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ELECTROMAGNETIC PULSE-INDUCED CURRENT MEASUREMENT DEVICE

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13. ABSTRACT (Maximum 200 words)

To develop safety guidelines for exposure to high fields associated with an electromagnetic pulse (EMP), it is necessary to devise techniques that would measure the peak current induced in the human body. The main focus of this project was to design, fabricate, and test a portable, self-contained stand-on device that would measure and hold the peak current and the integrated charge Q. The design specifications of the EMP-Induced Current Measurement Device are as follows: rise time of the current pulse, 5 ns; peak current, 20-600A; charge Q, 0-20 μcoulomb. The device uses a stand-on parallel-plate bilayer sensor and fast high-frequency circuits that are well-shielded against spurious responses to high incident fields. Since the polarity of the incident peak electric field of the EMP may be either positive or negative, the induced peak current can also be positive or negative. Therefore, the device is designed to respond to either of these polarities and measure and hold both the peak current and the integrated charge which are simultaneously displayed on two separate 3-1/2 digit displays. The prototype device has been preliminarily tested with the EMPs generated at the Air Force Weapons Laboratory (ALECS facility) at Kirtland AFB, New Mexico.

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INTRODUCTION

There is an increasing interest in understanding the coupling of the electromagnetic pulse (EMP) to the human body to insure the health and safety of US Air Force (USAF) personnel. Most of the research on electromagnetic (EM) bioeffects in the past has focused on occupational and general public exposures from low to medium power, continuous-wave (CW) radiation in the radiofrequency to microwave bands (10 kHz-10 GHz). To extend the present radiofrequency radiation safety standards to the domain of EMP, it is necessary to devise techniques that would measure the currents induced in the human body and use this information to calculate the mass-normalized energy absorbed (specific absorption) for the various regions of the body. In related work sponsored by USAF SAM (contract F33615-87-D-0609 Task 25) we have calculated the time-varying internal fields and the induced current densities using the anatomically based models of a human using 5,628 or 45,024 cubical cells of dimensions 2.62 and 1.31 cm, respectively. This information was used to calculate the total induced currents for the various sections of the body as a function of time and the integrated specific absorptions for the various organs such as brain, heart, lung, liver, kidney, etc. in millijoules per kilogram (mJ/kg) [1]. The calculated currents were characterized by a sharp peak that occurred 5-15 ns after the onset of the EMP with a decay time of 100-200 ns. Peak-induced currents on the order of 1-5 Amperes (A) per kilovolt per meter (kV/m) of peak incident electric field of the EMP were calculated for the various sections of the body with the highest currents being for the sections through the legs. Since peak incident fields on the order of tens of kV/m may be encountered for the EMPs, peak-induced currents on the order of several tens to hundreds of Amperes are therefore projected to flow through the human body.

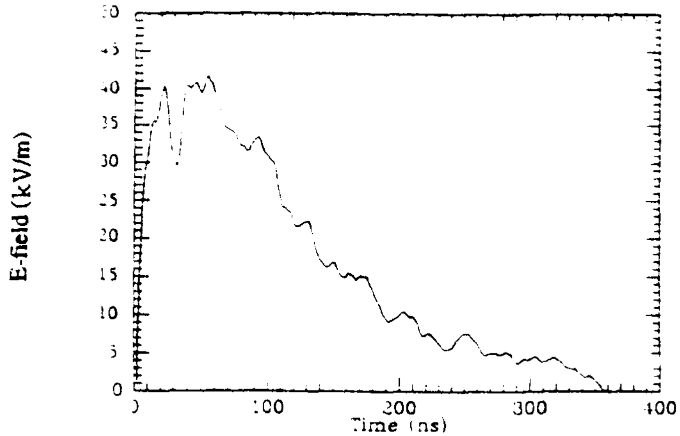
The main objective of this project has been to develop a portable stand-on device that would measure the peak current passing through the feet of a subject or a biological phantom surrogate, and the integrated charge $\int |I| dt$ that passes through the body. The design specifications of the EMP-induced current measurement device are as follows:

rise time of the current pulse:	5 ns
peak current:	20-600 A
integrated charge:	0-20 μcoulomb

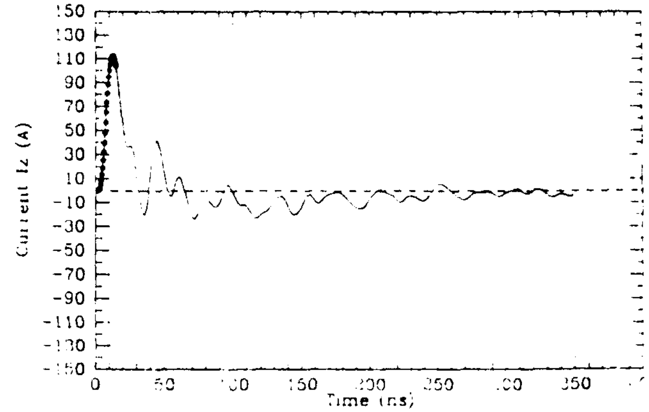
DESIGN DETAILS

Peak Current Measuring Circuit

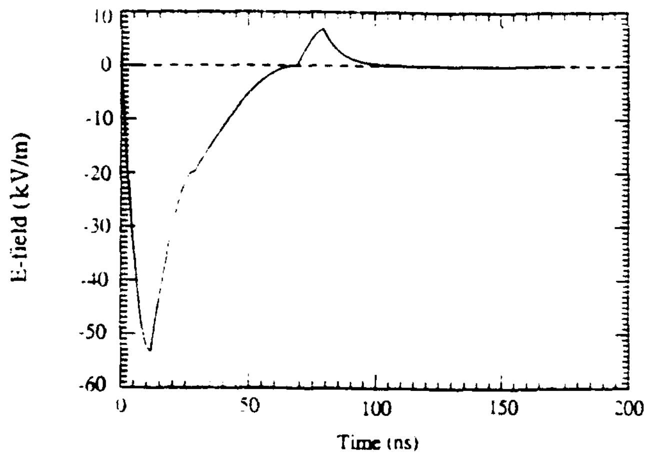
In Figure 1 we show the currents calculated for the section through the ankles for the anatomically based model of the human body for a couple of representative EMPs [1]. For the model with cell sizes of 2.62 cm the currents are shown as solid curves (Figures 1b, 1d), while the data calculated for the EMP of Figure 1a using a higher-resolution model (cell size = 1.31 cm) is shown by dots in Figure 1b. The points to note in Figure 1 are: peaks of the induced currents occur approximately 10 ns after the onset of the pulse, and peak currents for the ankle section are 3-4 A/(kV/m) in terms of the peak incident electric field.



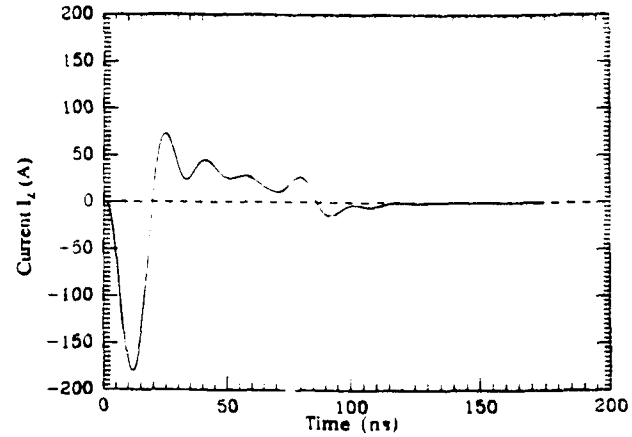
a. A positive EMP truncated in the time domain.



b. Calculated current through the ankle section for the EMP of Figure a.



c. A negative EMP truncated in the time domain.



d. Calculated current through the ankle section for the EMP of Figure c.

Figure 1. Induced currents for the body section through the ankles for a couple of representative EMPs.

The Fourier spectrum of the EMP-induced current of Figure 1b is shown in Figure 2. Fairly similar Fourier spectra have also been calculated for the currents through the other sections of the body such as through the knees, the thighs, the liver, the heart, etc. for the representative EMPs shown in Figures 1a and c, respectively. It is interesting to note that the strongest components of induced currents are for frequencies lower than about 100 MHz for the EMPs studied to date.

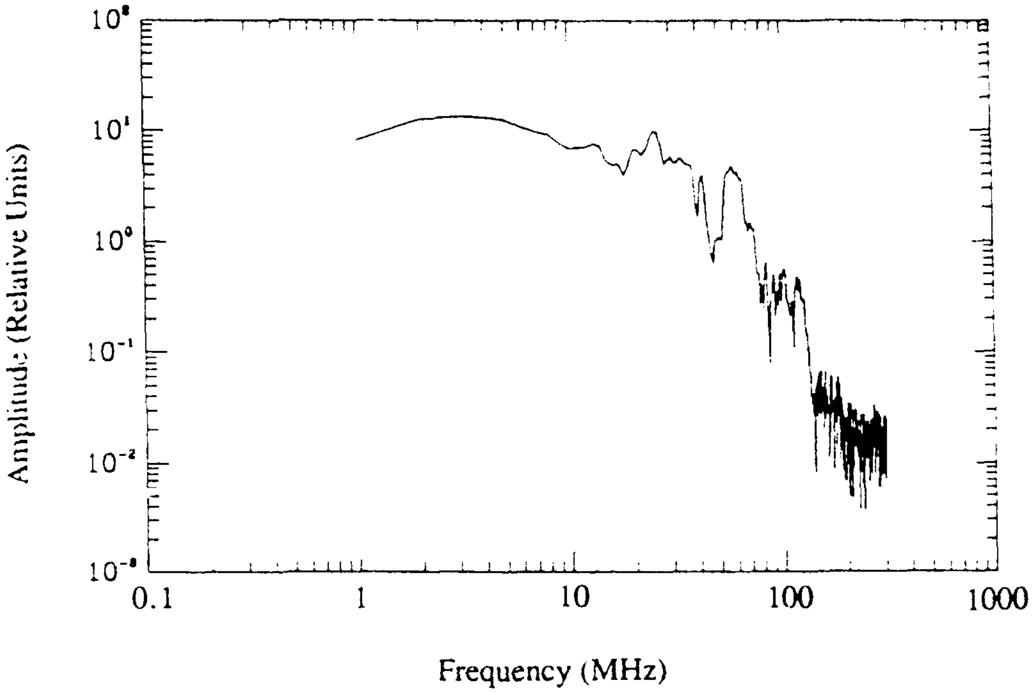


Figure 2. Fourier Spectrum of the EMP-induced current of Figure 1b.

To measure the EMP-induced current,we have used a parallel-plate bilayer sensor on which a subject can stand. This stand-on current sensor is constructed of two 0.01-in.-thick copper sheets that are glued on either side of a 1/4-in.-thick Plexiglas sheet of dimensions 11.5 × 11.5 in. The measured capacitance of this arrangement is 303 pF giving a calculated effective dielectric constant of 2.5 for Plexiglas. As seen in Figure 3, two relatively noninductive carbon resistors (8.2 ohms each) are connected in parallel between the two plates to allow flow of EMP-induced current $I_i(t)$ from a subject standing on Plate A to Plate B.

A slight inductance of about 2.8 nH is encountered due to the leads connecting the resistors to Plates A and B. The calculated impedance of the resistance-inductance-capacitance (RIC) combination representing the equivalent circuit between plates A and B is shown in Figure 4. It is interesting to note that the effective impedance of the parallel plate sensor is relatively independent of frequency up to about 170 MHz, which is in excess of the frequencies for most of the components encountered for the EMP-induced current (Figure 2).

The circuit used for the peak current measurement is shown in Figure 3. Since the polarity of the incident peak electric field of the EMP may be either positive or negative (Figures 1a, c), the induced peak currents to be measured can also be positive or negative (Figures 1b, d). As seen in part **D** of the circuit diagram in Figure 3, a full-wave rectifier is therefore used to allow rectification of the EMP-induced current for both its positive and negative parts. A balanced potentiometer

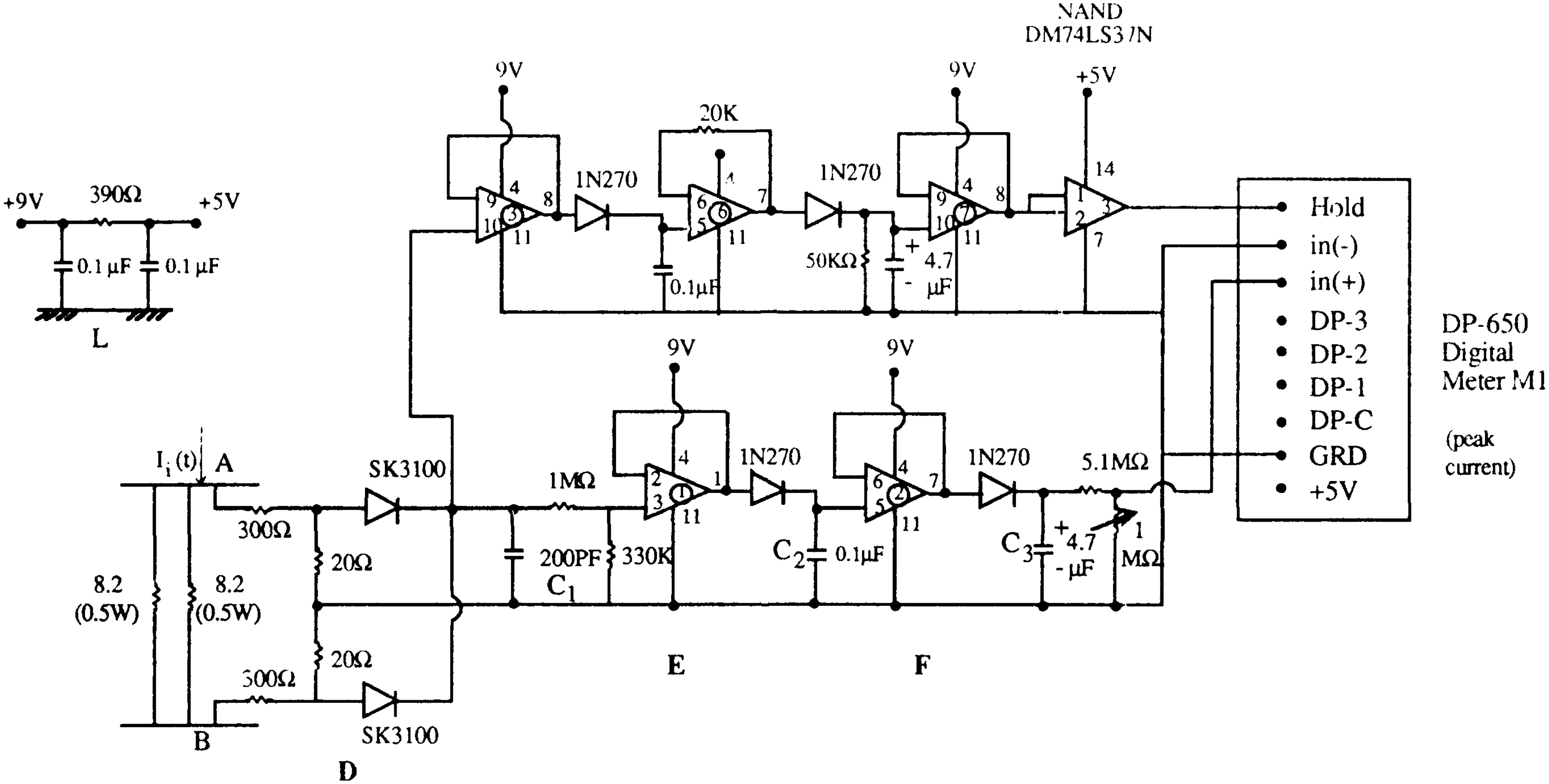


Figure 3. Electronic circuit for Peak-Current Measurement for an EMP of positive or negative polarity.

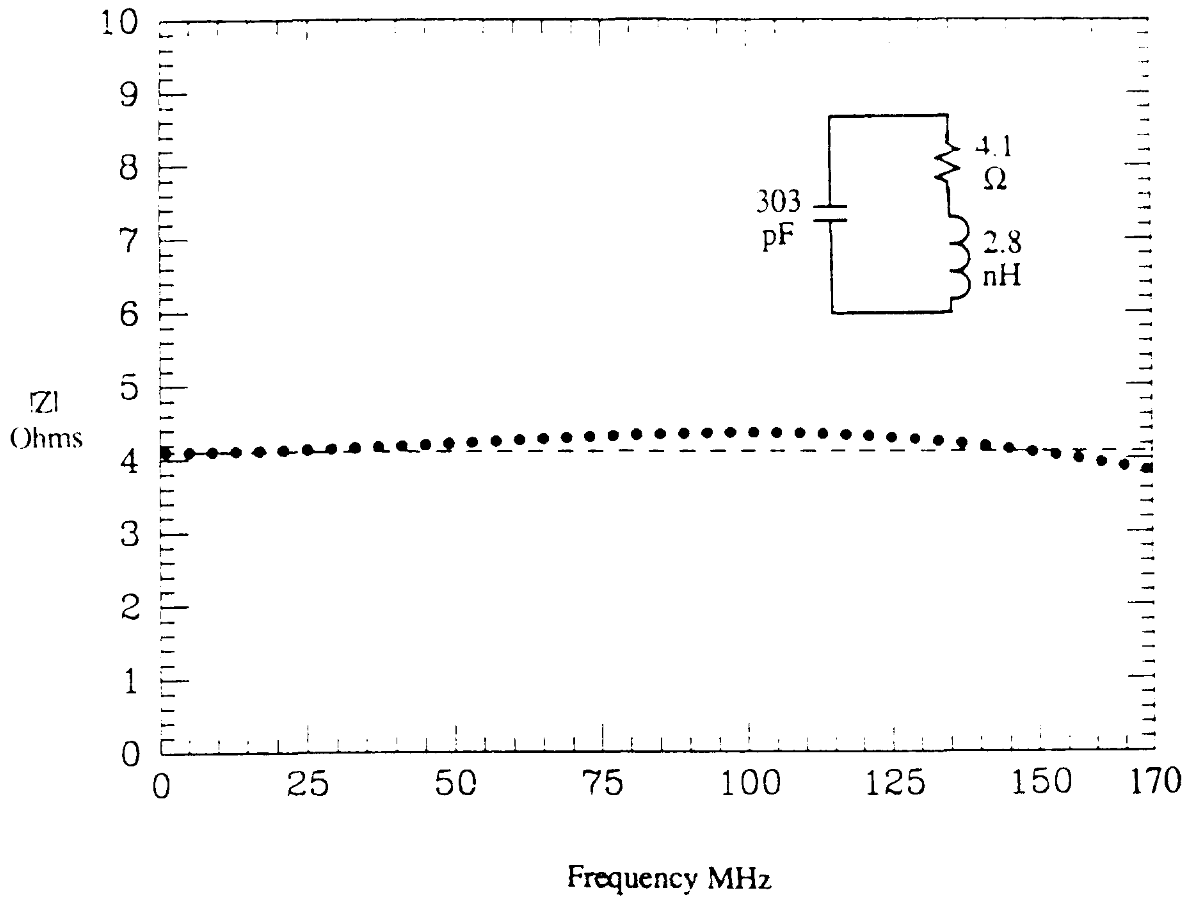


Figure 4. The calculated impedance of the parallel-plate sensor AB for the frequency band 0-170 MHz. Shown as an insert is the equivalent RLC circuit of the sensor.

consisting of 20 and 300 ohm fixed resistors are used to reduce the voltage applied to the rectifier (part **D**) by a factor of 640/20 or 32. We have tried several high-frequency diodes such as 1N60, 1N270, HP5082-2200, and the presently used diodes SK3100 (1N4448F). The SK3100 diodes provided the most satisfactory high-speed performance.

For rapid charging to the peak voltage accompanying the peak current, a fairly small capacitance C_1 of 200 pF is used at the output of rectifier **D**. Since a 200 pF capacitor has the disadvantage of discharging within a fraction of a millisecond once the induced current has stopped, we use a fraction of the signal on capacitor C_1 through a unity gain buffer amplifier marked ① (1/4 of Quad OPAMP LM324) and a rectifier 1N270 to charge a larger capacitor C_2 (0.1 μF) in Section **E** of the circuit. Because of the larger capacitance and a fairly high effective resistance, this capacitor can retain the voltage longer than C_1 in the previous stage. Another unity gain buffer amplifier marked ② (1/4 of OPAMP LM324) and a rectifier 1N270 are then used to charge a still larger capacitance (C_3 = 4.7 μF), which can retain the voltage proportional to the peak current for a few seconds.

The upper circuit in Figure 3 uses one additional quadrant of the first Quad OPAMP LM324 (marked ③) and two quadrants of a second Quad OPAMP LM324 (marked ⑥ and ⑦) to drive a NAND DM74L S37N. The output of the NAND is used to provide the "hold" signal to an Acculex sample-and-hold 3 1/2-digit panel meter DP-650. Since this sample-and-hold device uses a 5-V d.c. input rather than the 9-V battery required for OPAMP LM324, the circuit shown at L in the upper-left-hand corner of Figure 3 is used to reduce the voltage from a 9-V battery to the required 5 V needed for DP-650.

Integrated Charge Measuring Circuit

The complete electronic circuit used for the EMP-Induced Current Measurement Device is shown in Figure 5. The bottom two-thirds of the circuit is the same as that in Figure 3 and is used for the peak current detection and hold. The top circuit is used to measure integrated charge $Q = \int I dt$. A signal proportional to this charge is applied and held by means of a second Acculex sample and hold digital meter DP-650 shown in the upper-right-hand corner of Figure 5.

The charge measuring circuit (the top row circuit in Figure 5) uses the same parallel plate bilayer sensor AB that is also used for the peak current measuring part of the circuit (lower-most circuit in Figure 5). A second high-speed full-wave rectifier in section G of the circuit is used to create a time-varying voltage $V_i(t)$ across a 200-kΩ resistor R_1. Since the voltage drop across the high-frequency silicon diodes SK3100 is fairly small, $V_i(t)$ is related to the rectified version of the input current $I_i(t)$ as follows:

$$V_i(t) = |I_i(t)| \frac{8.2}{2} \frac{20}{240} = 0.34\, |I_i(t)| \tag{1}$$

For the RC circuit marked **H** in Figure 5,

$$V_i(t) = R\, I(t) + \frac{1}{C} \int I\, dt \tag{2}$$

The RC time constant of the circuit **H** is selected to be considerably larger than the time periods associated with the majority of the frequency components (> 0.1 MHz), so that from eq. (2)

$$V_i(t) \sim R\, I(t) \tag{3}$$

The output voltage $V_0(t)$ of circuit **H** is then given by

$$V_0(t) = \frac{1}{C} \int I(t)\, dt = \frac{1}{RC} \int V_i(t)\, dt = \frac{0.34}{RC} \int |I_i(t)|\, dt \tag{4}$$

The primary purpose of the unity gain buffer amplifier marked **J** using the last quadrant ④ of the first Quad OPAMP LM324 is to provide a very high input impedance (to prevent loading) and a fairly low output impedance. The latter is needed to allow rapid charging of capacitor C_4 = 0.01 μF. A second buffer amplifier marked **K** is subsequently used to allow charging of a larger 4.7 μF capacitor (C_5). An Acculex sample-and-hold digital meter DP-650 (M2) is used to display the integrated charge $\int |I_i(t)| dt$. The variable 1-MΩ resistor at the input to meter M2 is used for calibration.

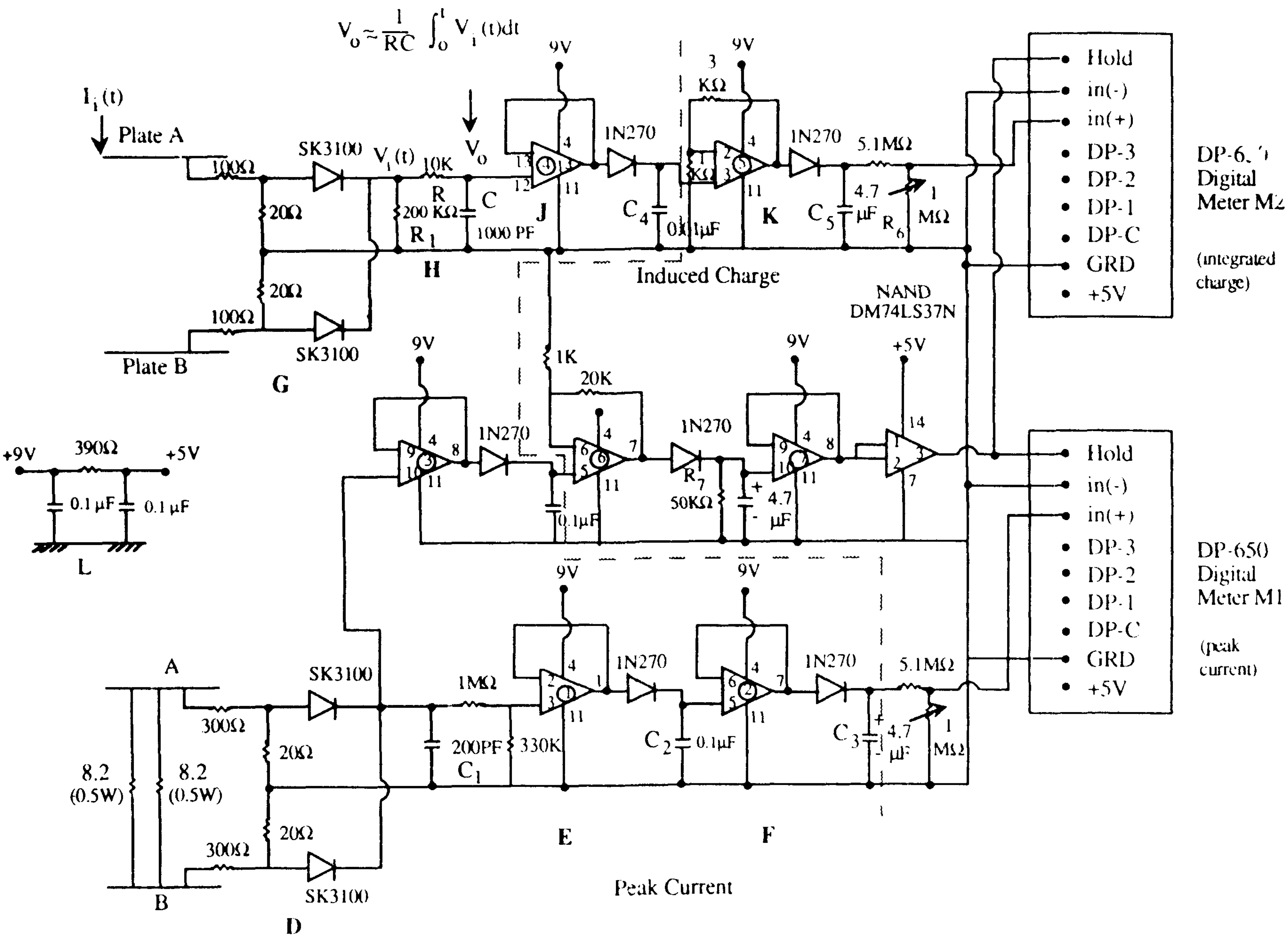


Figure 5. Electronic circuit for peak-current and integrated-charge measurement for an EMP of positive or negative polarity.

LABORATORY TESTING

The circuit in Figure 5 has been tested by applying single pulses from an E-H Research Laboratories (Oakland, California) Model EH139B Pulse Generator. By changing the knobs controlling the rise and fall times and width of the single pulse different pulse shapes could be obtained from this pulser. Some of these pulses are shown in Figure 6. The exact shapes of the pulses were detected using a Hewlett Packard model 54111D Digitizing (Storage) Oscilloscope. It should be noted that rise times on the order of 10 ns could be obtained using this pulser. Since voltages larger than 10-20 V could not be obtained from the Model EH139B pulser, we have used a low-inductance capacitive discharge circuit to obtain pulses of larger voltages. In this circuit a bank of three ceramic capacitors in series (0.022 μF each) is charged to voltages as high as 1000 V using a Kepco power supply (0-2500 V) and discharged through the sensor AB using a pushbutton switch.

The peak current-measuring circuit of Figure 5 has been tested in the laboratory by applying different types of pulses (magnitudes and shapes), some of which are shown in Figure 6. The results of these measurements are shown in Figure 7. Somewhat broader pulses of 200-300 ns were used to calibrate the integrated-charge measuring circuit of Figure 5. The calibration curve for the charge-measuring circuit is shown in Figure 8.

A photograph of the EMP-Induced Current Measurement Device is given in Figure 9.

PRELIMINARY FIELD TESTING

Preliminary testing of the first prototype of the EMP-Induced Current Measurement Device was conducted at the Air Force Weapons Laboratory (ALECS Facility) at Kirtland AFB, New Mexico, on May 22, 1990. The authors acknowledge with gratitude the full support and cooperation of Capt. S. Mason and Mr. Hull for these tests. Several vertically polarized pulses with peak magnitudes up to 42 kV/m were used. The results were inconclusive. It was conjectured that the pickup of the prototype device may be high.

As a result of these tests, we have completely redesigned the device to reduce the potential pickup. In particular, the following changes have been made:

a. A rotary switch which was used to allow two ranges (20-200 A, 200-600 A) in the first prototype has been eliminated. Only two toggle switches are used in the present device. It was felt that the metallic spindle of the rotary switch in the first prototype may have acted as an antenna and was therefore undesirable.

b. All of the RF electronics (circuit to the left of the dashed line in Figure 5) have been mounted in a shielded box within the parallel plate sensor. The shortest possible leads have been used to bring the rectified voltages to the circuits to the right of the dashed line in Figure 5.

c. The electronic box in the modified device (Prototype No. 2) is made of solid 1/4-in. aluminum trough (no seams) with a lid fastened securely onto it. This step eliminates all the joints at the various edges of the previous box which may have contributed to the pickup problem.

d. Several changes were also made in the electronic circuit; the final version is shown in Figure 5. In particular we shifted to the use of Acculex Model DP-650 digital display meters which offer the advantage of in-built latch circuits which were needed in the first prototype device.

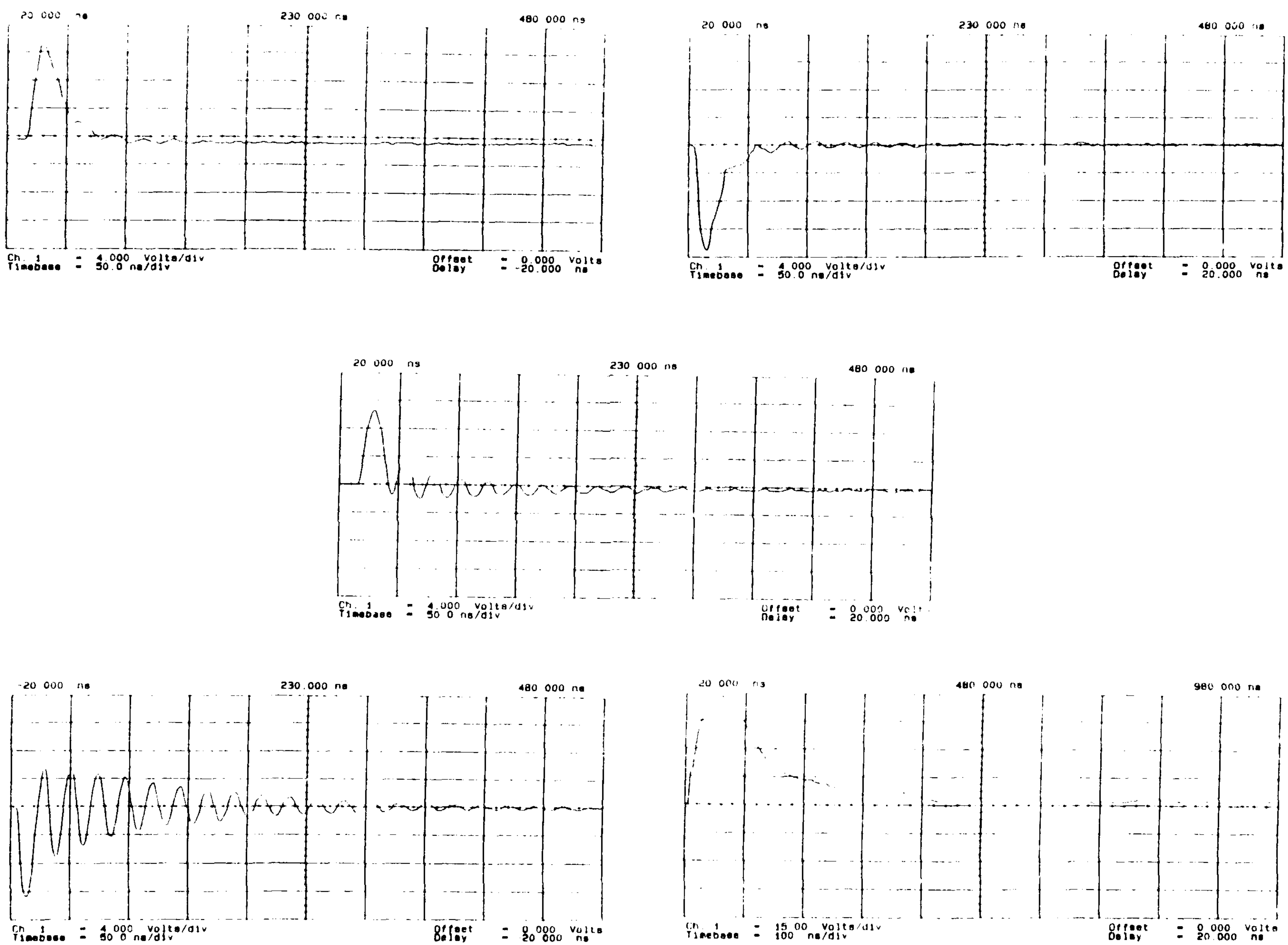


Figure 6. Some typical single pulses (positive or negative) used for calibration.

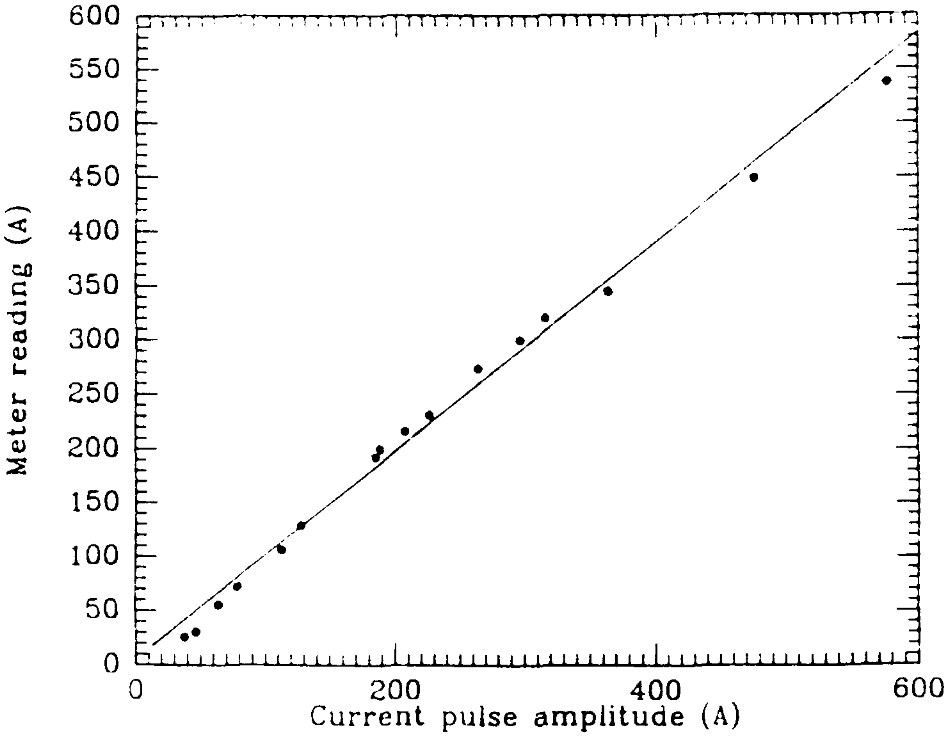


Figure 7. Laboratory testing -- meter reading as a function of applied current pulse amplitude.

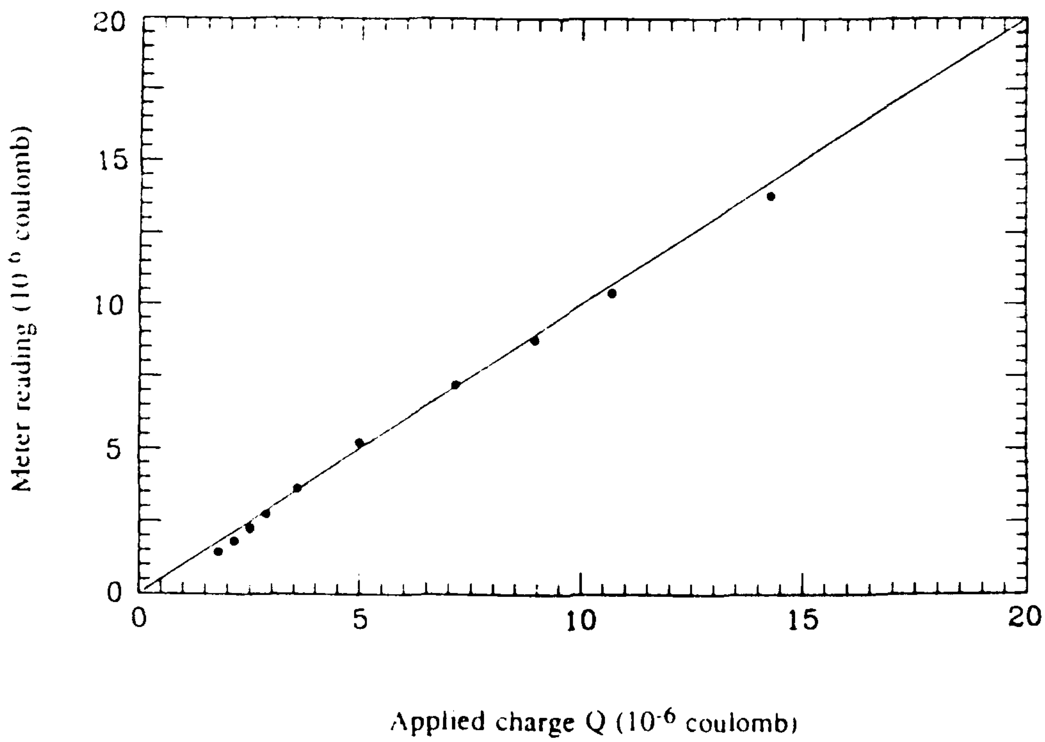


Figure 8. Laboratory testing -- meter reading as a function of applied charge Q = ∫ |I|dt.

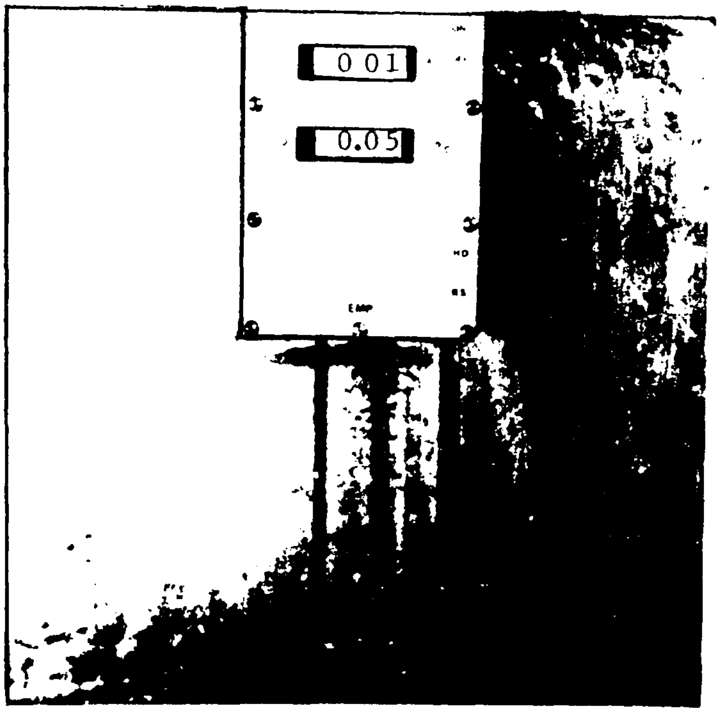


Figure 9. Photograph of the EMP-induced current measurement device.

Subsequently we tested the new device (Prototype No. 2) with respect to its hardness relative to stray pickup from the high incident fields associated with the EMP. Since adequate facilities were not available in our laboratory to generate open-air E-fields of 10-100 kV/m, we used a TEM cell with a center conductor to ground plate spacing of 15 cm. By applying high voltage pulses of 10-20 kV across the TEM line using a Magnetron Pulser, we were able to create pulsed E-fields up to 133 kV/m between the flat center conductor (width = 30 cm) and the ground plates. The magnetic field in this TEM cell is a factor of 377 lower than the E-field and is directed along the width of the center conductor.

In laboratory testing of the prototype No. 2 device using a TEM cell,we found the pickup to be negligible.

Prototype No. 2 was sent to Capt. S Mason at the Air Force Weapons Laboratory (ALECS Facility), Kirtland AFB, New Mexico. Capt. Mason and his colleagues were kind enough to test it for a number (18) of EM pulses. Because of the many changes in both the electronic circuit and shielding of the device, this prototype worked considerably better than the first prototype. For nearly identical pulses, relatively consistent readings were obtained for both the peak current and the integrated charge $Q = \int |I| dt$ for most of the EMPs. A vertical battery cable was used for the pickup as a crude surrogate of the human subject.

A disconcerting feature of these field tests, however, was that for two out of eighteen pulses the current meter either did not register the peak amplitude or gave a value that was very low compared to the expected value. Worse still, for five out of eighteen pulses, the charge-measuring digital display either did not register or gave values that were inconsistently low. Thinking that this lack of sensitivity was caused by the relatively short duration for which the latching circuit is activated, we have increased the resistance R_7 (see Figure 5 for the final electronic circuit of Prototype No. 3) from 36 kΩ to 50 kΩ. It was argued that this modification should help increase the time for which the latching circuit is activated.

Several other changes were also made in modifying the electronic circuit for Prototype No. 3 of the EMP-induced current measurement device. These changes are indicated in Figure 5 and described in the following:

a. The two resistances in the input voltage divider for the charge-measuring part of the stand-on sensor have been increased from 51 Ω each to 100 Ω each to reduce the voltage across the rectifier diodes SK3100. In laboratory testing it was found that peak voltage across these diodes could be very high for large input currents $I_i(t)$ on the order of several hundred amperes which could cause burnout of the rectifier diodes. Increasing the resistances to 100 Ω has reduced the voltages across the rectifying diodes. This voltage could not be reduced too much or else low-peak currents might not be measurable.

b. Because of somewhat lower rectified voltages V_i and V_o, a d.c. gain of about 3 has been built into the OPAMP marked ⑤ in the circuit (Figure 5) by connecting new resistances of 3 kΩ and 1 kΩ, respectively. A higher gain than 3 was not considered desirable; it created problems with zeroing the integrated-charge reading digital meter.

c. The output resistance R_6 for the charge-measuring circuit (Figure 5) has been altered by removing the fixed resistance of 100 kΩ in the previous circuit and replacing the 100 kΩ variable resistance by a new variable resistor of 1 MΩ.

The third prototype of the EMP-induced current measurement device was field tested at Kirtland Air Force Base on September 6, 1990, courtesy of Captain Mason and his staff. The device was found to be considerably more reliable than the previous prototype and gave both the peak current and integrated charge $Q = \int |I|dt$ readings for each of the fifteen EMPs. The peak current was found to be intermediate between the values read by HP oscilloscopes rated for 400 and 2,000 MHz, respectively. This difference is understandable since we had used a HP Model 54111D digitizing oscilloscope with a somewhat lower frequency rating (500 MHz) than the higher-frequency oscilloscope available at Kirtland Air Force Base.

The integrated charge readings, on the other hand, were higher by almost a factor of 2 which was ascribed to the imperfect calibration of the EMP-induced current measuring device, since only approximate magnitudes of the applied charge were used for this purpose. We have improved calibration by a more careful determination of the applied charge $\int |I|dt$ which was used to adjust the readout of the digital meter M2.

We have also assembled a duplicate of Prototype No. 3 so that two devices are now available for the measurement of induced currents in EMP-exposed humans as planned by David Erwin, William Hurt, and their colleagues at Brooks AFB, Texas.

REFERENCE

1. Chen, J. Y. and O. P. Gandhi. Currents induced in an anatomically based model of a human for exposure to vertically polarized EMP, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-39:31-39, 1991.