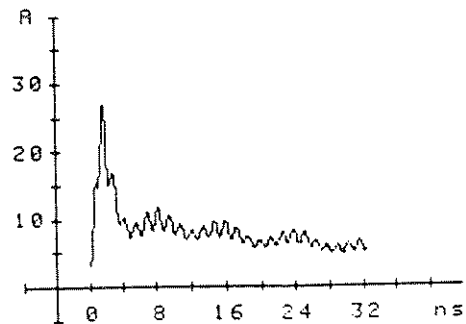


Figure 3 (b).
THE SAME COMPUTER SOLUTION AS
FIGURE 3 (a), EXCEPT WITH SIMULATED ARC
OSCILLATIONS PHASE-SHIFTED
 -144 DEGREES
5 kV INITIAL CHARGE VOLTAGE
5 A/DIVISION; 4 ns/DIVISION

MODELING OSCILLOSCOPE BANDWIDTH

As indicated, the circuit of Fig. 2 was solved on an HP-85 computer using numeric integration. It is assumed that the resulting current wave from the Discharge Tip flows into a zero-impedance return to ground. (The capacitance to free space of the discharge point on the victim equipment has been incorporated into the capacitance, C_H , representing capacitance of the hand and forearm.[4,5]) Oscilloscope bandwidth was then modeled by solving, again by numeric integration, for the result of passing a voltage proportional to this discharge current through a low-pass filter with bandwidth equal to that of the scope being modeled.

Figs. 4 (a) through 4 (f) show computer solutions without arc oscillations for the circuit of Fig. 2. Simulation has been carried out for single-pole oscilloscope bandwidths of 4 GHz, 1 GHz, 400 MHz, 100 MHz, 75 MHz and 60 MHz respectively. The hypothetical 4 GHz represents essentially infinite bandwidth – its equivalent rise time of 0.09 ns is far faster than the discharge current rise time with a value of 0.1 μ H for L_H . It is thus used to represent an "ideal" oscilloscope. 1 GHz corresponds with a Tektronix 7104 with 7A29 vertical amplifier. Rise time is 0.35 ns. 400 MHz represents the fastest storage scope available; its rise time is 0.9 ns (Tektronix 7834 with 7A19 or 7A29 amplifier). 100 MHz and 75 MHz are typical of the "fast" scopes that are widely available, with rise times of 3.5 and 4.7 ns respectively.

Finally, 60 MHz is not unusual for the high end of modest-priced instrumentation; rise time is 5.8 ns.

Even the 400 MHz scope has lost about 10% in peak amplitude. A 100 MHz scope has lost almost 40%, and its display, like those obtained using scopes with 75 and 60 MHz bandwidths, bears little relation to the original. It is no wonder that the initial current spike due to human ESD has received scant attention.

SINGLE VERSUS MULTI-POLE OSCILLOSCOPES

A single-pole representation for oscilloscope bandwidth is necessarily an approximation. It represents the use of a super wide-band vertical amplifier in a modest bandwidth, single-pole mainframe, for example. Thus a vertical amplifier like the Tektronix 600 MHz 7A19 or the 1000 MHz 7A29, used with the 100 MHz 7633 mainframe, will give a good approximation to a single-pole network at 100 MHz, if the 7633 is itself a good approximation to a single-pole network. Using the 1 GHz 7A29 vertical amplifier with the 400 MHz 7834 mainframe will do not quite as good a job of simulating a single-pole situation, since the amplifier-to-mainframe bandwidth ratio is only 2.5:1 instead of 6:1 with the 7A19/7633 combination: again assuming that both the 7633 and 7834 mainframes themselves have single-pole, non-peaking responses.

Computer simulations indicate that the results of using idealized, non-peaking two-pole rolloffs are not significantly differ-

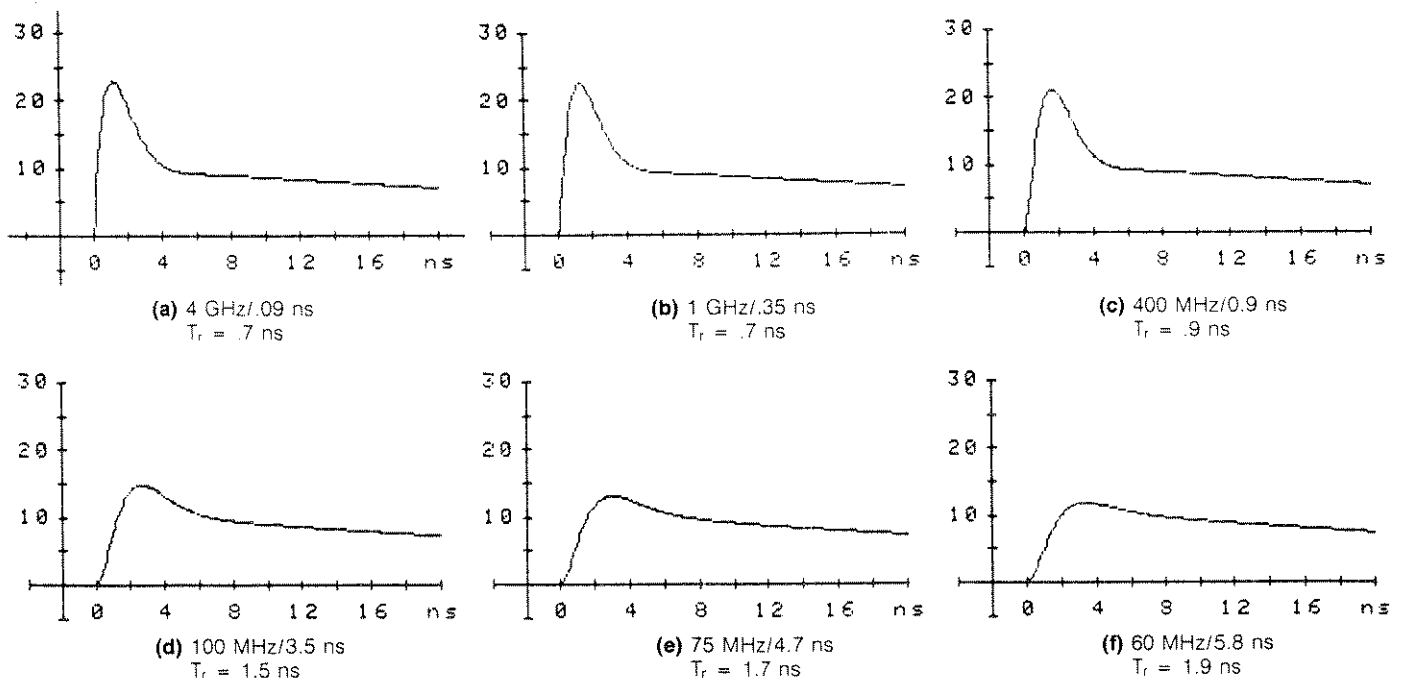


Figure 4.
COMPUTER SOLUTIONS FOR THE DUAL-RLCTM
ESD EQUIVALENT CIRCUIT, WITHOUT ARC OSCILLATIONS, USING
DIFFERENT SINGLE-POLE SIMULATED OSCILLOSCOPE BANDWIDTHS
5 KV INITIAL CHARGE VOLTAGE
5 A/VERTICAL DIVISION; 2 ns/HORIZONTAL DIVISION
NOTE THAT WAVE RISETIME T_r IS FASTER THAN THE OSCILLOSCOPE'S OWN,
FOR OSCILLOSCOPES OF DEFICIENT BANDWIDTH

ent from those obtained with single-pole networks, in peak measurements of ESD waves. In particular, less than 10% peak differences occur for typical ESD waves between idealized single-pole networks on the one hand, and either of the two following alternatives:

1. Two-pole networks with one pole identical in location to that of the single-pole reference network, with the second at a point at least 1.5 times higher in frequency; and
2. Two-pole networks with identical pole locations, when the combination -3db frequency point equals that of the single-pole reference network.

DISPLAYED RISE TIME CAN BE FAR FASTER THAN THAT OF THE OSCILLOSCOPE

The rise time of a pulse as it is displayed on an oscilloscope can be significantly faster – by a factor of 2 to 5 – than the oscilloscope’s own rise time. A 100 MHz scope with a corresponding rise time from 10 to 90% of 3.5 nsec for example, can easily show a pulse rise time of less than a nanosecond. This effect can be used as a diagnostic. It indicates not that the oscilloscope is outperforming its specifications, but that it is too slow to accurately represent fast-rise pulses with the short durations involved.

Computer simulations were used to obtain responses to measuring short, perfect, rectangular pulses on oscilloscopes of different bandwidths. Bandwidths for which solutions were obtained are given in Table 1. For reference, corresponding rise times in nanoseconds are also listed.

Table 1
OSCILLOSCOPES USED FOR THE RECTANGULAR PULSE INVESTIGATION

Bandwidth (MHz)	Nominal Rise Time (nsec)
4000	.09
1000	.35
400	.9
100	3.5
75	4.7
60	5.8

Figs. 5 (a) through (l) show computed responses for three of the bandwidths in Table 1: the hypothetical 4 GHz “reference” bandwidth, as well as the very real 400 MHz and 100 MHz examples. All three bandwidths are assumed to have single-pole frequency rolloffs. Results are given for rectangular pulse durations of 1, 2, 4 and 8 nsec.

The 10-90% rise time T_r associated with each current is given in Fig. 5 as well. One of the more interesting examples is the response of a 100 MHz (3.5 nsec) oscilloscope with 2 ns duration rectangular input pulse, shown in Fig. 5 (f). The displayed rise time will be only about 1.5 nsec. It would most probably give the user the mistaken impression that the oscilloscope is “hot,” i.e. has far greater than its specified 100 MHz bandwidth (or correspondingly, much less than its specified 3.5 ns rise time). Of course, the wave’s significant departure from a rectangular shape should be a tipoff; but only if the input is known a priori to be rectangular! For other input waves, not already known to be rectangular, displayed shapes would provide no such hint, as shown in the next section.

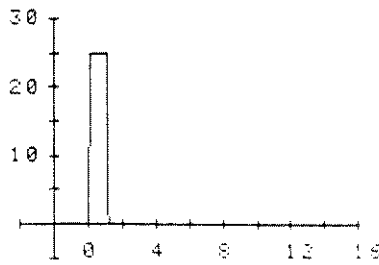
Table 2 summarizes rise time data from Fig. 5. It includes data for oscilloscopes with bandwidths of 1000, 75 and 60 MHz as well as results for the 4 GHz, 400 MHz and 100 MHz oscilloscopes already simulated in Fig. 5. Information is included in Table 2 for rectangular input pulse widths from 1 to 10 nsec in 1 nsec increments. It shows that as oscilloscope bandwidth is reduced, observed rise time increases asymptotically to a figure equal to about 0.8 times the rectangular pulse duration. For measured rise times to reasonably approximate that of the oscilloscope, input pulse duration must be 1.5 to 2 times nominal oscilloscope rise time. (This rule of thumb applies not to displayed pulse duration, but to input pulse duration. They are typically not very different, however, for the examples of Fig. 5.)

DISPLAYED VERSUS ACTUAL WAVEFORMS FOR REAL HUMAN DISCHARGE AND TRUE-ESD™

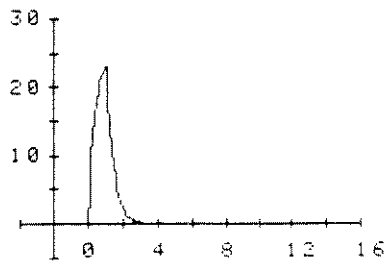
As previously indicated, the current spike from the capacitance of the hand and forearm to free space can be modeled by assuming a 7.5 pfd capacitance, discharging through an induc-

Table 2
APPARENT RISE TIMES, ON OSCILLOSCOPES OF DIFFERENT BANDWIDTHS, AS A FUNCTION OF RECTANGULAR PULSE WIDTH

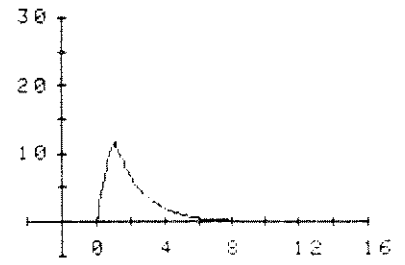
Width of Rectangular Pulse (nsec)	Calculated 10-90% Rise Time in ns for Bandwidth of:					
	4000 MHz ($T_r = .09$ ns)	1000 MHz ($T_r = .35$ ns)	400 MHz ($T_r = .9$ ns)	100 MHz ($T_r = 3.5$ ns)	75 MHz ($T_r = 4.7$ ns)	60 MHz ($T_r = 5.8$ ns)
1	.08	.34	.66	.79	.79	.80
2	.08	.34	.83	1.5	1.6	1.6
3	.08	.34	.85	2.2	2.3	2.3
4	.08	.34	.86	2.6	2.9	3.0
5	.08	.34	.86	3.0	3.4	3.6
6	.08	.34	.86	3.2	3.8	4.1
7	.08	.34	.86	3.3	4.1	4.5
8	.08	.34	.86	3.4	4.3	4.9
9	.08	.34	.86	3.5	4.4	5.1
10	.08	.34	.86	3.5	4.5	5.3



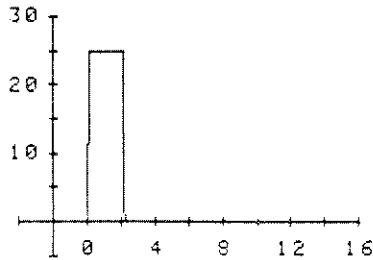
(a) 1 ns PULSE
4 GHz/.09 ns SCOPE
 $T_r = .09$ ns



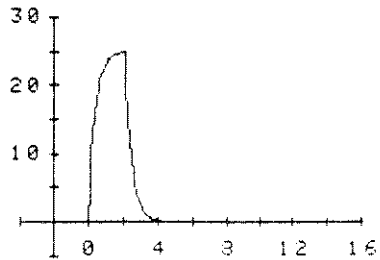
(b) 1 ns PULSE
400 MHz/.9 ns SCOPE
 $T_r = .7$ ns



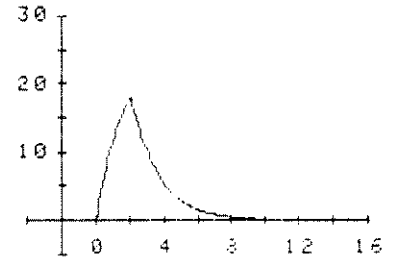
(c) 1 ns PULSE
100 MHz/3.5 ns SCOPE
 $T_r = .8$ ns



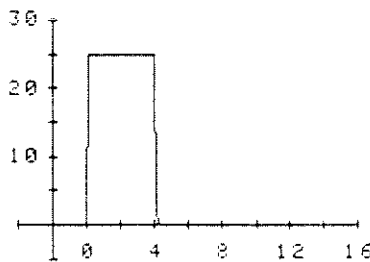
(d) 2 ns PULSE
4 GHz/.09 ns SCOPE
 $T_r = .09$ ns



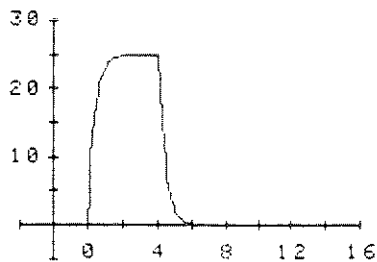
(e) 2 ns PULSE
400 MHz/.9 ns SCOPE
 $T_r = .8$ ns



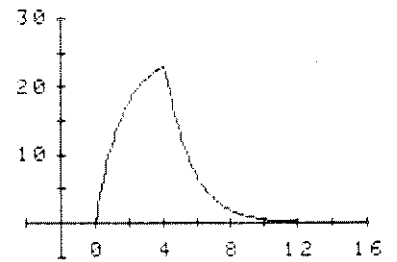
(f) 2 ns PULSE
100 MHz/3.5 ns SCOPE
 $T_r = 1.5$ ns



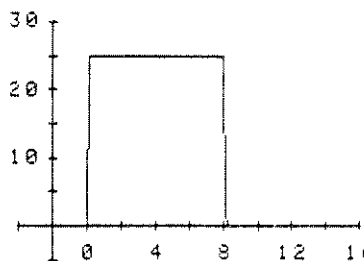
(g) 4 ns PULSE
4 GHz/.09 ns SCOPE
 $T_r = .09$ ns



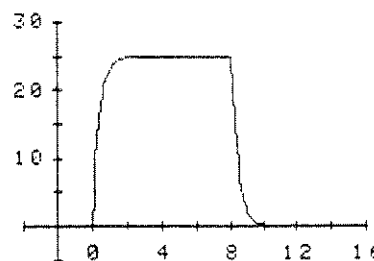
(h) 4 ns PULSE
400 MHz/.9 ns SCOPE
 $T_r = .9$ ns



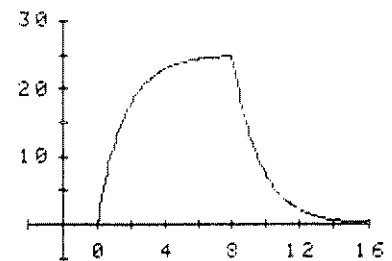
(i) 4 ns PULSE
100 MHz/3.5 ns SCOPE
 $T_r = 2.6$ ns



(j) 8 ns PULSE
4 GHz/.09 ns SCOPE
 $T_r = .09$ ns



(k) 8 ns PULSE
400 MHz/.9 ns SCOPE
 $T_r = .9$ ns



(l) 8 ns PULSE
100 MHz/3.5 ns SCOPE
 $T_r = 3.4$ ns

Figure 5.
COMPUTER SOLUTIONS FOR
OBSERVED RISETIME FOR 1, 2, 4 AND 8 ns RECTANGULAR PULSES
FOR OSCILLOSCOPES WITH SIMULATED BANDWIDTHS OF 4 GHz, 400 MHz and 100 MHz
5 A/VERTICAL DIVISION; 2 ns/HORIZONTAL DIVISION
NOTE THAT WAVE RISETIME IS FASTER THAN THE OSCILLOSCOPE'S OWN,
FOR OSCILLOSCOPES OF DEFICIENT BANDWIDTH

tance of 0.1 μH and a resistance of 200 ohms. The spike generated in this way, along with the main body discharge wave, was shown in Figs. 4 (a) through (f) for oscilloscopes of different bandwidths. Calculated risetimes for these waves, shown in the curves in Fig. 4, are summarized in Table 3.

As shown in Figs. 4 (a) through (f), the super-fast rise times as summarized in Table 3 will be the *only* clues to deficient bandwidths. Unlike the rectangular waves of Fig. 5, the real ESD waves of Fig. 4 don't automatically reveal the character of their source. Put another way, the wave of Fig. 4 (d), for example, could be the actual observed ESD wave, if its rise time weren't less than half that of the oscilloscope on which it is being observed!

Table 3

RISE TIMES OF THE COMPUTED ESD WAVES OF FIGURES 4 (a) THROUGH 4 (f). SHOWING THE EFFECT OF DEFICIENT OSCILLOSCOPE BANDWIDTHS

Fig. 4	Scope Bandwidth (MHz)	Rise Time (nsec)	Rise Time of Displayed Wave (nsec)
(a)	4000	.09	.7
(b)	1000	.35	.7
(c)	400	.9	.9
(d)	100	3.5	1.5
(e)	75	4.7	1.7
(f)	60	5.8	1.9

SIMULTANEOUS DISPLAYS OF THE SAME ESD EVENT ON TWO OSCILLOSCOPES

Comparisons were made between ESD current waves observed on pairs of oscilloscopes of different bandwidths. These comparisons were carried out both for human ESD and for ESD events from a simulator of new design, termed a TRUE-ESD™ simulator.

To simultaneously view the wave from the same discharge on two oscilloscopes, the technique used was the same as that described by Tasker in reference [6]. It employs a slightly modified IEC coaxial target [8] with the discharge to a ball separated from the target plate by the thickness required to interpose a 500 ps rise time Tektronix CT-2 current transformer — about 6 mm or .25 inch. In addition, the target was mounted on an extended ground plane. This test setup is shown in Fig. 6.

Comparisons were made first for some typical discharges from human hands with associated metal objects. These are termed "hand/metal" situations, representing the discharge from a human hand via a ring, bracelet, tool or key. Comparisons were then *also* made for some typical discharges from so-called TRUE-ESD™ simulators, designed in accordance with the Dual-RLC™ equivalent circuit of Fig. 2. (These discharges quite accurately replicate human hand/metal ESD events.)

All of the work was done at about 40% relative humidity, and with medium approach speeds. Different waves can of course result from successive air discharges made under what are seemingly the same conditions. Waves selected for presentation in Fig. 7 do, however, represent the majority of those observed. To allow comparison and to stay below the corona-

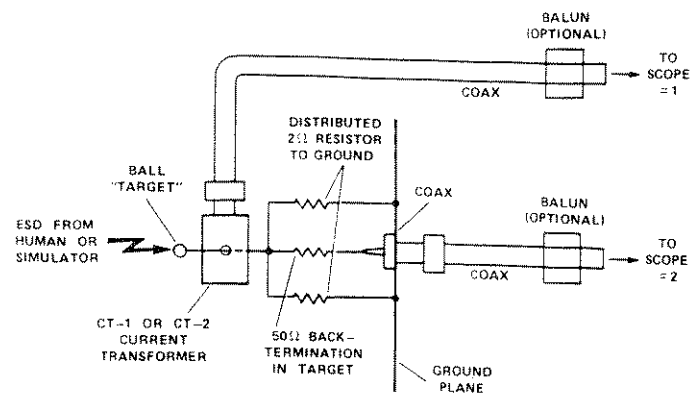


Figure 6.
TEST SETUP FOR MEASURING THE SAME ESD EVENT SIMULTANEOUSLY ON TWO OSCILLOSCOPES (SEE REFERENCE 6)

inception voltage above which rise times become slower, all data were taken for an initial charge voltage of 5 kV, and identical noise-control techniques were used for all experiments, independent of oscilloscope bandwidth.

Differences are displayed for two different oscilloscopes, in two of the three cases with different bandwidths, in the left-hand pairs of waveforms in Fig. 7 for human (hand/metal) discharges (Figs. 7 (a) and (b), (e) and (f), (i) and (j)). Differences are displayed for two different oscilloscopes, again in two of the three cases with different bandwidths, in the right-hand pairs of waveforms in Fig. 7 for discharges from the new, so-called TRUE-ESD™ simulator (Figs. 7 (c) and (d), (g) and (h), (k) and (l)). The TRUE-ESD™ simulator design was based on references 4, 5 and 7.

Figs. 7 (a) and (b) show results of IEC coax target and Tektronix CT-2 outputs for the same ESD event, viewed on oscilloscopes of nominally identical 400 MHz bandwidths, for reference purposes. Both oscilloscopes were Tektronix 7834's with EMI options and 7A19 vertical amplifiers. Data were for the same human (hand/metal) discharge. Figs. 7 (c) and (d) show a similar comparison pair, using the same two oscilloscopes for a discharge from a TRUE-ESD™ simulator. Again, data in Figs. 7 (c) and (d) were for the same discharge.

No significant differences were apparent between the two 400 MHz oscilloscopes in extensive interchange testing. These photographs, as well as all others in Fig. 7, were taken at 5A/small division and 5 nsec/small division.

Fig. 7 (e) and (f) show the difference between displays of the same hand/metal discharge, again viewed *simultaneously* on two different oscilloscopes. Bandwidths for this pair, however, were 400 MHz and 100 MHz for Fig. 7 (e) and Fig. 7 (f) respectively. (The 400 MHz oscilloscope was a Tektronix 7834 with EMI option and 7A19 vertical amplifier. The 100 MHz oscilloscope was a Tektronix 7633 with EMI option and 7A19 vertical amplifier.) Figs. 7 (g) and (h) show an analogous comparison for another ESD event, for a TRUE-ESD™ simulator discharge; 7 (g) is the 400 MHz display and 7 (h) is the 100 MHz oscilloscope display.

Figs. 7 (i) and (j) show a 400 MHz – 75 MHz comparison: the same hand/metal discharge is viewed on the two instruments. The 400 MHz oscilloscope is the same as for previous figures; the 75 MHz oscilloscope is a Tektronix 7633 with EMI option and 7A18N vertical amplifier. Finally, Fig. 7 (k) and 7 (l) show a second 400 MHz –75 MHz comparison; the same TRUE-ESD™

simulator discharge is viewed on the two instruments.

Results for the various oscilloscopes agree quite well with the computer simulations of Fig. 4 (c), (d) and (e). Evidently both 100 MHz and 75 MHz oscilloscopes are untrustworthy for critical ESD work.

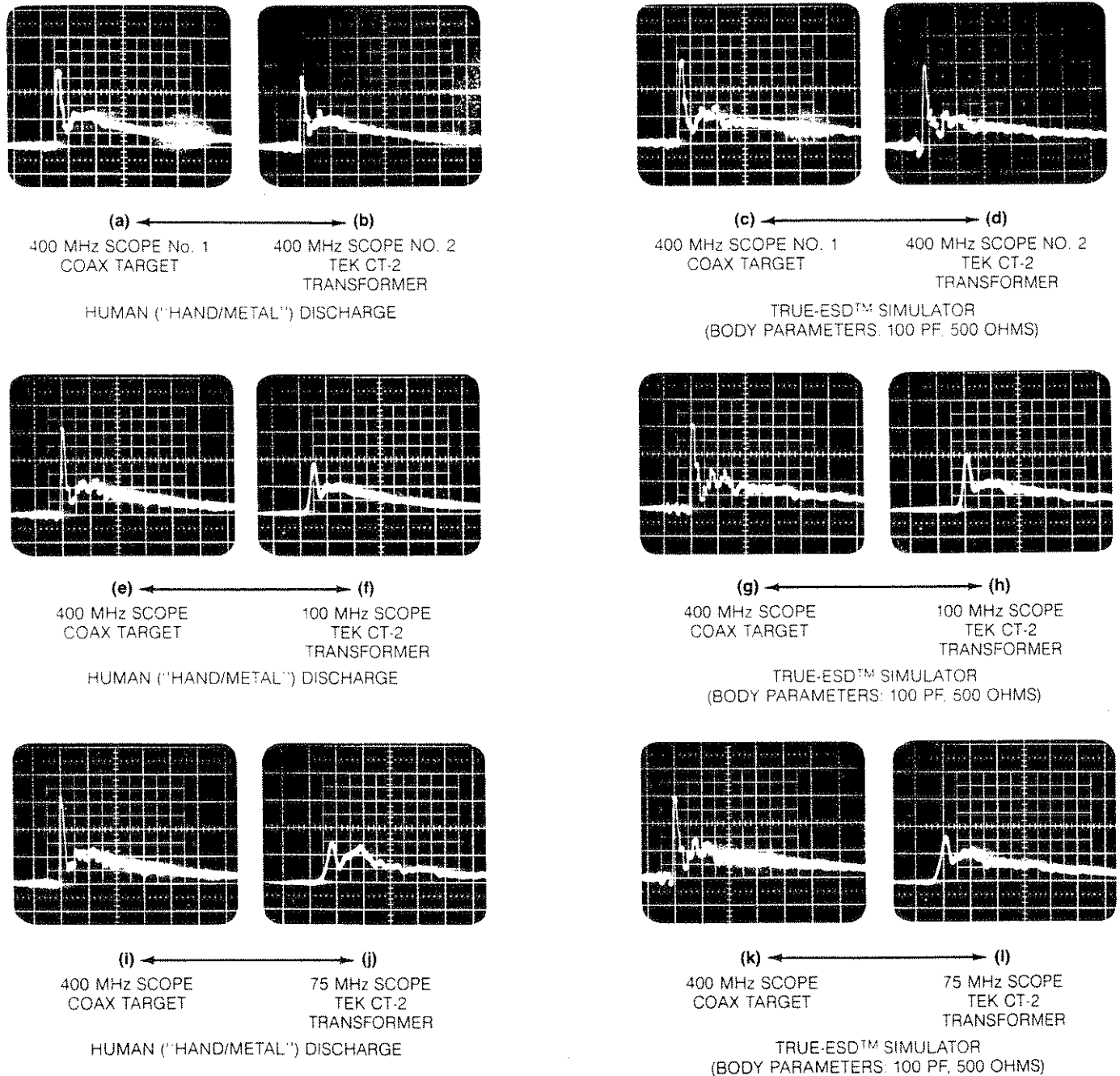


Figure 7.
 CURRENT WAVES DUE TO ESD, VIEWED SIMULTANEOUSLY ON PAIRS OF DIFFERENT OSCILLOSCOPES
 STEEP EDGES BRIGHTENED FOR READABILITY
 5 kV INITIAL CHARGE VOLTAGE
 5 A/HALF CM (SMALL DIVISION) 5 ns/HALF CM (SMALL DIVISION)

CONCLUSIONS

When the rise time of an oscilloscope's vertical amplifier is on the same order as — or longer than — the duration of a pulse to be observed, then the pulse's observed amplitude will be significantly lower than its actual peak value. This effect may well have been responsible for the fact that the sharp initial spike in an ESD discharge has been largely overlooked.[8-12] The current spike's duration is 1 to 4 nsec; the 75 to 100 MHz oscilloscopes in widespread use have rise times of 4.7 to 3.5 nsec. Consequently they only show 50 to 60% of the current spike's actual peak. Data presented elsewhere indicate that the initial ESD current spike can in fact have a rise time at least as fast as 350 ps,[1] and quite possibly faster.

Perhaps even more startling is the fact that the observed rise-time of a pulse whose duration is comparable with or shorter than the oscilloscope rise time, can be significantly — 2 to 5 times — faster than the oscilloscope's own rise time. This counter-intuitive result may be used as a diagnostic. When it occurs, it usually implies not that the oscilloscope out-performs its specifications, but that the displayed rise time is still far lower than the actual one, and that the displayed peak current is probably far lower than the actual value. A faster oscilloscope is, consequently, clearly needed.

In the last analysis, one of the most damaging features of a real ESD event, or the output from a TRUE-ESD™ simulator that replicates it, is probably the rise time, *in amperes per nanosecond*, of the initial spike. This rise time and the number of amperes for which it lasts can be accurately measured only with instrumentation of 400 MHz and higher bandwidth.

REFERENCES

- [1] W. M. King and D. Reynolds, Personnel Electrostatic Discharge: Impulse Waveforms Resulting from ESD of Humans Directly and Through Small Hand-Held Metallic Objects Intervening in the Discharge Path, Proc. IEEE Int'l Symposium on EMC, Aug. 18-20, 1981, pp. 577-590.
- [2] P. Richman, A Realistic ESD Test Program for Electronic Systems, EMC Technology, Vol. 2, No. 3, July-Sept. 1983, pp. 50-56.
- [3] B. Daout and H. Ryser, Fast Discharge Mode in ESD Testing, Proceedings of the Sixth EMC Symposium, Zurich, Switzerland, March 5-7, 1985, pp. 41-46.
- [4] P. Richman and A. Tasker, ESD Testing: The Interface Between Simulator and Equipment Under Test, Proceedings of the Sixth EMC Symposium, Zurich, Switzerland, March 5-7, 1985, pp. 25-30.
- [5] P. Richman, An ESD Circuit Model with Initial Spikes to Duplicate Discharges from Hands with Metal Objects, EMC Technology, Vol. 4, No. 2, Apr-July, 1985, pp. 53-59.
- [6] A. Tasker, ESD Discharge Waveform Measurement, the First Step in Human ESD Simulation, Proc. IEEE Int'l Symposium on EMC, Aug. 20-22, 1985.
- [7] P. Richman, Comparing Computer Models to Measured ESD Events, Proc. of the EOE (Electrical Overstress Exposition), Apr. 9-11, 1985, Boston, MA, pp. 110-114.
- [8] IEC (International Electrotechnical Commission) Standard: Electrostatic Discharge for Industrial Process Control, IEC Pub. 801-2 (formerly IEC 65(Seccr)80).
- [9] MIL STD 883B, Test Methods and Procedures for Micro Electronics.
- [10] NEMA, Residential Controls, Environmental Testing for Electronic Controls, Part DC33, Draft Proposed June 24-25, 1982.
- [11] EIA (Electronic Industries Association) Standards Project PN-1361, Environmental and Safety Considerations for Voice Telephone Terminals, Draft 5, Nov. 24, 1981.
- [12] SAE Standard Recommended Practice Information Report J-1211, June 1978, pp. 20-99.



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Testing Equipment and Circuits for ESD Sensitivity*

M. J. Hopkins

ABSTRACT

With the ever-increasing sensitivity of modern electronic equipment, ESD has become a major concern for every manufacturer of electronic equipment. In order to market an electronic product successfully, a manufacturer must be able to quantify his product's ESD sensitivity, and if necessary take steps to reduce it.

In order to test circuits and equipment for the effects of ESD, it is first necessary to establish standard test waves which accurately duplicate the human ESD event. Next, test methods must be developed to determine whether the circuit or equipment is adequately protected and, if not, to provide the test engineer with diagnostic information to assist him in decreasing its ESD susceptibility.

Although some standards do exist for equipment ESD testing, they appear to be quite different from one another in terms of test criteria. Significant uncertainty and confusion result from the fact that no established ESD test methods exist on an industry-wide basis.

INTRODUCTION

Recent work has resulted in the development of methods for accurately characterizing and measuring the human ESD event.[1,2] Consequently it has become apparent that ESD test methods commonly used in industry today must be re-evaluated in light of the new data. New circuits to accurately model the human ESD event are described, and corresponding test methods are discussed. These include use of improved simulations for the human body in an ESD discharge, electric and magnetic field tests, and ground planes. Emphasis is placed on practical application of the new work to help obtain better correspondence between test results and

real-world ESD exposure. The object is to provide the means for obtaining meaningful and consistent ESD susceptibility tests, leading to more reliable electronic products in the marketplace.

TEST CIRCUITS AND STANDARDS

Measurements

In light of the very fast (less than one nanosecond) risetimes reportedly associated with human ESD, [1,2] and the fact that these are single-shot events, it has proven difficult to establish generally acceptable measurement techniques for ESD from both humans and simulators. However, the Tektronix CT-1 and CT-2 current transformers, as well as a commercial current-viewing resistor and a coaxial resistor target specified by the IEC,[3] were recently evaluated and found to be suitable for observing the current pulse generated by an ESD event.[4]

Typical ESD Standards

A number of industry standards exist that specify simple R-C networks to simulate ESD from a human body. A summary appears in Table 1. Capacitance values range from 60 to 300 pf, and resistances from 150 ohms to 10K.

In addition, many individual manufacturers have established in-house specifications, calling for simple R-C networks to simulate human ESD. Network values again differ widely from one another: capacitance values range from about 100 pf to several hundred pf, and resistances typically from 150 to 1500 ohms.

It is important to note here that circuit inductance L, surprisingly ignored by all these standards, is the dominant factor which limits discharge current rise time, and therefore the high frequency content of the impulse.[1]. At time $t=0$, the

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Table 1

STANDARDS THAT SPECIFY SIMPLE R-C NETWORKS TO SIMULATE ESD FROM A HUMAN BODY

Organization*	Standard Number	Intended Application	C(pf)	R(ohms)
IEC ^[3]	801-2 was 65 (Secr) 80	Process Control	150	150
NEMA ^[5]	Part DC33 (Draft)	Residential Electronic Controls	100	1500
MIL ^[6]	STD 883C	Microelectronic Devices	100	1500
EIA ^[7]	PN 1361 (Draft)	Voice Telephone Terminals	60 100	10000 500
SAE ^[8]	J1211	Vehicle Electronics	300	5000
UL ^[9]	1023	Household Burglar Alarms	250	1500
ECMA ^[10]	TR/23	Computers	150	1000

di/dt is equal to V/L ** and is therefore the same, with given load conditions, for all the simple R-C networks described so far. If the inductance can be reduced, a faster current rise time, more in line with observed human ESD, will result.

The current wave produced by a typical simulator using a so called single R-C network as described above is shown in Fig. 1. The discharge was done from a 5 kV initial charge voltage. It is clear that the wave produced is more complex than the expected double exponential, and that further study is required.

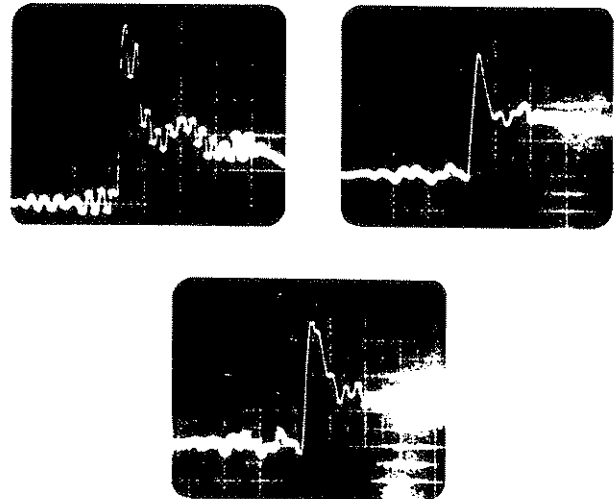


Figure 2.

THREE ESD WAVES FROM A HAND-HELD KEY. ALL WERE AT 5kV AND UNDER "IDENTICAL" CONDITIONS. STEEP EDGES BRIGHTENED FOR READABILITY. 5 kV INITIAL CHARGE VOLTAGE. 2.5 A/HALF CM, 2 ns/HALF CM

voltage was again 5 kV to facilitate comparison with the waves of Fig. 1. It should *also* be noted that discharges in the 3 to 6 kV range, at relative humidities from about 10 to 35%, typically have the sharp initial spikes. At higher voltages corona often eliminates them. This is the reason that low to intermediate voltage ESD can often cause failures when higher voltage ESD may not. In addition, ESD events are inherently statistical. Consequently, steep initial spikes have occasionally been observed at higher voltages, and discharges between 3 and

HUMAN ESD

ESD from a hand with an associated metal object, representing a ring, bracelet, tool or indeed a key, has become a de-facto standard. Three typical ESD current waves from a human holding a key are shown in Fig. 2. The initial charge

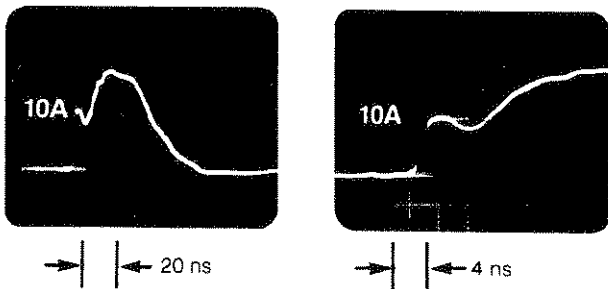


Figure 1.

DISCHARGE FROM A TYPICAL (IEC) ESD SIMULATOR
C=150pf R=150 ohms
5 kV INITIAL CHARGE VOLTAGE
RATE OF RISE ~5A/ns, WITH A VERTICAL TRAVERSE OF ABOUT 10A AT THAT RATE

* IEC = International Electrotechnical Commission, NEMA = National Electrical Manufacturers Association, MIL = Military Standard, EIA = Electronic Industries Association, SAE = Society of Automotive Engineers, UL = Underwriters Laboratories, ECMA = European Computer Manufacturers Association

** di/dt is rate of change of discharge current with respect to time. V is initial or stored voltage; L is total circuit inductance.

6 kV have been observed without the initial spike; however typical 3 to 6 kV discharges are as described above.

The photographs in Fig. 2 are the result of charging a person standing on a rubber mat and then observing the current discharge using an IEC-defined coaxial resistive target.[3,4] It is apparent that the very narrow current spike at the beginning of the wave cannot be attributed to the conventional, single R-C model commonly specified to simulate human ESD (Table 1). Instead, the more complex Dual-RLC™ circuit of Fig. 3 was found to accurately simulate human ESD discharge currents.[1,11]

The Dual-RLC™ circuit is based on the discovery that the real-world discharges of Fig. 2 result from two separate R-L-C circuits. One represents the body (R_B , L_B , C_B in Fig. 3; L_B , C_B in Fig. 4). The other represents the far lower inductance hand and forearm capacitance to free space (R_H , L_H , C_H in Fig. 3; L_H , C_H in Fig. 4). It is the hand/forearm R-L-C path that generates the sharp initial spike that seems to cause such upset and damage due to ESD.

Fig. 5 shows a series of computer simulations of the current wave delivered by the circuit shown in Fig. 3. Comparison of the computer-generated waveforms with the actual human ESD current waves in Fig. 2 show good correlation for body

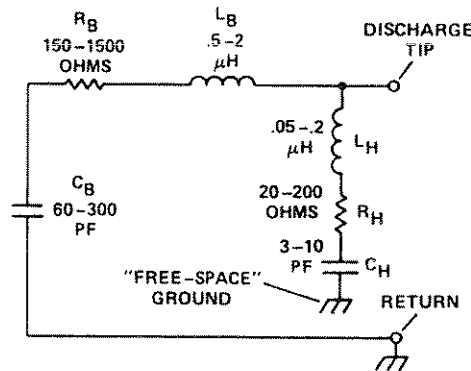
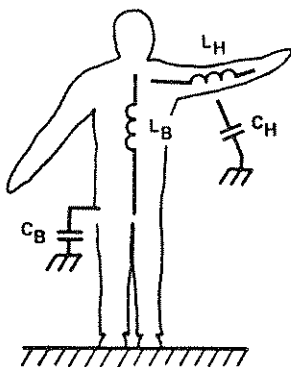


Figure 3.
THE DUAL-RLC™ MODEL FOR ESD PROPERLY SIMULATES THE INITIAL SPIKE



L_H = INDUCTANCE TO REACH HAND / FOREARM CAPACITANCE C_H
 $L_H \sim .1 \mu\text{H}$
 C_H 7.5 TO 15 pf

L_B = INDUCTANCE TO REACH BODY CAPACITANCE C_B
 $L_B \sim .7 \mu\text{H}$
 C_B 50 TO 150 pf

Figure 4.
REAL-WORLD HUMAN-BODY ESD MODEL WITH RESISTANCES OMITTED FOR SIMPLICITY

values of 500 ohms, .7 μH and 100 pf, and hand/forearm values of 200 ohms, .1 μH and 7.5 pf (i.e., the center wave Fig. 5) [11].

Fig. 6 shows the output of a new, so called True-ESD simulator designed using these optimum parameters in the circuit of Fig. 3.[4] Good correlation exists between the actual human ESD event, for which waves are shown in Fig. 2, and the True-ESD™ simulator waves of Fig. 6. In Fig. 6 the same discharge was viewed simultaneously on two, 400 MHz oscilloscopes, using the output from an IEC coaxial target to one and the output from a Tektronix CT-2 current transformer the other. Correspondence between the two measuring techniques was also thereby demonstrated.

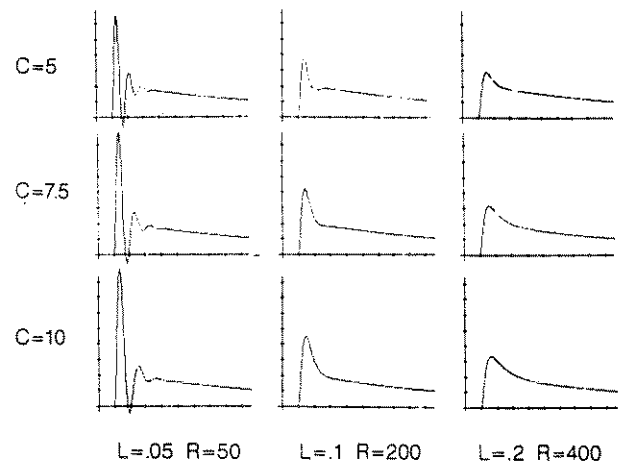
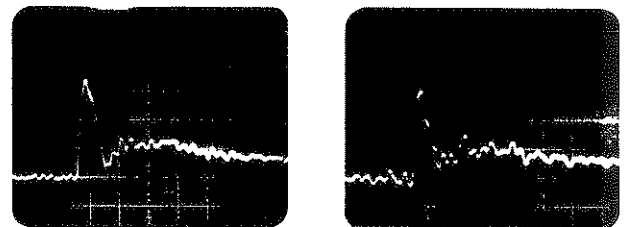


Figure 5.
COMPUTER SIMULATIONS FOR THE DUAL-RLC™ EQUIVALENT ESD CIRCUIT
BODY PARAMETERS: 500 OHMS, .7 μH , 100 PF
HAND/FOREARM PARAMETERS: SHOWN IN FIGURE;
UNITS IN PF, μH , OHMS

Note that oscilloscope bandwidth is a crucial factor in observing the initial discharge spike, and it has often been overlooked in previous work. When using a 100 MHz scope, the measured ESD peak current value is reduced by almost



(a) 400 MHz SCOPE IEC COAXIAL TARGET (b) 400 MHz SCOPE TEKTRONIX CT-2

Figure 6.
SIMULTANEOUS TRUE-ESD™ SIMULATOR CURRENT WAVEFORMS FROM THE IEC COAXIAL TARGET AND THE TEKTRONIX CT-2 CURRENT TRANSFORMER STEEP EDGES BRIGHTENED FOR READABILITY
5 kV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 2 ns/HALF CM



50%. [12] Fig. 7 shows this effect, for a 400 MHz versus a 100 MHz oscilloscope.

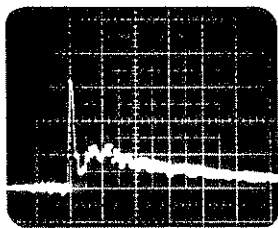
It is important to note the difference between actual human ESD current and that generated by a typical R-C network (whose implicit, often significant circuit inductance makes it, in effect, an R-L-C circuit). First of all, the initial peak current spike, due to the hand/forearm capacitance to free space, can be more than twice the peak current produced by ignoring the hand/forearm capacitance. Second, the rise time of the initial current spike is typically a nanosecond or less, producing energy into the 1GHz region; as opposed to the typical R-C network simulator's risetime of five to ten nanoseconds which results from the inevitable series inductance in any practical ESD discharge circuit.

TEST METHODS

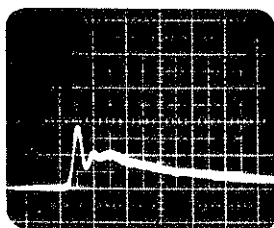
In the process of performing ESD testing, the question of discharge path, determined by *both* the point of discharge on the EUT and the ground return lead from the simulator, is often an issue.

Actual Human ESD Discharge Path

When a human being is charged by the triboelectric (friction) effect, the charge on his/her body is with respect to the surrounding masses — typically the walls, floor and ceiling of the room (Fig. 8). This charge cannot be equalized unless the return path is back to this "free space," or in effect to the average potential of the room (Fig. 9).



(a) 400 MHz SCOPE
IEC COAXIAL TARGET



(b) 100 MHz SCOPE
TEKTRONIX CT-2

Figure 7.

CURRENT WAVES DUE TO ESD, VIEWED SIMULTANEOUSLY ON TWO DIFFERENT OSCILLOSCOPES FOR HUMAN ("HAND/METAL") DISCHARGE
STEEP EDGES BRIGHTENED FOR READABILITY
5 KV INITIAL CHARGE VOLTAGE
5 A/HALF CM, 5 ns/HALF CM

In the case of a person discharging to a telephone, computer or other electronic equipment, the primary high-frequency discharge return path is undoubtedly via capacitance between the person and the surrounding masses, in series with capacitance between the discharge object and the same surrounding masses.

ESD Discharge Path

When using an ESD simulator, the current return path must be back to the low, or ground, side of the simulator. To accom-

plish this, several recommendations have been proposed:

1. Connect the simulator return to the third wire (green ground) on the ac power cord of the EUT (Equipment Under Test).
2. Connect the simulator return to any convenient metal on the EUT.
3. Connect the simulator return to a ground plane (either insulated from or connected to the EUT) below the EUT.

It is clear that none of these actually duplicate the path that exists from actual human ESD. It is also apparent that results obtained using the above methods can differ significantly.

For example, if the simulator return is wired to the third wire ground on the ac power line (alternative 1), the result may be a slow ESD current rise time since the return path has significant inductance. On the other hand, connecting the simulator return to chassis metal (alternative 2) or to a ground plane (alternative 3), can result in a far faster and higher ESD current. This is due to the inherently low inductance of both chassis metal and the ground plane; but it will happen if (and *only* if) the simulator return can be *quite* short.

A True-ESD™ simulator, however, does indeed work on the same basis as real human discharge: the hand/forearm portion of the simulator actually returns it's part of the discharge

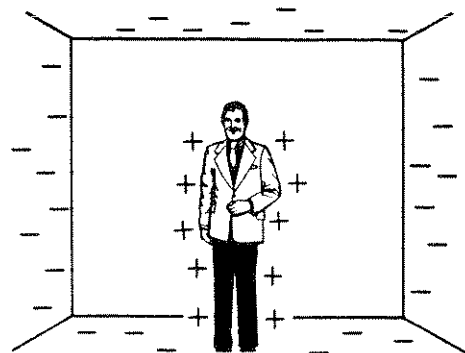


Figure 8.

THE CHARGE ON A HUMAN IS WITH RESPECT TO THE SURROUNDING MASSES

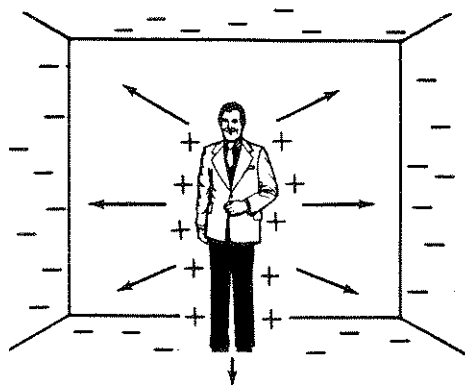


Figure 9.

TO EQUALIZE CHARGE, THE RETURN PATH MUST BE TO THE SURROUNDING MASSES



to free space, producing the high initial current spike previously described.

One thing is certain: correlation with the actual ESD threat is unlikely unless standards for simulation specify realistic test methods that do in fact duplicate real human ESD.

Fields

In addition to the current impulse generated by an ESD event, it is important to consider the effects that fields present both before and during a discharge.

After a person is charged to a significant voltage, a static electric field exists near that person — he or she is at a static voltage different from that of the surrounding masses, including the victim equipment, the walls, etc. As the person moves, so does the field. If the field lines happen to move through a metal object or an electronic circuit, a current can be induced in that object or circuit. In the case of a high-impedance electronic circuit, typical of modern logic forms like CMOS, upset of circuit operation can occur.

In addition, when a discharge occurs from a charged person, two things happen:

1. The electric field collapses rapidly and is radiated (Fig. 10).
2. A magnetic field is produced and is radiated as a result of the current flow (Fig. 11).

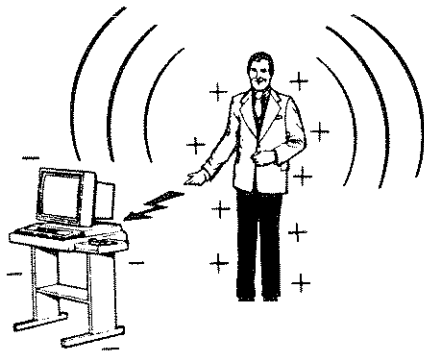


Figure 10.

ESD CAUSES THE E-FIELD SURROUNDING THE BODY TO COLLAPSE RAPIDLY, RADIATING RF



Figure 11.

CURRENT FLOW DURING AN ESD GENERATES A CORRESPONDING MAGNETIC FIELD

The radiated electric and magnetic fields may be sufficient to cause upset in electronic circuits several meters from the point of discharge, *even within a metal box if it has slots or apertures*. There is evidence that these fields contain significant energy to well above 1 GHz.[13] Also, since the discharge current may flow unevenly in a crack or other micro defect in the case or cabinet that houses the victim EUT, fields can be radiated (by such defects) inside a seemingly-shielded metal box.

RECOMMENDATIONS

The simple R-C networks used for ESD simulation by manufacturers today, have been successful in identifying many ESD susceptibility problems. However, major discrepancies between test waves and real-world ESD waves make it only logical that the next step be taken, which is to more accurately simulate the initial current spike typically seen during real human ESD. This implies development of both test circuit and test methods, to duplicate the very low-inductance ground return paths associated with the capacitances of both person and victim equipment to free space.

In addition, specific tests and techniques must be developed and specified to simulate the electric and magnetic field resulting from ESD — particularly those with the wide bandwidths implied by the same low-inductance discharge path that cause the steep-rise current waves.

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REFERENCES

- [1] P. Richman and A. Tasker, ESD Testing: The Interface Between Simulator and Equipment Under Test, Proceedings of the Sixth EMC Symposium, Zurich, Switzerland March 5-7, 1985: "EMC 1985," pp. 25-30. (KeyTel Application Note AN 151)
- [2] W. M. King and D. Reynolds, Personnel Electrostatic Discharge: Impulse Waveforms Resulting from ESD on Humans Directly and Through Small Hand-Held Metallic Objects Intervening in the Discharge Path, Proc IEEE Int'l Symposium on EMC, Aug. 18-20, 1981, pp 577-590.
- [3] IEC (International Electrotechnical Commission) Standard: Electrostatic Discharge for Industrial Process Control, IEC Pub. 801-2 (formerly IEC 65(Secr)80).
- [4] A. Tasker, ESD Discharge Waveform Measurement, the First Step in Human ESD Simulation, Proc. IEEE Int'l Symposium on EMC, Wakefield, MA, Aug. 20-22, 1985 pp. 246-250. (KeyTel Application Note AN 161)
- [5] NEMA, Residential Controls, Environmental Testing for Electronic Controls, Part DC33, Draft Proposed June 24-25, 1982.
- [6] MIL STD 883C, Test Methods and Procedures for Micro Electronics.

- [7] EIA (Electronic Industries Association) Standards Project PN-1361, Environmental and Safety Considerations for Voice Telephone Terminals, Draft 6, 1985.
- [8] SAE Standard Recommended Practice Information Report J-1211, June 1978, p. 20.99.
- [9] Underwriters Laboratories Inc. Standard UL 1023, Household Burglar-Alarm Units, May 13, 1983, p. 33.
- [10] ECMA (European Computer Manufacturers Association), Electrostatic Discharge Susceptibility, TR/23, Sept. 1984.
- [11] P. Richman, Comparing Computer Models to Measured ESD Events, Proc. EOE (Electrical Overstress Exposition), Apr. 9-11, 1985, Boston, MA, pp. 110-114. (KeyTek Application Note AN 153)
- [12] P. Richman, Computer Modeling the Effects of Oscilloscope Bandwidth on ESD Waveforms Including Arc Oscillations, Proc. IEEE Int'l Symposium on EMC, Wakefield, MA, Aug. 20-22, 1985, pp. 238-245. (KeyTek Application Note AN 162)
- [13] M. Honda and Y. Ogura, Electrostatic Spark Discharges: This Nuisance With 3 Faces, Proc. EOS/ESD Symposium, EOS-7, Sept. 10-12, 1985.



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