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CONTROL OF ELECTROSTATIC DAMAGE TO SOLID STATE DEVICES

Technological Spinoff Report

Prepared by:
W. J. Kirk, Jr.,
L. S. Carter, and
M. L. Waddell

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MASTER

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Department 845

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Static voltages generated on human bodies by normal movement of assembly personnel can degrade or destroy many solid state devices not normally expected to be susceptible to damage from such a source. An energy-storage model of the human body was developed and used to determine the levels of static voltage that degrade various devices. A system was assembled and used to continuously monitor and display the level of static voltage on an operator. The additional problem of static voltages created by solvent-spraying was studied and the benefits of varying the solvent volume resistivity were verified.

THE BENDIX CORPORATION

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INTRODUCTION

Static voltages generated on human bodies by normal movement of assembly personnel can degrade or destroy many solid state devices not normally expected to be susceptible to damage from such a source. In addition to metal oxide semiconductors (MOS), which are commonly recognized as being static-sensitive, junction field effect transistors (JFET), some bipolar transistors, diodes, thick film resistors, integrated circuit capacitors, and other small junction area devices can be damaged by relatively low levels of static voltage. Potential for damage from these voltages is especially severe in low relative humidity (RH) environments sometimes required in assembly areas. Discharge of static voltages through sensitive devices during assembly operations can lead to a non-functional assembly fabricated from parts which previously were acceptable or to later failure of an assembly which was functional after fabrication.

Figure 1 shows a 2N3112 JFET that was degraded by a static discharge. The JFET would have functioned in some circuits even though the reverse breakdown voltage was lower than normal. A scanning electron microscope image showed that the silicon melted in a thin eliptical section from localized heating due to gate-source breakdown and solidified in the ridge centrally located within the molten region. Numerous defects of this type have been observed in several different types of devices; however, the damage is not always visible on the surface of the silicon.

HUMAN BODY ENERGY STORAGE MODEL

An energy-storage model of the human body was used to study the effects that static energy discharge from an operator has on semiconductor devices. The human body acts as one plate of a capacitor, C_H, with the other plate being ground. The skin and body resistance, R_H, in series with the body-plate complete the simplified model. Published values of C_H range from 100 to 10,000 pF and R_H from 0 to 18,000 ohms[1-16] and are dependent on the measuring method. The R-C series combination used was shown to be a valid approximation of the human body static discharge model.

A person was connected to the circuit shown in Figure 2 by a 40-cm^2 surface area wrist strap and charged with a dc voltage (200 to 2,000 volts). The voltage was then discharged into a 1-kΩ resistor. The discharge current waveform was used to obtain the peak current (I_p) and discharge time constant (TC). I_p was compared to the peak current (I_{1K}) obtained using a human body model of R_H = 0, C_H = 270 pF. The calculated resistance of 87-190Ω and capacitance of 132-190 pF were similar to reported values obtained under body-discharge test conditions.[8,15]

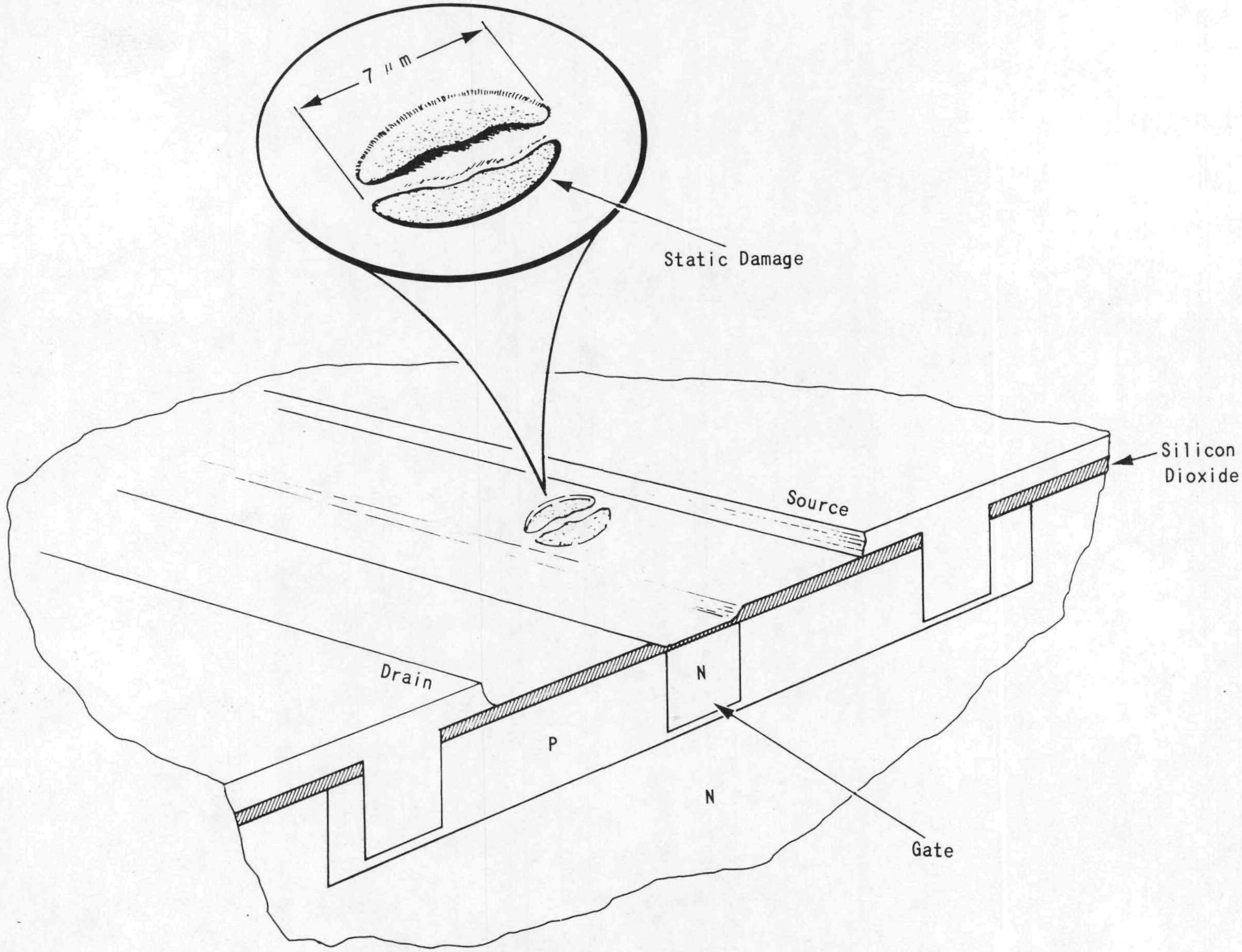

Figure 1. Degraded 2N3112 JFET

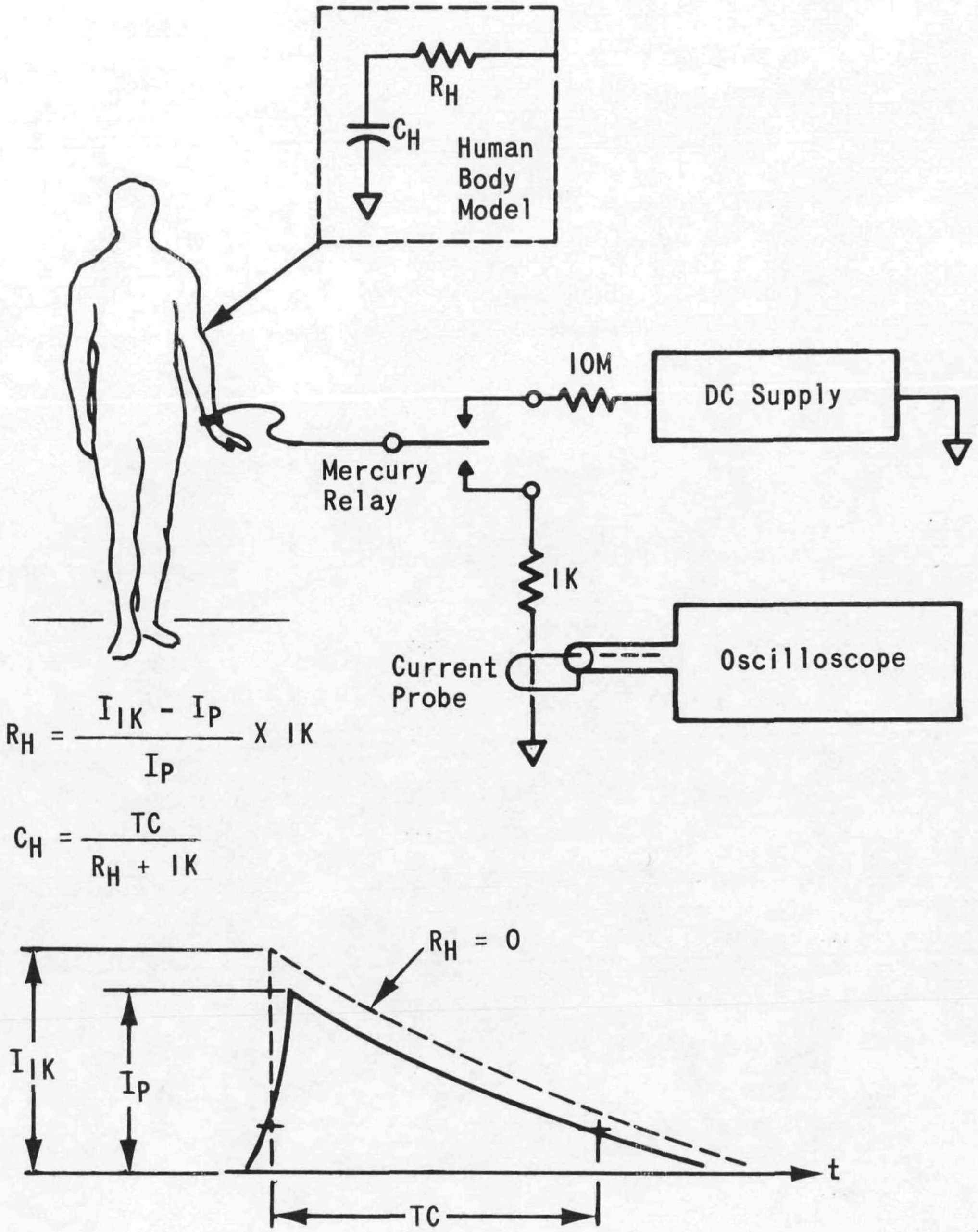

Figure 2. R_H and C_H Measurement Method

Slightly conservative but realistic values of 100Ω resistance and 218 pF capacitance were used to simulate energy storage in the human body under typical manufacturing conditions.

DAMAGE TO DEVICES

A static-sensitive JFET, the 2N4118A, was used to determine the effects of selected variables on the degradation of the device caused by static voltage discharge. In each test, a capacitor was charged to a known voltage and then discharged through the gate-source junction of the JFET as shown in Figure 3. A change in the reverse breakdown voltage of the junction at 5 μA junction current provided a sensitive indicator of degradation. The following results were noted.

- Energy discharge with a reverse breakdown polarity on the gate-source junction caused failure at a lower voltage (100 to 380 V) than with forward conduction polarity (600 to 765 V).

- Similar degradation voltages were obtained for three test conditions shown in Table 1: a model of the human body charged with a dc power source, a human body charged with static voltage by movement, and a human body charged with a dc power source. This similarity of results verified the electrical model's validity.

- The capacitance value (energy level) had some effect on the voltage required for degradation of JFET's. (Complementary MOS devices with diode protection were also energy sensitive. Unprotected MOSFET's were voltage sensitive rather than energy sensitive.)

- Repeated pulses below the degradation voltage did not statistically lower the degradation voltage magnitude, indicating that progressive degradation from repeated pulses did not occur.

- Approximately 50 percent of the 2N4118A's exhibited a decrease in breakdown voltage (leakage current) with no significant change in transconductance or pinch-off voltage. This 50 percent of the sample would have performed normally (for a time) in many circuit applications. However, the effects observed in Figure 1 are similar to the melt transition caused by second breakdown of a P-N junction.[2,3] Increased current density in the melt region may result in a reduced power dissipation capability and operating life.

The value of the resistance in series with the FET gate has a current limiting influence on the degradation voltage of JFET's

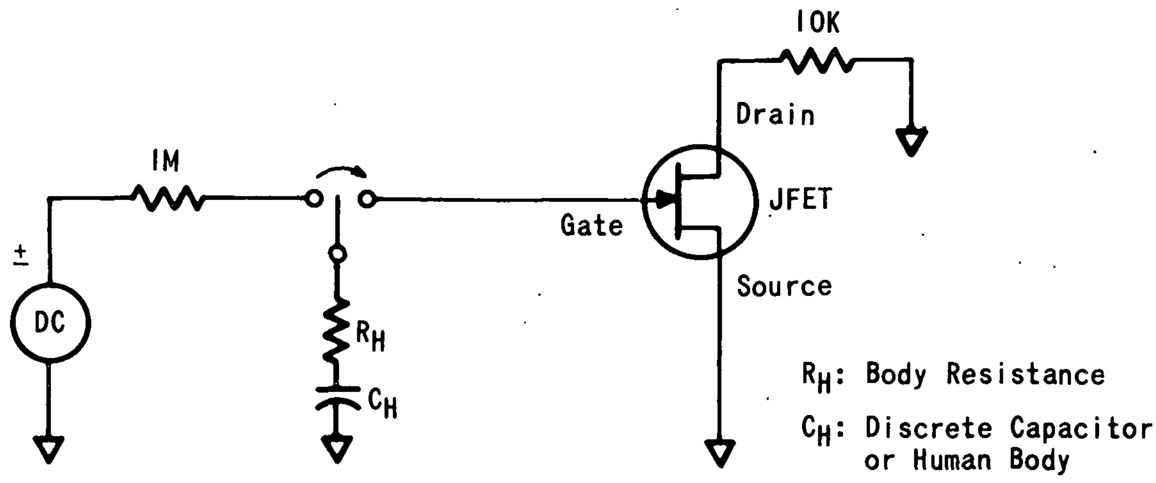

Figure 3. Static Discharge Test Circuit

Table 1. 2N4118A JFET Static Degradation

Test Voltage	Electrical Model (Figure 2) $R_H (\Omega)$ $C_H (pF)$	0 97	0 218	0 425	100 218	Charged Operator 154
70						
85						
100				C		
120						
140			CCD	C		DDC*
160		D		C		CD*
190				D	D	
230					CCCD	C
270		D	CC		CDDD	
320		D			CCDD	
380					CC	D*

Each letter represents a failure for a JFET gate that received one discharge pulse at each test voltage in increasing sequence until failure occurred.

D: DEGRADED (50 percent decrease in 5 μA gate-source reverse breakdown voltage, $V_{(BR)GSS}$).

C: CATASTROPHIC ($V_{(BR)GSS} < 3V$).

*: Charge obtained by operator movement.

and CMOS integrated circuits. Normal body resistance does not provide sufficiently high isolation to protect JFET's. Series resistances well above 1 MΩ are required to protect the 2N4118A JFET from static voltages (up to 4kV) normally encountered in a production environment.

The static voltage degradation thresholds of a limited number of bipolar transistors, diodes, and FET's are shown in Table 2. Each device received one 70 volt* discharge pulse from the human body equivalent circuit (Figure 3). If the reverse breakdown voltage was unchanged, the pulse voltage was increased in 20 percent steps and the test repeated (up to 3000 V). Although the FET devices were most sensitive, diodes and bipolar transistors were also degraded by static voltage discharge. Until a model for predicting the threshold for degradation by static discharge is available, all FET's and other small junction semiconductors should be tested with the circuit given in Figure 3 to determine the protection level required.

DETECTION SYSTEM

Electrostatic voltages on operating personnel were measured and recorded using the method shown in Figure 4. Response time of the detection system was 12 μs. A critical feature shown is maintenance of the capacitively coupled probe at a fixed calibrated distance from the conductive disc connected to an operator.[19] A typical insulated operator voltage waveform when gliding in a chair or walking on a conductive floor is shown in Figure 5. This operator, who generated 700 V, has the potential for degrading small junction area semiconductors during normal manufacturing activities. Portable static meters[20] and electrostatic voltmeters provided an indication of dc static voltages, but could not detect the transients observed in Figure 5.

VOLTAGES GENERATED BY OPERATORS

The peak static voltages generated by an operator during a variety of work motions were monitored for several facility variables. The voltages obtained from significant operator-facility combinations are shown in Figure 6. Several important conclusions resulted from this study.

- Unless otherwise indicated in Figure 6, the peak voltages occurred when an operator lifted her feet from a ground plane

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*The initial voltage for MOSFET's was 16 V.

Text continued on page 16.

Table 2. Static Voltage Degradation Threshold of Selected Semiconductors

Device	Static Voltage Degradation Threshold* (Volts)	Degradation Criteria
Diodes:		
1N459	**	50% drop in V_R, I_R = 5 μA
1N916	3000	
TI551	450	
1N4151	**	
Zener Diodes:		
LVA356	**	50% drop in V_R, I_R = 5 μA
Transistors:		
2N2432A	620	50% drop in BV_{CBO}, I_B = 5 μA
2N3117	1000	
2N2222	1200	
JFET's:		
2N2608	320	50% drop in $V_{(BR)GSS}$, I_G = 5 μA
2N3112	530	
2N3971	160	
2N4118A	140	
MOSFETs: GI MEM 520c (chip)	58	I_G>5 μA at V_{GS} = 22 V
CMOS Integrated Circuits: RCA CD4001	250	***

*Reverse breakdown polarity.
**No degradation occurred up to 3000 V.
***Input: >0.5 μA at 10 V.
Output: >10 percent decrease in output voltage across 100 kΩ load.

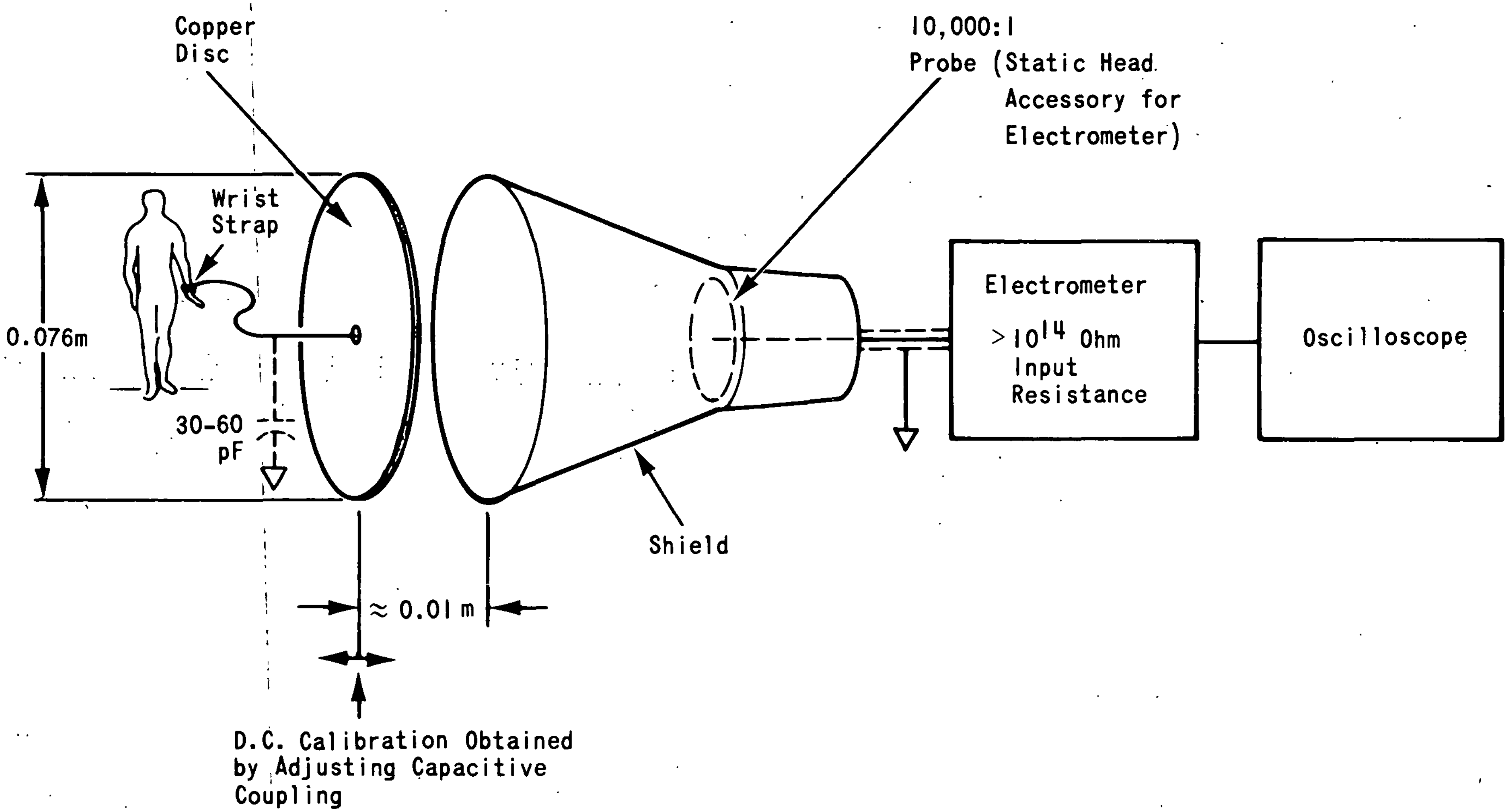
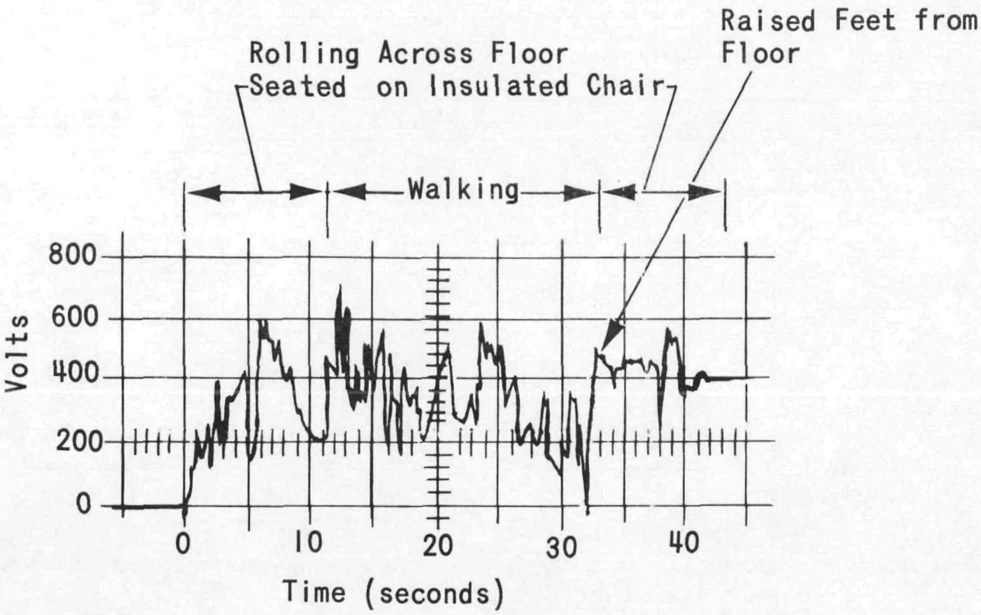
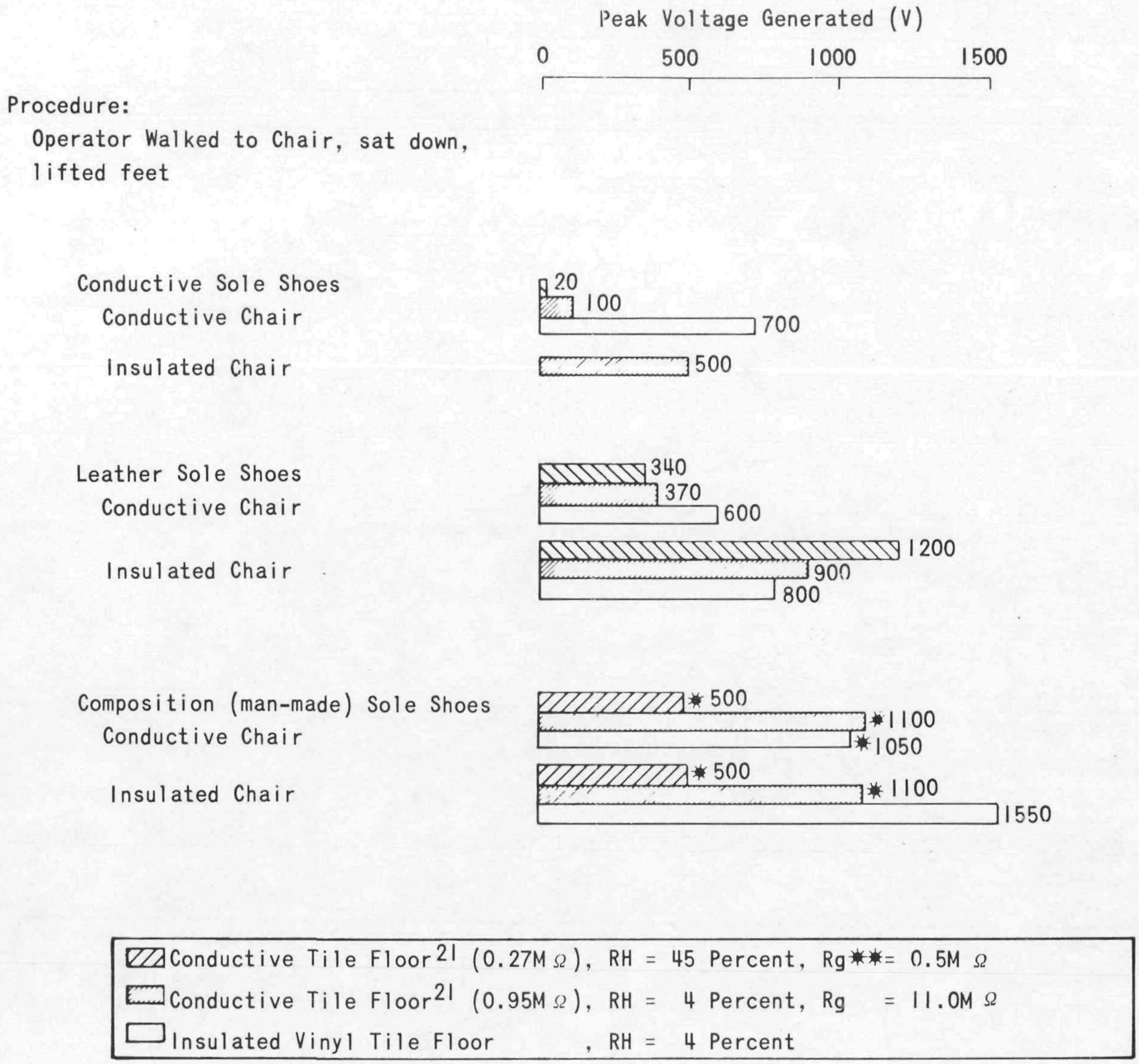


Figure 4. Static Voltage Monitoring Setup



Floor: Conductive Vinyl Tile[21] (R = 0.95M Ω)
Shoes: Composition Sole Street Shoes
Chair: Insulated with Rubber Rollers
Humidity: 4 Percent RH

Figure 5. Monitored Variations of Voltage Level on an Operator



*Peak obtained when walking.

**Rg is resistance from operator through conductive shoes and floor to ground with 1 μA measuring current.

Figure 6. Operator Voltage Versus Facility Variables

(conductive or reinforced concrete floor). These occur when an operator rocks back on her heels, sits in a chair and lifts both feet at once prior to putting them on a foot rest, or pushes to glide the rollered chair to another location. This is a classical demonstration of the increase of triboelectric voltage due to capacitance reduction.

- Conductive-sole shoes (or conductive shoe covers) used on a conductive floor[21] limit static voltage generation to 50 V when an operator's shoes remain on a conductive surface.

- In a 4-percent RH atmosphere, the conductive seat on a conductive chair does not provide adequate contact through an operator's clothing to her skin to prevent static accumulation. A typical resistance through the operator's street clothing was 10 GΩ. To maintain a low-resistance path to ground, conductive shoes must contact a grounded foot rest or floor at all times.

- Conductive shoes on an insulated floor or street shoes (insulated) on a conductive floor do not provide static protection.

The time required for static voltage on an operator to discharge is also important. The voltage discharges shown in Figure 7 were obtained on an operator charged to 500 volts. Conductive shoes on a conductive floor provided a discharge time of less than one millisecond, providing a good statistical probability that those voltages generated will be dissipated prior to contact with a static-sensitive device. Leather street shoes on a conductive floor provided a variable discharge rate and should not be relied on to provide adequate protection; all other combinations shown did not provide adequate discharge rates.

Although increased humidity reduced the discharge time for composition-sole street shoes on a conductive floor, relative humidity much higher than 45 percent would be required to provide adequate protection. Damage in a moderately humid atmosphere is less likely to occur, but JFET's have been easily damaged in a 35-percent-RH environment when an operator wearing street shoes lifted one of her feet off a conductive floor and touched the gate of a 2N4118A JFET when the drain (or source) was grounded.

The shunt resistance from an operator to ground affects the peak voltage obtained as shown in Figure 8. Any combination of conductive devices (shoes, floors, chairs, wriststraps, etc.) that *always* ensure less than 10 MΩ resistance from body to ground will provide good static protection for MOSFET's for the shoe and floor materials tested. Less than 100 MΩ will be adequate to protect JFET's. Other material combinations (such as rubber-soled shoes or waxed floors) may produce higher peak voltages.

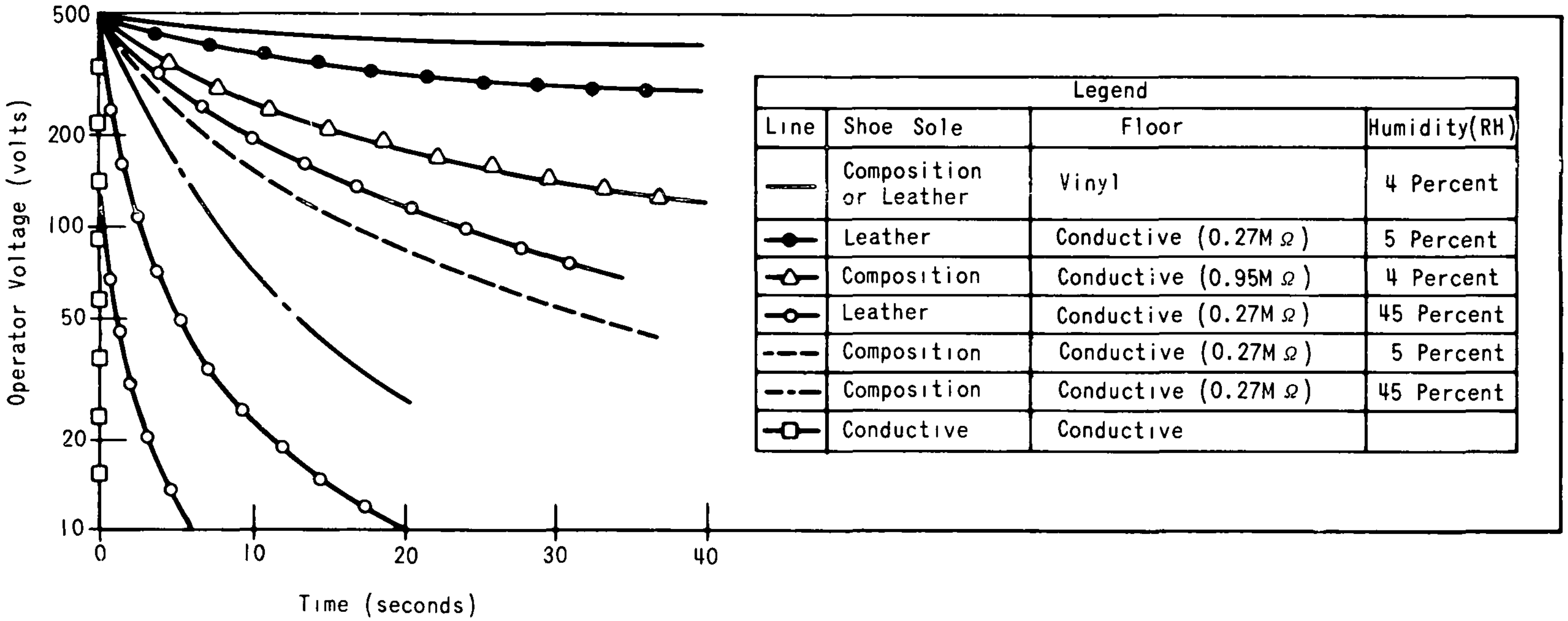


Figure 7. Voltage Discharge for Standing Operator

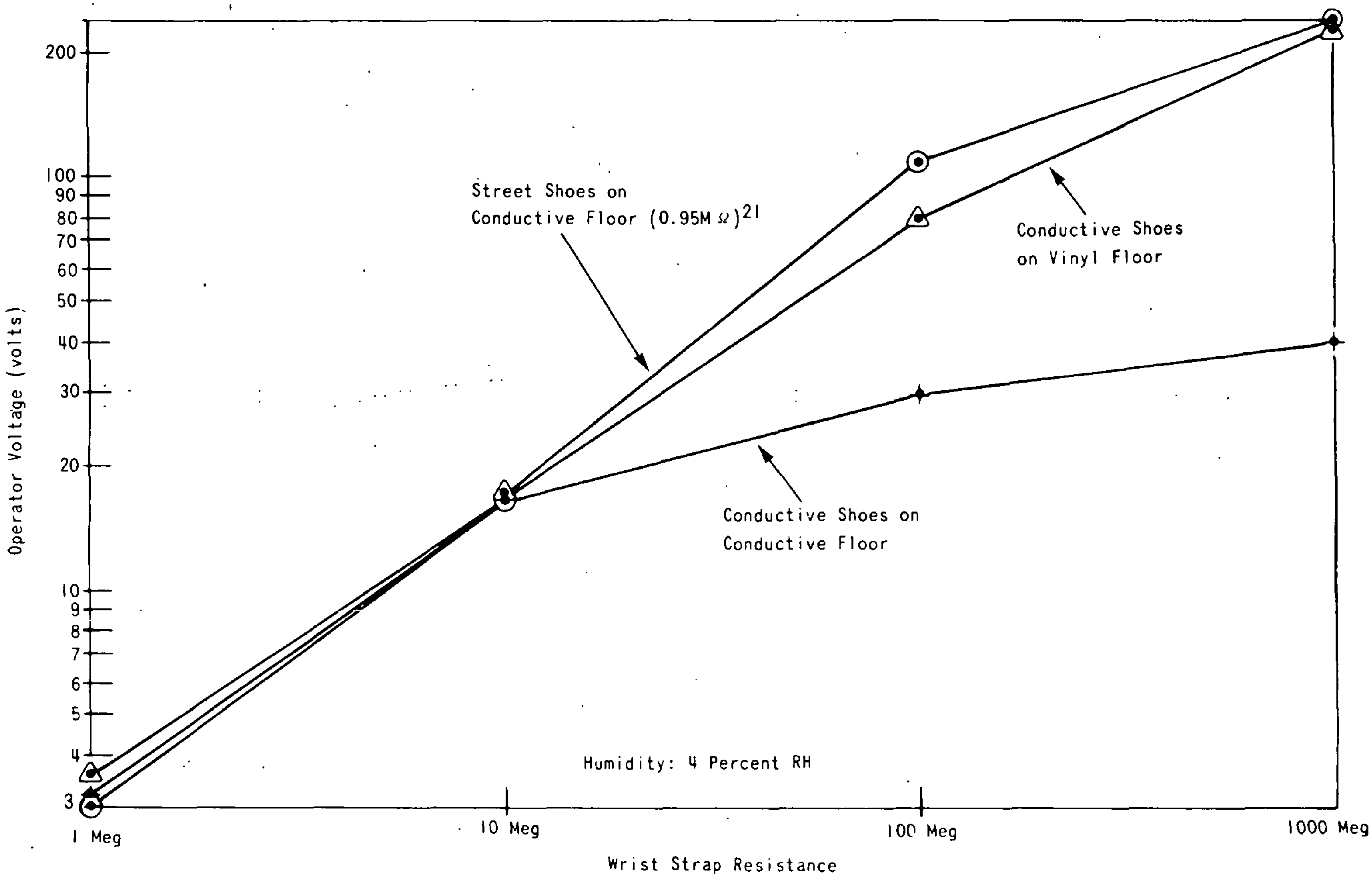


Figure 8. Peak Walking Voltage Versus Wrist Strap Resistance to Ground

VOLTAGES GENERATED BY SPRAY CLEANING

Excessive electrostatic voltages can be generated by spray cleaning an electronic assembly with solvent after soldering operations. The polarity and magnitude of the generated voltage is a function of the solvent resistivity, the spray rate, and the triboelectric voltages (contact potential) of the solvent and assembly materials. A typical cause of damage is accidentally grounding the gate of a JFET in a pre-charged assembly. The polarity must be correct to impose an excess reverse-breakdown potential on the JFET gate.

Solvents producing positive and negative voltages were mixed to cancel the voltage on the test circuit board. Mixing a low resistivity solvent with the normal cleaning solvent produced a better control of static voltage. A volume resistivity of 50 kΩ-m maximum provided an adequate system for the materials shown in Table 3 and Figure 9. Although ethanol was used for resistivity control, other polar solvents could also provide a low resistivity.

FACILITY DESIGN FOR LOW STATIC VOLTAGE

Suitable facility and process design should eliminate the need for an operator to intentionally touch a grounded surface prior to handling sensitive components or assemblies. The main objections to a wrist strap as the sole means of protection from excessive static voltages are carelessness in consistently being grounded, the nuisance factor, lack of freedom to move from the work station while carrying a sensitive device or assembly, the hazard of moving from the station without disconnecting the ground connection, and undetected failure of the strap continuity to ground.

A facility to provide adequate protection includes the following minimum design requirements.

- A conductive floor with a resistance between 25 kΩ and 0.3 MΩ when tested per NFPA 56A.[21] (The normal 1 MΩ upper limit is marginal. An upper limit nearer 0.3 MΩ implies a more uniform distribution of conductive paths and lower peak voltages as shown in Figure 6.)

- Conductive shoes with a maximum resistance of 0.5 MΩ per NFPA 56A.

- A conductive chair with a resistance from the seat to a metal plate under the chair of 1 MΩ maximum. (If a foot rest or rollers are provided, they must also be condutive. Although conductivity through an operator's clothing to the seat may

Table 3. Test Solvents

Solvent	Blend (Percent by Volume)				
A Trichloroethylene	100	90.0	80.0	72.5	50.0
Trichlorotrifluoroethane	---	6.5	13.0	17.9	32.5
Ethanol	---	3.2	6.3	8.6	15.7
Methanol	---	0.3	0.7	1.0	1.8
B Tetrachloroethylene	80	66.4	60.0	53.6	40.0
2-Ethoxy-Ethanol	20	16.6	15.0	13.4	10.0
Trichlorotrifluoroethane	---	11.0	16.3	21.5	32.5
Ethanol	---	5.4	7.8	10.3	15.7
Methanol	---	0.6	0.9	1.2	1.8
C Trichloroethylene	59.6	Azeotrope			
Ethanol (200 Proof)	40.4				

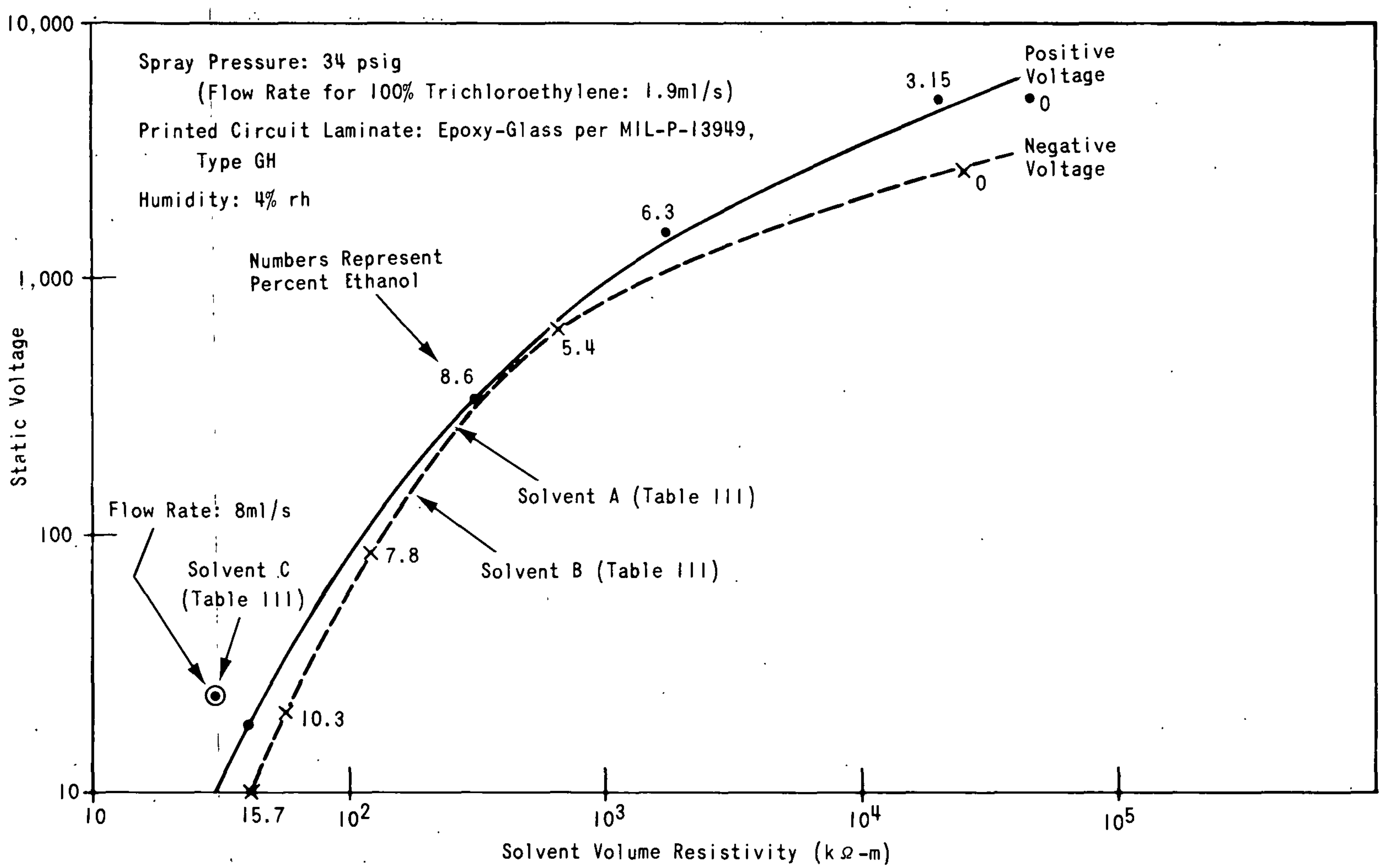


Figure 9. Assembly Static Voltage Versus Spray Solvent Resistivity

be low, the presence of the grounded seat reduces the voltage amplification obtained when an operator's feet are lifted from a ground-plane.)

- A conductive foot rest under the operator's work table.

A periodic resistance check of each operator at his work station should be made to check the total system. Resistance from an operator to ground (which is voltage-dependent) at the required voltage protection level must not exceed the limiting protection resistance implied in Figure 8. A system check takes account of the random distribution of conductive particles in both the floor and shoes and should be used to supplement standard floor and shoe test methods. In addition, conventional precautions such as conductive table tops, conductive foam packaging, and grounded-tip soldering irons should be used.

CONCLUSIONS

The degree of protection from static voltage required depends on the type of device being handled. The JFET's investigated can be safely handled in a facility which controls the maximum operator resistance-to-ground to 100 MΩ maximum under all conditions.* Unprotected MOSFET's require a resistance to ground of 10 MΩ maximum* under *all* conditions when the input leads are not shorted together. This low resistance can be obtained with the operator wearing conductive shoes, provided the shoes are always in contact with a conductive floor or a conductive foot rest. Spray cleaning solvents with less than 50 kΩ-m volume resistivity are safe to use on semiconductors mounted on epoxy-glass printed wiring boards.

All devices which are suspected of being static-voltage sensitive or which exhibit unexplained failures should be evaluated to determine their threshold of static voltage sensitivity. Effective facility revisions can then be made to economically reduce static voltage to a safe level. The combination of conditions which cause failure due to static discharge may be thought by some to be unlikely to occur. All conditions investigated here can easily occur and have occurred in a production environment.

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*A current limiting resistance of greater than 100 kΩ is used to protect the operator from electrical shock.

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