Electromagnetic Pulse and the Radio Amateur

Part 1: Will your station survive the effects of lightning strikes or electromagnetic pulse (EMP) generated by nuclear explosions? The information in this series will help you harden your radio system.

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Radio amateurs have long been concerned with protecting their radio installations against lightning. Many have applied lightning protection where required by local electrical codes. Traditionally, the installed protection is designed to combat "slow" lightning strikes (having rise times on the order of tens of microseconds) with protection from direct overhead strokes obtained by sheltering important conductors with a grounding system.

To address the transient threat, including lightning-voltage surges and electromagnetic pulse (EMP), it is necessary to protect installations against electromagnetic fields rising to a peak intensity of 50 kV/m in several nanoseconds. While some modern lightning-protection devices are effective against a lightning transient threat, the majority of them will not act in time to prevent the faster EMP from entering the radio equipment.

Protection of Amateur Radio installations is becoming more difficult as circuit components become more sensitive to transients. ICs are susceptible to damage at transient levels smaller than those of discrete transistors, which are more susceptible than vacuum tubes. New protection devices such as metal-oxide varistors (MOVs) offer protection within one nanosecond of the arrival of a transient pulse such. When properly selected and installed, such devices show promise of providing protection against the universal transient threat.

Background

One of the primary reasons for the existence of Amateur Radio is to provide a public service. Over many years, this service has proven to be most valuable during emergencies. At first, the amateur public emergency service existed spontaneously on an individual basis. Today, it has evolved into a well-established system that includes the Amateur Radio Emergency Service (ARES), the National Traffic System (NTS), the Radio Amateur Civil Emergency Service (RACES) and the Military Affiliate Radio System (MARS).[1]

Radio amateurs have provided communications during natural disasters such as tornadoes, hurricanes, floods and blizzards when other forms of communication have been inadequate. The amateur uses portable, mobile and fixed-station radio equipment that is not necessarily dependent on commercial power. In almost every community large and small, there is a cadre of experienced radio amateurs willing to respond to the need for emergency communications.

In addition to the role amateurs fill during natural disasters, the National Communications System (NCS) has long recognized that the Amateur Radio community provides a great national resource. It is of value not only to the public, but also to augment civil and military agencies. To enhance the nationwide posture of telecommunications readiness for national emergencies, the NCS and the ARRL have a written memorandum of understanding. Its purpose is to establish a broad framework of cooperation and a close working relationship with volunteer radio amateurs for national emergency-communications functions. Therefore, it is in the national interest to find ways to enhance the survivability of the Amateur Radio system in a nuclear environment.

EMP Defined

Electromagnetic Pulse (EMP) is defined as a large, impulsive type of electromagnetic wave generated by a nuclear explosion. EMP commonly refers to a nuclear electromagnetic pulse (NEMP). In this usage, it is a plane-wave, line-of-sight electromagnetic phenomenon that occurs as a result of an above-ground nuclear detonation. NEMP has an electric field strength of 50 kV/m horizontally and 20 kV/m vertically, with a pulse rise time to peak of 5 to 10 nanoseconds.

There are several different types of EMP resulting from a nuclear explosion. One of the more significant types is the High-altitude EMP (HEMP) that results from a nuclear explosion above 30 miles in altitude. The HEMP is created by the interaction of high-energy photons (gamma rays) with atmospheric molecules, producing Compton electrons. These electrons decay in the Earth's magnetic fields, emitting photons in the process.

System-Generated EMP (SGEMP) is produced by the direct interaction of high-energy photons with systems (equipment), rather than through their interaction with atmospheric molecules. SGEMP is important because of its effects on satellite systems and in-flight missiles.

The third type, Magnetohydrodynamic EMP (MHD-EMP) is different because of its distinct physical generation mechanism, later occurrence, smaller amplitude and longer duration. It is sometimes referred to as late-time EMP. MHD-EMP poses a threat for very long landlines (including telephone cables and power-distribution lines) or submarine cables.

EMP Description

Of the three types of EMP, HEMP poses the greatest threat to the Amateur Radio operator's equipment. Therefore, this report deals primarily with HEMP and lightning.

Generation Process

A major threat exists to every Amateur Radio installation in the US from the possibility of high-altitude nuclear explosions over the central part of the country. One such detonation at a height of 250 to 300 miles could produce an EMP/transient effect over the contiguous US. Significant

[1]Notes appear on page 36.

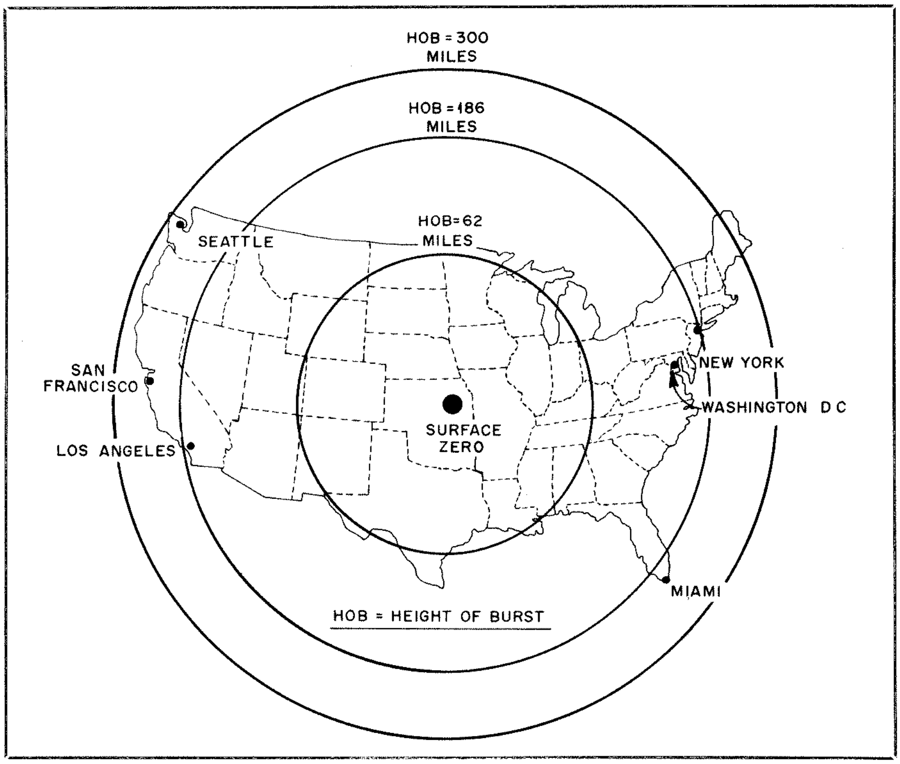

Fig 1—EMP ground coverage for high-altitude, 10-megaton nuclear explosions at altitudes of 62, 186 and 300 miles.

electrons are deflected from their original path by the Earth's magnetic field and spiral around the geomagnetic field lines. They complete about one-third of a revolution before they decay and are reabsorbed by the atmosphere. The current generated by this magnetic deflection is a major component of the deposition region in a high-altitude nuclear blast.

Deposition Region

In a high-altitude nuclear blast (30 miles or more above the Earth's atmosphere) the gamma rays radiated in a downward direction travel through the near vacuum of space until encountering a region where the atmospheric density is sufficient to produce the Compton Effect and the resulting deposition region. The deposition region is generally circular and is approximately 50 miles thick in the center and tapers toward the outer edge, with a mean altitude of 25 to 30 miles (Fig 2). The radius of the deposition region is determined by the height of the burst, the yield of the nuclear device, and is limited by the curvature of the earth. The deposition region is formed quickly since the gamma rays and the Compton electrons both travel at nearly the speed of light (186,000 mi/s) in a vacuum. The rapid generation of the deposition

EMP levels can occur on the Earth's surface at all points within line-of-sight from the explosion. If high-yield weapons are used, the EMP field strength felt on the earth will not vary significantly with the height of the explosion. Therefore, a high-altitude explosion, which can cover a large geographic area, will produce essentially the same peak field strength as a low-altitude explosion, which covers a small geographic area. Fig 1 illustrates the areas that EMP would affect based on height of burst (HOB) above the US.

The Compton Effect

During a nuclear explosion, gamma rays (high-energy photons) are radiated in all directions from the source. These gamma rays react with the atmosphere to produce large electrical charges and currents, which are the sources of the electric and magnetic fields that comprise the EMP. The basic physical process that converts the gamma-ray energy into EMP energy is known as the Compton Effect.

When a gamma ray strikes an atom in the atmosphere, it knocks an electron free and drives it outward from the detonation. Since the electrons (Compton electrons) are smaller, they are moved outward more rapidly than the remaining large positively charged portion of the atom. The results are a charge separation in the atmosphere, and creation of a huge electric current. This charged region in the atmosphere is called the "deposition region." An additional current is generated when the Compton

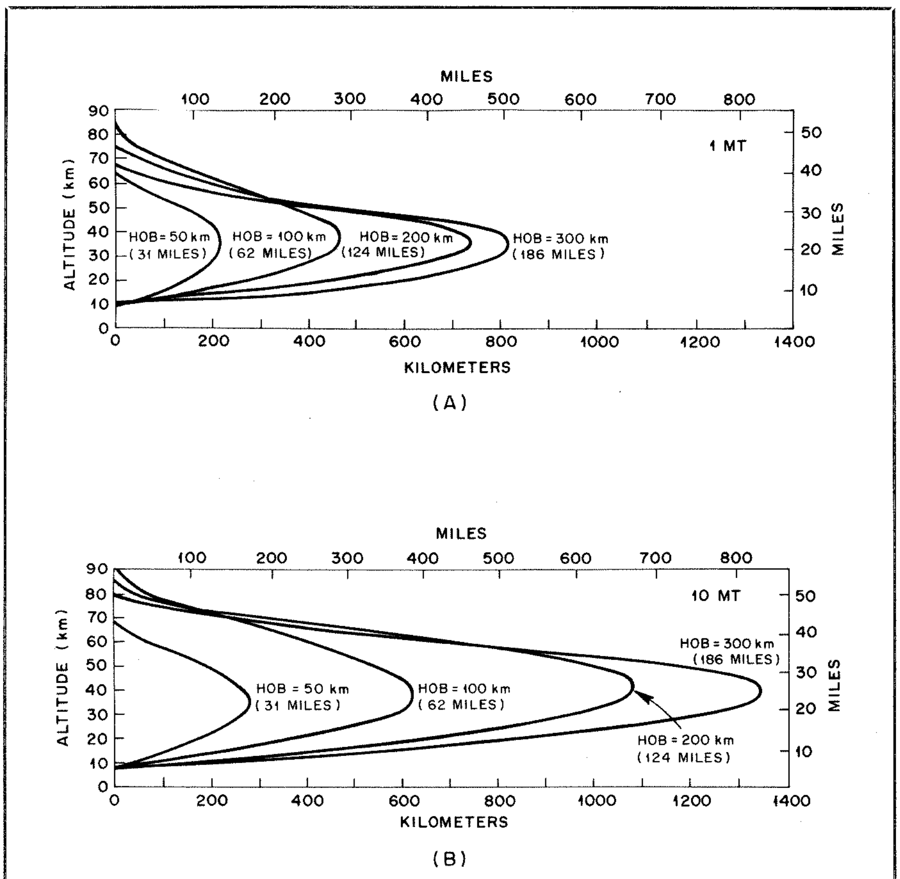

Fig 2—At A, deposition regions for a 1-megaton nuclear explosion at altitudes of 31, 62, 124 and 186 miles. Deposition regions for a 10-megaton nuclear explosion at the same heights are shown at B.

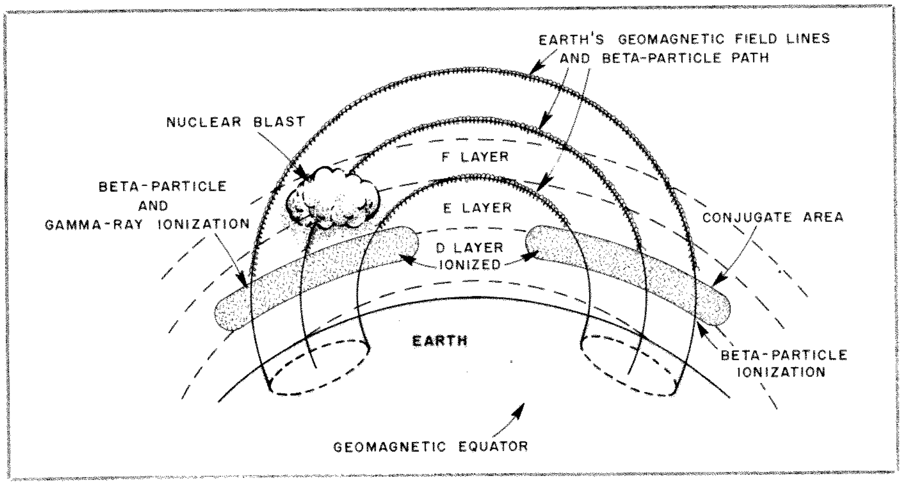

Fig 3—Depiction of the magnetic conjugate.

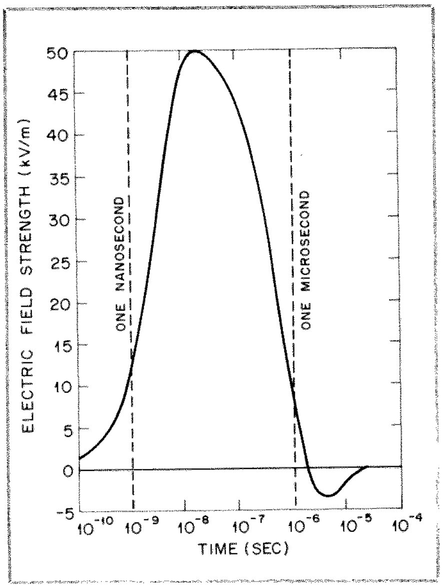

Fig 4—Electric field strength of a typical EMP wave.

region results in a pulse with a very fast rise time, covering a broad frequency range.

Magnetic Conjugate

A high-altitude detonation also generates beta particles, or free electrons, that spiral along the Earth's magnetic field lines. This creates an increase in the ionization of the D layer of the atmosphere not only at the local area, but also in the area known as the magnetic conjugate—in the opposite hemisphere! Fig 3 graphically depicts the immensity of EMP's widespread effects. Amateurs in both the local and opposite hemisphere may find a sudden loss in their ability to communicate.

Electromagnetic Spectrum Effects

Amplitude (Waveform)

An EMP has a fast rise time and a short duration when compared to lightning surges. A high-altitude EMP rises to peak voltage in approximately 10 nanoseconds (ten billionths of a second) and has a duration of approximately 1 microsecond (1 millionth of a second); see Fig 4. A lightning stroke, on the other hand, rises to peak voltage in about 2 microseconds and lasts 100 times longer (1 thousandth of a second) than an EMP.

A significant difference between EMP and lightning is that EMP effects are felt over a much larger area simultaneously, not just locally. Any conductor within the area of an EMP will act as an antenna and could pick up the electromagnetic energy. The voltages and currents induced in these conductors are comparable to those produced by the largest lightning bolts. However, the total energy of the EMP current is not as large as a nearby lightning-current pulse because of the short duration of the EMP.

Lightning can be viewed almost as a steady current when compared with EMP. The instantaneous peak-power density for an EMP is typically 6 MW/m^2. However, since the pulse is of such short duration, the total energy received on the ground is only about 0.6 J/m^2.[2]

Radio Frequencies

The energy of a high-altitude EMP is spread over a major part of the RF spectrum. Since the pulse has such a fast rise time and short duration, it covers a broad frequency range extending from 10 kilohertz to 100 megahertz. The electric field strength remains fairly constant in the 10-kHz to 1-MHz band; it decreases by a factor of 100 in the 1- to 100-MHz band and continues to decrease at a faster rate for frequencies greater than 100 MHz. Most high-altitude EMP energy is at frequencies between 100 kHz and 10 MHz, and 99% lies in the frequency spectrum below 100 MHz (Fig 5).

Coupling

Electromagnetic energy is radiated downward from the deposition region to the earth. Any conductor beneath or near the deposition region will act as an antenna and pick up the electromagnetic energy. Long power-transmission lines are effective in picking up the low-frequency components of the EMP. Short metallic conductors, including internal parts of electronic equipment, pick up the high-frequency components of the EMP. A list of collectors is shown in Fig 6. The energy on the conductor is in the form of a strong current and voltage surge that is transmitted to the attached electronic equipment. Table 1 illustrates EMP-induced surges on conductors.

Equipment does not have to be attached directly to a collector (conductor) to be damaged; EMP/transient-pulse energy can be coupled to the equipment in other ways. For example, an electric current can be induced, or a spark can jump, from a primary conductor that collects the EMP energy to a nearby secondary conductor

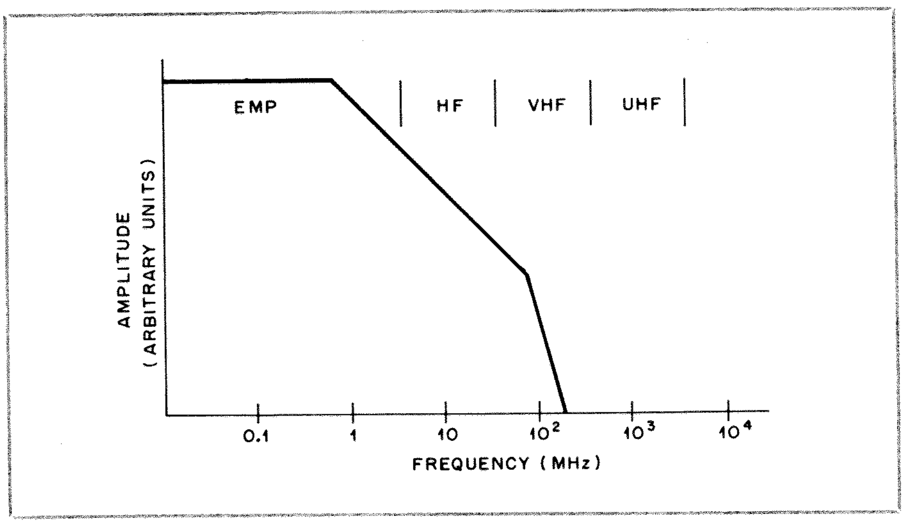

Fig 5—The frequency spectrum of EMP.

Typical Collectors of EMP Energy

Long runs of cable, piping or conduit
Large antennas, antenna feed lines, guy wires, antenna supports (towers)
Overhead power and telephone lines and supporting towers
Long runs of electrical wiring, conduit, and so forth in buildings
Metallic structural components, girders, reinforcing bars, corrugated roofs, expanded metal lath, metal fences
Railroad tracks
Aluminum aircraft bodies

Fig 6

Table 1
EMP-Induced Surges on Conductors

Conductor Type	*EMP Rise Time (Microseconds)*	*Peak Voltage (Volts)*	*Peak Current (Amperes)*
Long, unshielded wires (power lines, large antennas)	0.01-0.1	100 k-5 M	1 k-10 k
Unshielded telephone wires at wall outlet	0.01-1	100-10 k	1-100
Ac power lines at wall outlet	0.1-10	1 k-50 k	10-100
HF antennas	0.01-0.1	10 k-1 M	500-100 k
VHF antennas	0.001-0.01	1 k-100 k	100-1 k
UHF antennas	0.001-0.01	100-10 k	10-100
Shielded cable	1-100	1-100	0.1-50

Table 2
Effects of Nuclear Detonations on Radio Systems

Frequency Range	*Degradation Mechanism*	*Spatial Extent and Duration of Effects*	*Comments*
VLF	Phase and amplitude changes	Hundreds to thousands of miles; minutes to hours.	Ground wave not affected, lowering of sky-wave reflection height causes rapid phase change with slow recovery. Significant amplitude degradation of sky-wave modes possible.
LF	Absorption of sky waves, defocusing.	Hundreds to thousands of miles; minutes to hours.	Ground wave not affected; effects sensitive to relative geometry of burst and propagation path
MF	Absorption of sky waves.	Hundreds to thousands of miles; minutes to hours.	Ground wave not affected
HF	Absorption of sky waves, loss of support for F-region reflection and/or multipath interference.	Hundreds to thousands of miles, burst region and conjugate; minutes to hours.	Daytime absorption greater than night-time, F-region disturbances may result in new modes, multipath interference
VHF	Absorption, multipath interference, or false targets resulting from resolved multipath radar signals.	A few miles to hunreds of miles; minutes to tens of minutes.	Fireball and D-region absorption, circuits may experience attenuation or multipath interference
UHF	Absorption.	A few miles to tens of miles; seconds to a few minutes.	Only important for line-of-sight propagation through highly ionized regions

that is connected to the equipment, but not to the primary conductor.

There are three basic ways to couple the EMP energy from a high-altitude nuclear explosion to a conductor on the earth: electric induction, magnetic induction and resistive coupling (direct-charge deposition). Electric induction occurs when a current is induced in a conducting element by the electric-field component that is in the same direction as the conductor's length. Magnetic induction takes place in conductors that are in the form of a closed loop. The magnetic-field component moving perpendicular to the plane of the closed loop causes a current to flow in the conducting loop. Resistive coupling occurs when a conductor is located in another conducting medium, ie, the earth, water or the air. When a current is flowing in the conducting medium, the conductor provides an alternative current path and shares the current with the medium. Resistive coupling can be generated as a by-product of electric or magnetic induction.

Nuclear Weapons Effects on Radio Signals

Nuclear weapons can degrade and black out radio signals far from the immediate blast zone. Degradation of radio signals by nuclear weapons varies with the explosion yield, distance and altitude. Signal degradation may include high noise levels, absorption, attenuation, ionization and partial or complete blackout. The effects may extend hundreds to thousands of miles and last from minutes to hours. Normal HF ionospheric propagation paths (below the Maximum Usable Frequency—MUF) may be disrupted at the same time that new paths that were not previously available are created in the upper HF or low VHF bands. It is by no means certain, however, that HF communications will be completely disrupted under all circumstances (Table 2).

Lightning

Lightning and EMP have similar characteristics. Both take the form of a fast-rising electromagnetic pulse that can generate large currents in conductors. Earlier studies generally stated that the effects of EMP exceeded those of lightning, but more recent reports indicate that lightning effects can be equal to or exceed those of EMP in the lower-frequency spectrum, while EMP effects are more severe in the higher-frequency spectrum.

Lightning Description

Lightning is a natural, transient, high-current electrical discharge occurring in the atmosphere. Lightning occurs when a region of the atmosphere attains a huge electric charge with the associated electric fields large enough to cause electrical breakdown of the air, creating a discharge path for the charge.

The most common lightning path is the intracloud discharge path. From an electrical equipment standpoint, however, the cloud-to-ground lightning discharge path has the highest potential for causing power disruption and equipment damage. Typically, the upper portion of the thunder cloud carries a greater positive charge while the lower part of the cloud carries a large negative charge. In a cloud-to-ground lightning discharge, the negative charge in the cloud is lowered by the dissipation of the electrons into the earth. A typical cloud-to-ground lightning discharge can last from 1/5 to 1/2 of a second and is composed of several discharge components. The total discharge occurrence is called a *flash*. The typical lightning flash is composed of three to four high-current pulses called *strokes*. Each stroke lasts about 1 millisecond with a delay between strokes of 40 to 80 ms. The first stroke is initiated by a preliminary breakdown in the cloud, which channels a negative charge toward the ground in a series of short luminous steps called the *step* *leader*. As the step-leader tip approaches the ground, the electric field beneath it becomes large and causes one or more upward-moving discharges to be initiated from the ground. When the downward-moving leader contacts one of the upward-moving discharges, the leader tip is connected to ground potential. The leader path ionizes the air making it a conductive plasma that is luminous. The return stroke, a ground potential wave, propagates up the ionized leader path discharging the leader channel. The return stroke produces a peak current of typically 30 kA in its lower portion, with a rise time of from zero to peak in about 2 μs. The return-stroke energy heats the leader channel to temperatures approaching 60,000 °F and produces a high-pressure channel that expands to generate a shock wave that is heard as thunder. If a residual charge is available at the top of the channel, a charge called a *dart leader* may propagate down the first stroke channel. The dart leader initiates the second, third and fourth return strokes, if any.

Lightning Energy

The normal peak current in a single return stroke will range from 10 to 40 kA with 175 kA for a severe stroke and with a charge transfer of 2.5 C (coulombs).[3] The total lightning discharge, when composed of several strokes, can transfer a charge of 25 C. The energy associated with a typical lightning stroke will vary depending on the dynamic resistance of the conducting channel, with values estimated to range from 250 J to 10 MJ.

Lightning and EMP Compared

A direct or nearby lightning strike can equal or exceed the electromagnetic field strength of EMP. To compare a direct lightning strike with EMP, 35 kA will be used as an average value of the peak current of the first return stroke and 175 kA as the value of the peak current of a severe first return stroke. At 1 meter from a direct lightning ground strike, the magnetic-field energy for the average return stroke is equal to the EMP at a frequency near 10 MHz and exceeds the EMP at frequencies below 10 MHz. At 1 meter from a direct lightning ground hit, the energy of a severe lightning return stroke exceeds the EMP to frequencies above 10 MHz. At 50 meters from a severe lightning stroke, the energy of the total electric field exceeds that of EMP at frequencies below about 1 MHz; and for the average first return stroke, the total lightning electric-field energy exceeds that of EMP below about 300 kHz.

The major difference between lightning and EMP is the area affected. EMP can affect an area of thousands of square miles, while lightning can affect an area of only a few square miles, with severe effects normally within a few hundred feet from the lightning discharge path. EMP can damage small electronic components and transmission lines, while a direct lightning strike can cause major structural damage to antennas and towers, as well as electronic equipment.

Physical Effects on Equipment

The primary effects of EMP that are of interest to the Radio Amateur are those that would produce direct damage to the sensitive electronic components of the station. The amateur is also interested in the temporary blackout caused by disruption to the ionosphere. A nuclear detonation causes intense changes in the ionosphere that increase or decrease the amount of ionization within a particular layer of the atmosphere. This change can result in the absorption of the radio signal or change the signal path (refraction) to the extent that communication is not possible. The fireball itself can disrupt communications because it generates an opaque area that radio signals cannot penetrate.

More widely known disturbances such as blackout (the complete disruption of electromagnetic signals for a short period) and scintillation (the scattering of signal energy caused by fast-changing ionization irregularity) should not be confused with EMP. Neither of the foregoing can damage equipment like EMP can. Radio propagation degradation, through refraction and absorption, usually lasts for a few minutes to a few hours, depending on the frequency. It is important only where continuous communications are of vital importance, because blackout and scintillation are only temporary and produce no permanent damage to primary or ancillary radio equipment. EMP, however, produces almost instantaneous and possibly permanent damage to sensitive electronic components. Fig 7 shows how signal propagation may be affected.

The components of the amateur's radio system that can be most affected are those directly attached to a primary collector (conductor) of EMP energy. The amateur's transceiver is most sensitive where it is connected to the commercial power lines and the antenna transmission line. Other sensitive connection points include the microphone, telephone lines and any remote-control lines.

There is a large number of electronic and electrical components that can be permanently damaged by the voltage and current surges induced by EMP/transients. As a general rule, smaller components are more susceptible to damage than larger ones. The most susceptible components are ICs, then discrete transistors. Somewhat less susceptible components are capacitors, resistors and inductors. Least susceptible are the large components such as solenoids, relays, circuit breakers, motors and transformers.

Transceivers

The typical amateur transceiver is subject to EMP/transient damage and temporary effects from a number of sources. The primary sources are EMP energy collected by antennas, transmission lines and electrical-power lines; to a lesser extent by remote-control, telephone, microphone and speaker lines, and so on. The transceiver would be damaged primarily where these lines enter it at the antenna matching network, internal power supply, telephone-patching equipment, microphone and speaker connections, and so on. If the transceiver case is metallic, it may provide enough shielding to prevent damage from EMP energy collected directly by the transceiver's internal wiring and circuits.

Where EMP energy does enter the transceiver, it may burn out ICs and FETs. More hardy components, when not destroyed completely, may have degraded performance because of changes in their electrical properties. All solid-state components may experience a change in state that causes temporary signal errors or that requires resetting. Vacuum tube equipment has shown little vulnerability to EMP.

Small VHF radios contained in metal cases are not vulnerable if the external microphone and antenna are disconnected. Also, the radio must be physically removed from other external conductors such as power cords and telephone lines.

Antennas

Antennas are designed to be efficient collectors of electromagnetic energy at their design frequency. An antenna designed to operate in that part of the RF spectrum where EMP energy is high will exhibit a high coupling efficiency for EMP. It is possible for high voltages and currents to be coupled into these efficient EMP antennas. Equipment attached to these antennas will likely be damaged by the resulting energy. Antennas designed to operate at frequencies outside the EMP energy spectrum will be less likely to act as efficient couplers and may not collect high voltages and currents.

Since most high-altitude EMP energy is concentrated between 100 kHz and 10 MHz, antennas in this frequency range will be subject to the strongest EMP-induced voltages and currents. All antennas designed to operate between 10 and 100 MHz will also be subject to high EMP-induced voltages and currents; however, the EMP energy decreases steadily as the frequencies increase. In general, all antennas designed to operate at frequencies below 100 MHz will be subject to strong EMP coupling, since 99% of the EMP energy is found below 100 MHz. Unfortunately for the radio amateur, the HF bands fall within that part of the spectrum that contains a great amount of EMP energy and a high coupling efficiency. On the other hand, amateur VHF antennas are less efficient collectors of EMP energy since they operate above 100 MHz.

When exposed to a high-altitude EMP event, the amateur's HF antenna could collect a potential of several thousand volts. These high voltages could physically damage the antenna line, balun and any at-

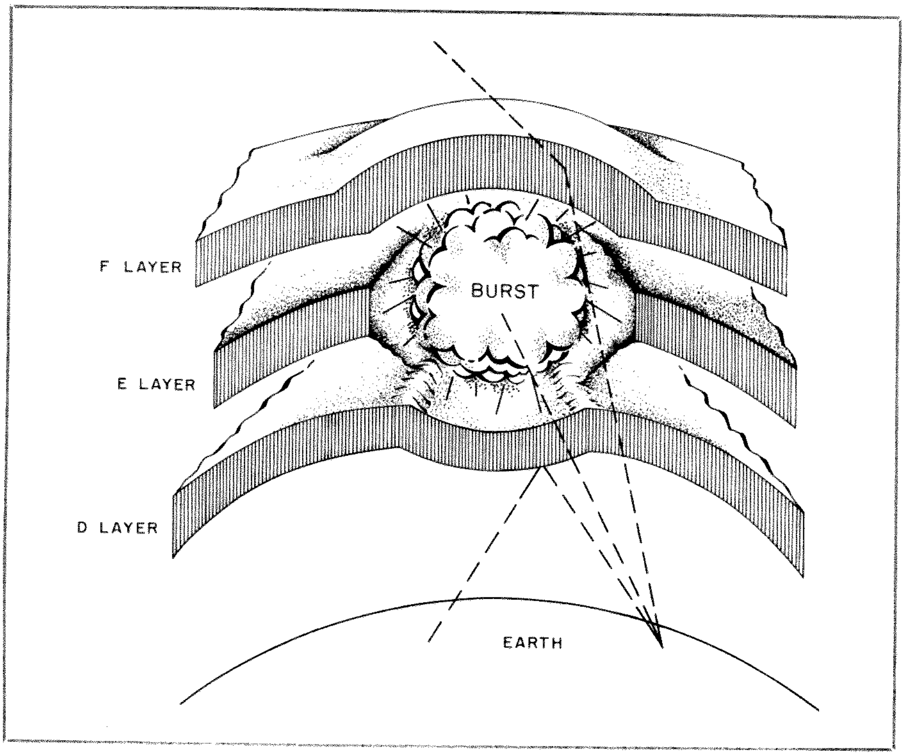

Fig 7—Atmospheric disruption and warping of the Earth's atmosphere caused by a nuclear explosion. Dashed lines show hypothetical signal propagation

tached electronic equipment. Other conductors associated with the antenna system can act as collectors of EMP energy. They are the control cables to the antenna rotator, the antenna mast, guy wires and even the ground system. These all can collect high levels of energy and conduct it directly or indirectly to sensitive electronic equipment. These unintentional collectors are, in many instances, more efficient EMP antennas than the RF antenna they support. Their coupling efficiency is determined primarily by their length, which may be long enough to allow them to operate as an EMP antenna in the strongest part of the EMP energy spectrum. Energy from these collectors, when not directly connected to sensitive radio equipment, can jump or arc to conductors (even short ones) that are connected to radio equipment.

Commercial Power Equipment

Transmission Lines

Power-transmission lines are extremely efficient collectors of EMP energy. The long runs of open, exposed wire can couple large voltage and current transients. Long, unshielded power lines can experience peak EMP-induced surge voltages of between 100 kV and 5 MV, and peak currents of between 1 kA and 10 kA.

Power-transmission lines act as long current conductors with the earth acting as a return conductor. The EMP-induced current flows down the line through the load (equipment) to ground. The amount of energy dissipated in the load depends on the impedance of the load path to ground. Equipment that presents a large impedance will experience larger peak voltages than equipment exhibiting a smaller impedance and therefore may experience more damage.

Power-Line Transformers

Normal power-line transformers will pass a part of EMP-generated currents through capacitive coupling across the windings. Commercial power transformers reduce the severity of the EMP by decreasing the peak voltage and extending the rise time of the pulse. In addition, the internal inductive and capacitive reactances of the transformer make the transformer act like a band-pass filter that attenuates frequencies below 1 and above 10 MHz.

Power-Phase Differences

EMP currents that are generated in the three phases of a power line are similar, and voltages in all three phases are nearly equal with respect to ground. The greatest danger exists to equipment connected from one phase to neutral or ground. Less danger exists to equipment connected between phases. The typical household wall outlet supplies 117 V, single phase. Therefore, amateur equipment using this 117-V power source is susceptible to receiving damage from EMP.

Household Circuit Breakers

Household circuit breakers will not offer EMP protection to the amateur's radio equipment because the damaging pulse will pass through the circuit breaker before it has time to react. However, internal arcing in the breaker box and in normal household wiring may limit the peak pulse to about 6 kV.

The amateur should expect the local commercial power system to be damaged and experience outages from the EMP transient. These outages could last for several hours to several days. The power-line EMP transients can cause component damage.

Telephone Equipment

The commercial telephone system consists, in large part, of unshielded telephone switches and cable systems. Although a considerable amount of lightning protection has been built in, there is little protection provided for EMP voltage and current surges. An unshielded telephone line may experience a peak voltage between 100 and 10 kV and a peak current of between 1 and 100 A. In recent years, the telephone companies have started using solid-state switching systems that could be highly sensitive to EMP. The older, existing transient over-voltage protection for telephone circuits is robust and can withstand repeated EMP transients without damage. Even the typical telephone handset is likely to withstand EMP without damage. Amateur telephone-patching equipment, however, is subject to EMP damage and should be protected.

Computers

One price that modern users pay for the convenience of microelectronics is a greater susceptibility to electrical transients. In computers, particularly when used with Amateur Radio equipment, the same kinds of vulnerability exist as with regular ham gear, only more so. In a typical amateur setup, the program and data are input through a keyboard, cassette recorder or disk drive, and a video display terminal (VDT), printer, cassette recorder and disk drive serve as output devices.

Microprocessors are especially susceptible to EMP and transient-voltage surges. Damage to an amateur's computer can run from simple logic upset or temporary memory loss to fused components and permanent memory loss. Increased voltage may destroy the cathode-ray tube (CRT) and disrupt or otherwise impair disk drives and other ancillary equipment.

Repeaters

Microcomputers are having a large impact on FM repeater design and on an increasing number of automated systems under program control. Repeaters are subject to the same threats as any amateur

(continued on page 36)

Electromagnetic Pulse

(continued from page 20)

piece of equipment. Often, repeaters are collocated with other communications equipment on a joint-use antenna tower. This makes them quite susceptible to receiving an EMP.

Antenna Rotators

Heavy-duty motors are less susceptible to EMP than smaller, less-rugged electronic components. Antenna rotators, although fairly immune to EMP effects because of their normally heavy metal cases and large components, may be rendered useless if there is a line-voltage surge to the rotator remote-control box. The line surge need not be caused by an electromagnetic pulse.

Satellite Transceivers and Antennas

Because of the sophisticated nature of satellite transmitters and receivers, and especially of their antenna systems, EMP and line-voltage transients remain serious problems. As noted earlier, the satellite itself is susceptible to SGEMP.

Satellite antenna systems require azimuth and elevation rotators. These rotators are fairly resistant to EMP. However, the antenna tower or mast and the remote-control lines are very likely to pick up large surge currents from EMP and lightning. The ac power supply for the rotators may fail, leaving the antenna array useless or extremely difficult to aim. Marrying a computer and satellite transceiver increases the station vulnerability. Virtually all stations, regardless of the type of equipment used, will be hostage to the commercial power supply unless, served by a separate, emergency back-up power source.

Part 2 will discuss the testing of EMP/transient protection devices.

[Editors Note: This series of articles is condensed from the National Communications System report (NCS TIB 85-10) "Electromagnetic Pulse/Transient Threat Testing of Protection Devices for Amateur/Military Affiliate Radio System Equipment." A copy of the unabridged report is available from the NCS. Write (no SASE required) to Dennis Bodson, Acting Assistant Manager, Office of Technology and Standards, National Communications System, Washington, DC 20305-2010, or call 202-692-2124 between 8:30 AM and 5 PM Eastern Time.]

Notes

[1]When the term "radio amateur" is used in this report, it includes the MARS amateur volunteer.

[2]One joule (J) is the energy expended during one second by an electric current of 1 ampere flowing through a 1-ohm resistance. One joule is equal to 1 watt-second. A 60-W light bulb burning for 1 second expends 60 J of energy.

[3]The coulomb is defined as the ampere-second. One ampere is the current intensity when 1 coulomb flows in a circuit for 1 second.

Electromagnetic Pulse and the Radio Amateur

Part 2: This month, we present the method and results of the first of two series of tests of EMP/transient-protection devices.†

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The inherent weakness of solid-state components to damaging transient electrical energy has stimulated the electronics industry to develop a large variety of transient-protection devices. In order to identify low-cost, commercially available devices capable of protecting Amateur Radio equipment, an extensive market search was made and a representative number of protective devices were purchased. The protection devices purchased were the most current types available for use with Amateur Radio equipment where it connects to power lines, antenna systems, communications lines and other potential transient sources. The test program was divided into two stages: First, the protection devices, then the Amateur Radio equipment.

Test Objectives

No common test procedure existed for determining the effectiveness of different types of protection devices. Therefore, we sought to develop a common test procedure to ascertain the average performance of a wide variety of devices against the fast-rising and powerful transient pulses that are generated by lightning and EMP. Three standard electromagnetic pulses were used to simulate the expected transient waveforms associated with ac power connections, short interconnecting wires and long exterior conductors that are found in the typical Amateur Radio installation.

Protection devices that allowed a voltage spike to exceed their rated clamping voltage by 100% (6 dB), or exhibited a significant delay in response time, were rejected. The 6-dB overload level was selected because it is common to design electronic circuits to withstand such an overload for short durations. Those devices that suppressed the initial voltage spike to an acceptable level, less than twice the clamping voltage, were accepted for further testing.

Table 3
Peak Voltage and Current Values vs Conductor Type

Conductor	*Peak Voltage (Volts)*	*Peak Current (Amperes)*	*Test Class*
Power Connections	600	120	A
Box interconnections	600	20	B
Exterior Conductors	4500	1000	C

Test Program

Threat Definition

Other than in the case of a direct lightning strike, EMP is generally considered a more stringent threat to electrical systems than lightning. Consequently, the test pulses approximated the characteristics of EMP, rising to full strength in approximately 10 ns and decaying exponentially in about 1 μs. The waveform that is frequently used in unclassified work was used for this test; it is expressed as:

$$E(t) = 5.25 \times 10^4 \exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t) \qquad \text{(Eq 1)}$$

where
E is volts per meter
t is time in seconds

The transient threat to electrical hardware does not come directly from the free field, but from the interaction of the electric and magnetic fields with electrical conductors. Current peaks in excess of thousands of amperes are predicted as a response to EMP. Similarly, voltage levels may reach hundreds of kilovolts. In practice, however, the physical dimensions and characteristics of the conductors themselves tend to limit current and voltage amplitudes, although not always without physical damage to the conductors. For example, it has been proposed that the highest transient voltage transmitted through a residential power-distribution breaker box would be limited by air-discharge breakdown. Conversely, in an Amateur Radio station, the transients experienced, if limited at all, would be determined by the lengths and configurations of conductors exposed to the fields, and the dielectric strength.

The peak values shown in Table 3 were used in the protective-device qualification tests for this program. These peak values were used because they are representative of the transient pulses expected in a typical Amateur Radio system, and they could be readily reproduced in a laboratory test environment.

To test for insulation breakdown of the protective devices, the highest pulse level obtainable in the laboratory (25 kV) was used. Each protective device was subjected to ten equal pulses in order to ensure that protection was not circumvented by the first transient received. A cooling time of approximately one second was allowed between pulses.

Direct Testing

Direct device testing consisted of driving the device terminals with a differential-mode signal from a pulse generator. The test was conducted once with a source impedance appropriate to the voltages and currents listed in Table 3, and once with the tabulated voltage and a source impedance of 50 ohms. This impedance was chosen because it is encountered most commonly in house wiring and antenna circuits. The input- and output-pulse magnitudes were recorded photographically. A comparison was made of the input and output voltages with and without the device in the circuit,

†Part 1 appears in Aug 1986 *QST*. Part 3 will appear in a subsequent issue.

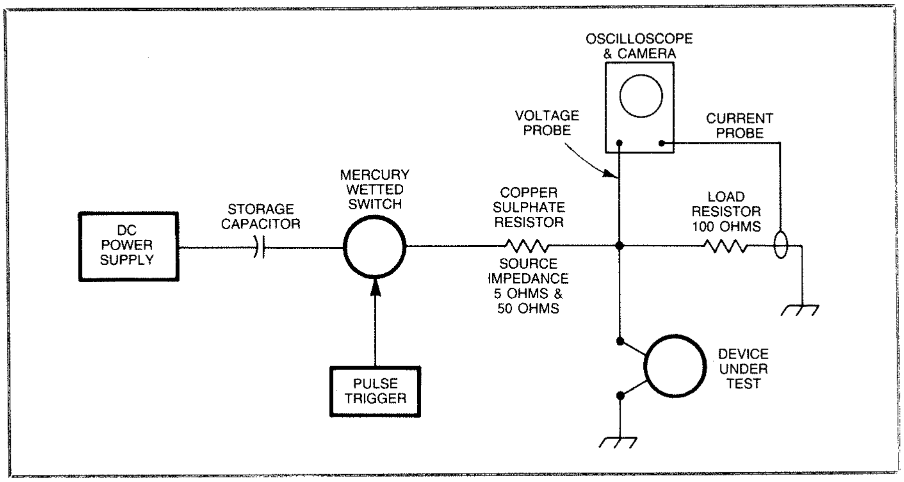

Fig 8—Low-voltage pulser; below 5 kV.

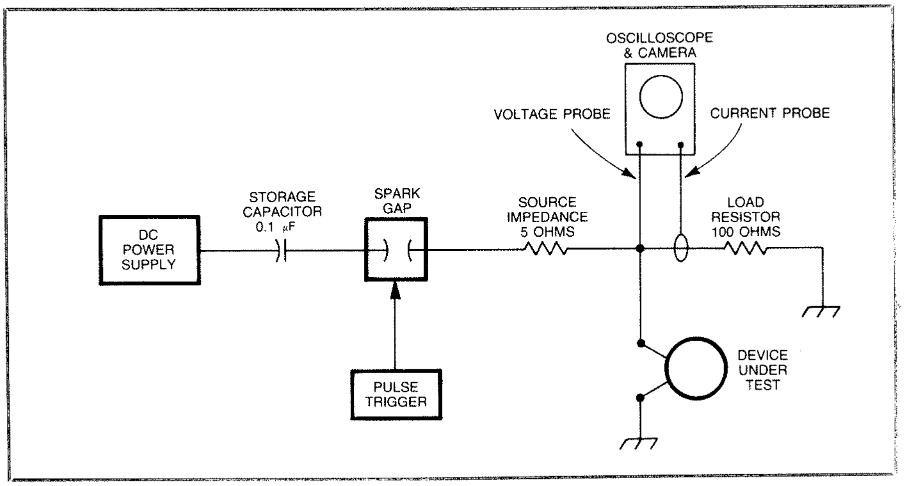

Fig 9—High-voltage pulser; above 5 kV.

and a transient-rejection ratio (in decibels) was calculated using the relationship:

$$\text{RR dB} = 20 \log_{10} \frac{\text{peak signal in}}{\text{peak signal out}} \qquad \text{(Eq 2)}$$

From one to 15 devices of each type were tested. When 10 identical devices of any one type had been tested with forward and reverse polarity, the data were statistically analyzed to determine if further testing was required. For statistical analysis, 10 items were considered to provide a representative sample of the device's performance, since the devices performed consistently.

Test Equipment

Two pulse generators were used. One provided pulses below 5 kV (600-V and 4.5-kV tests), the other produced pulses above 5 kV (25-kV test).

Pulses Below 5 kV

Transient pulses for this test were generated by manually firing a mercury-wetted switch to discharge a storage capacitor through a copper-sulphate source resistance of the appropriate size to generate the desired current pulse (see Fig 8). The capacitor was charged to the desired voltage level by a quick-recovery, high-voltage power supply. Transients were fired across a 100-ohm load resistor protected by the device under test.

Data were recorded by photographing a properly calibrated oscilloscope display. For repeated pulse requirements, the camera shutter was held open to record all (nominally 10) of the pulses of one polarity, and then, after removal of the device under test, to record the applied transient with the same exposure. Reverse-pulse measurements were obtained by reversing the leads of the device under test and repeating the photographic sequence.

Pulses Greater Than 5 kV

Transient pulses for this test were generated by manually firing a 2-inch spark gap to discharge a 0.1-μF storage capacitor through a 5-ohm copper-sulphate source resistance to generate the desired current pulse (see Fig 9). The capacitor was charged to the desired voltage level by a quick-recovery, high-voltage power supply. The transients were fired across a 100-ohm load resistor protected by the device under test.

Again, data were photographically recorded. Current and voltage were recorded for the initial pulses of each device. The voltage probe was attenuated by a flexible copper-sulphate resistance of suitable value. For repeated pulse requirements, the camera shutter was held open to record five of the pulses and the reference in a manner similar to that of the lower-voltage measurements described previously. The polarity of the second set of five pulses was not reversed, and the current trace was usually omitted from the second data set.

Small-Device Tests

For physically small devices, test measurements were conducted inside a metal enclosure. Penetrations of the enclosure were made by the high-voltage lead from the mercury-wetted switch, the system ground and the voltage probe. Currents were measured by a sensor on the system ground, but were not regularly recorded as part of the test data. The voltage probe was run in solid-sheath coaxial cable to the metal enclosure, and the internal probe was shielded by a metal braid to within a few millimeters of the probe tip.

Shunt-protective devices were connected between the high-voltage input terminal and system ground. The voltage probe and load resistor were also connected to the same terminals. For device combinations containing series elements, the line side of the device was connected to the input terminal, and the voltage probe and load resistor connected between the load side terminal and ground.

Large Devices

For devices with special connectors too large to fit within the test chamber, connecting adapters were made of straps and braid to provide the lowest-impedance circuit available. In many cases, however, the inductance of the connection did affect the measurement, particularly in the case of determining the reference grounds.

Ac Power Tests

To test the ability of the devices to function when connected in a 117-V ac circuit, ac was provided by an isolation transformer connected to the device through a large inductance. If the device continued to arc or pass current after the pulse, the transformer was manually disconnected (but not always before the device had melted).

Test Results

A total of 56 different devices were tested. All of the devices substantially suppressed the test pulses. However, not all of the devices suppressed the test pulse to an acceptable voltage level on every test.

Twenty-six of the 56 devices passed the low-impedance drive tests and 40 passed the high-impedance drive test. To pass the particular test, the device had to suppress the peak-voltage pulse to less than two times its published, designed clamping

Table 4
Devices with Acceptable Clamping Voltages
Low-Impedance Drive Tests

Manufacturer and Device	*Designed Maximum Clamping Voltage (MCV) (Volts)*	*Average Measured Peak Clamping Voltage at 600 V and 4.5 kV (APV) (Volts)*	*Acceptable Clamping Voltage (APV = <2 MCV)*
Fischer			
FCC-120-P	300 (1)	200	300
FCC-250-300-UHF	300	1333	
FCC-250-300-UHF	350	1633	
FCC-450B-75-BNC	75	670	
FCC-250-150-UHF	150	1700	
FCC-250-120-UHF	120	1700	
FCC-450-120-UHF	120	800	
Joslyn			
2027-23-3B	230	600	
2027-35-B	350	1940	
1270-02	190	400	
1250-32	350	2300	
1663-08	66		
2027-09-B	90	1820	
2027-15-B	150	1620	
2022-44	250	1460	
2031-23-B	230	1560	
2031-35-B	350	1360	
General Electric			
V39ZA6	76	132	76
V82ZA12	147	230	147
V180ZA10	300	428	300
V8ZA2	20	120/690	60 (3)
V36ZA80	63	120	63 (3)
PolyPhaser Corporation			
IS-NEMP	200 (2)	380	200
IS-NEMP-1	200 (2)	380	200
IS-NEMP-2	200 (1)	600	
TII			
Model 428	280	350	280
Siemens			
S10K11	40	120/690	
S20K25	80	131/720	80
S14K50	125	220/620	125
S10K60	160	265/710	160
S14K130	340	464/1050	340
B1-C75	75 (2)	600/910	
B1-C90/20	90 (2)	600/938	
B1-C145	145 (2)	600/880	
B1-A230	230 (2)	600/960	
B1-A350	350 (2)	632/1020	
S8-C150	150 (2)	600/4500	
T61-C350	300 (2)	672/990	
Alpha Delta Communications, Inc (4)			
LT	635 (1)	4500	
R-T	635 (1)	400	635
General Semiconductor			
587B51	650	290	650
ICTE-5	7.1	112/560	60 (3)
ICTE-15	20.1	116/580	60 (3)
ICTE-8C	11.4	119/510	
LCE-6.5A	11.2	239/780	
LCE-15A	24.4	158/590	
LCE-51	91.1	188/770	
LCE-130A	209	270/830	209
PHP-120	319	—	—
GHV-12	8	155/590	80 (3)
GSV-101	0.85	115/500	60 (3)
GSV-201	1.7	120/570	60 (3)
Electronic Protection Devices, Inc			
Lemon	300 (1)	380	300
Peach	300 (1)	350	750 (3)
S. L. Waber			
LG-10	300 (1)	550	300
Archer (Radio Shack)			
61-2785	300 (1)	90	300

(1) Estimated or calculated
(2) Dc break-down voltage
(3) Acceptable above 2 MCV
(4) Alpha Delta recently released new versions of their Transi-Trap™. These units are the Model R-T and LT having an "EMP" suffix. In these units, the EMP clamping level is three times lower than previous designs.

voltage, or exhibit an acceptable response waveform.[4] The manufacturer of the protection device normally establishes the maximum clamping voltage using a much slower pulse (8 μs rise time and 20 μs decay time) than the expected electromagnetic pulse and the test pulse (10 ns rise time and a 1 μs decay time). In some cases, the dc breakdown voltage is used as the reference clamping voltage. Therefore, the measured clamping voltage of the devices was expected to be higher than the published figure. During the tests, these higher clamping voltages were found with few exceptions.

Low-Impedance Testing

The low-impedance test was conducted at two different voltage levels (600 V and 4.5 kV). The devices were tested with positive- and reverse-polarity pulses. There was no significant difference in response caused by the different polarity pulses, with the exception of certain General Semiconductor TransZorbs®.

Twenty-six devices were considered to have acceptable pulse-suppression characteristics. The most consistent performer was the metal-oxide varistor (MOV)[5]. Varistors suppressed the leading edge of the pulse wave to less than two times the designed clamping voltage. Table 4 shows those devices that have acceptable clamping performance. The accepted devices have rejection ratios that range from 0.75 dB to 16.47 dB for the 600-V test pulse, and from 13.06 dB to 21.47 dB for the 4.5-kV pulse.

Gas-discharge tubes and devices containing only gas-discharge tubes did not respond well to the 600-V pulse. The rise time (10 ns) and the low voltage level were not sufficient to cause the tube to ionize and conduct the test pulse to ground within the rise time. With 10 pulses being injected at a 1-second injection rate, the gas-tube ionization was delayed for periods of up to 4000 ns for each pulse, and in some cases, the measurements were off the observable scale. This slow response time makes the gas-discharge tube an unacceptable device to use as the sole protection unit for a low-voltage pulse with a slow rise time such as experienced with the 600-V pulse that had a rise time of only 60 V/ns.

Twenty devices were considered to have acceptable measured clamping voltages on the low-impedance test. Six other units had a satisfactory response waveform and were accepted although their clamping voltage was over two times their published or design clamping level. Not all of the devices were tested at the 600-V level. Of the ones that were, the varistors and the ac power-line protection devices were the best performers.

High-Impedance Testing

This test was conducted only at the 4.5-kV level. The devices were tested with positive- and reverse-polarity pulses. Again, no significant response differences were noted with the different polarity pulses, except with the TransZorbs. The 4.5-kV, 50-ohm test pulse is considered to be the most accurate simulation of the expected EMP energy that will be impressed on the ac power and coaxial-cable

[4]Notes appear on page 26.

Table 5
Devices With Acceptable Clamping Voltages High-Impedance Drive Test

Manufacturer and Device	*Designed Maximum Clamping Voltage (MCV) (Volts)*	*Average Measured Peak Clamping Voltage at 4.5 kV 50 Ohms (APV) (Volts)*	*Acceptable Clamping Voltage (APV = <2 MCV)*
Fischer			
FCC-120-P	300 (1)	420	300
FCC-250-300-UHF	300	393	300
FCC-250-300-UHF	350	260	350
FCC-450B-75-BNC	75	210	
FCC-250-150-UHF	150	220	150
FCC-250-120-UHF	120	240	120
FCC-450-120-UHF	120	120	120
Joslyn			
2027-23-3B	230	310	230
2027-35-B	350	366	350
1270-02	190	600	500 (3)
1250-32	350	940	
1663-08	66	90	66
2027-09-B	90	378	
2027-15-B	150	242	150
2022-44	250	294	250
2031-23-B	230	336	230
2031-35-B	350	291	350
General Electric			
V39ZA6	76	254	150 (3)
V82ZA12	147	254	147
V180ZA10	300	388	300
V8ZA2	20	174	100 (3)
V36ZA80	63	170	100 (3)
PolyPhaser Corporation			
IS-NEMP	200 (2)	140	200
IS-NEMP-1	200 (2)	150	200
IS-NEMP-2	200 (1)	160	200
TII			
Model 428	280	410	280
Siemens			
S10K11	40	186	100 (3)
S20K25	80	190	150 (3)
S14K50	125	234	125
S10K60	160	232	160
S14K130	340	436	340
B1-C75	75 (2)	220	
B1-C90/20	90 (2)	210	
B1-C145	145 (2)	200	145
B1-A230	230 (2)	218	230
B1-A350	350 (2)	230	350
S8-C150	150 (2)		
T61-C350	300 (2)	250	300
Alpha Delta Communications, Inc (4)			
LT	635 (1)	700	635
RT	635 (1)	720	635
General Semiconductor			
587B51	650	600	650
ICTE-5	7.1	134	
ICTE-15	20.1	146	
ICTE-8C	11.4	124	
LCE-6.5A	11.2	250	
LCE-15A	24.4	200	
LCE-51	91.1	220	
LCE-130A	209	210	209
PHP-120	319	400	319
GHV-12	8	218	
GSV-101	0.85	168	
GSV-201	1.7	174	
Electronic Protection Devices, Inc			
Lemon	300 (1)	580	300
Peach	300 (1)	1000	750 (3)
S. L. Waber			
LG-10	300 (1)	600	300
Archer (Radio Shack)			
61-2785	300 (1)	300	300

(1) Estimated or calculated
(2) Dc break-down voltage
(3) Acceptable above 2 MCV
(4) Alpha Delta recently released a new version of their Transi-Trap™. This unit has an EMP suffix. In these units, the EMP clamping level is three times lower than previous designs.

interfaces to the amateur's equipment. Therefore, the results of this test were expected to be the most significant of the program. The devices tested are listed in Table 5.

Varistors

Varistors performed adequately during the test. The General Semiconductor, General Electric and Siemens varistors performed consistently. The varistors tested had clamping voltages ranging from 0.85 V to 350 V. The average measured varistor clamping voltage ranged from a low of 168 V to a high of 436 V. Nine out of 12 varistors were found to have acceptable clamping voltages. Three varistors exceeded their designed clamping voltage, but performed consistently and could be used at a higher voltage level if desired.

Gas-Discharge Tubes

The advantage of using a gas-discharge tube is in its ability to handle large power transients for short periods.[6] One of the disadvantages of gas tubes is that once they begin to conduct, a continuous ac or dc operating voltage of the proper level will keep the tube in the conductive state after the pulse has passed. This characteristic can result in the destruction of the tube, as was experienced during another phase of this test program. Several gas tubes were destroyed when attached to an isolated ac power source and then exposed to a 25-kV pulse. The pulse started the tube's conduction and the ac power sustained the tube's ionization and conduction until the tube was destroyed.

In a special test, two gas tubes were connected in series between the pulse source and system ground. An ac voltage was impressed across the source circuit and then through a 100-ohm resistor to ground. The gas tubes did not begin to conduct until they were pulsed. When pulsed, the tubes ionized and conducted the pulse to ground, then shut off. The applied ac power did not sustain the ionization across the series-connected tubes.

Similarly, a gas tube and a varistor were connected in parallel to ground with an ac current in the circuit. When pulsed, the tube ionized and conducted the transient current to ground while sharing the current with the varistor, then shut down without being destroyed. It was concluded that gas tubes could be used for their high power handling capabilities, but only when used at the proper voltage levels or with another device to cut off the tube. This design adaptation is found in commercial ac-power protection devices and RF devices using gas tubes.

Coaxial-Line Protectors

Eleven RF protection devices from three suppliers were tested. These devices are designed to be placed in the coaxial transmission line. All of the units, with the exception of the one with the lowest clamping voltage, were accepted. This exception, the Fischer FCC-450B-75-BNC, is rated to clamp at 75 volts. It did suppress the 4.5-kV pulse to an average of 210 V and was given a rejection ratio of 26.62 dB, still very good performance.

The measured clamping voltages ranged from a low of 120 V (for a device rated at 120 V) to a high of 720 V (for a unit rated at 635 V). The coaxial-line protectors exhibited a very high rejection ratio to the 4.5-kV high-impedance pulse, starting at a low of 16.15 dB for the Alpha Delta Transi-Trap R-T to a high of 30.14 dB for the Polyphaser IS-NEMP devices. The Fischer FCC-250-350-UHF clamped 90 V below its rated clamping voltage of 350 V. This was not considered to be a problem, but a lower clamping voltage potentially could interfere with the transmitted RF signal.

Power-Line Protectors

There are numerous ac power-line protection devices available, but our selection was limited to the lowest-cost devices. Ten devices from seven sources were tested. All of the units, with the exception of the Fischer FCC 120 F-P, Joslyn model 1250-32 and the General Semiconductor models 587B051 and PHP 120, could be plugged directly into an ac wall outlet.

Internally, the devices consist of a combination of gas-discharge tubes, varistors or other protective circuitry. All except one were found to be acceptable. The published clamping voltages ranged from a low of 190 V to a high of 650 V. For several devices, the designed clamping voltage was not known, so a 300-V level was assigned to them for purposes of comparison. The measured clamping voltages ranged from a low of 300 V to a high of 1 kV.

TransZorbs

Seven units from General Semiconductor were checked in an effort to find a device that would clamp at a very low voltage level. The one with the lowest-rated clamping voltage is the ICTE-5 (7.1 V); the unit with the highest-rated clamping voltage is the LCE-130A (209 V). Average measured clamping voltages ranged from a low of 124 V to a high of 250 V. Only one of the units was accepted — the LCE-130A. Rated at 209 V, it had an average clamping voltage of 210 V. All of the other TransZorbs conducted only at levels considerably above their ratings.

Test to Failure

The larger of the two pulse generators was used to generate a 25-kV pulse at 4 kA for 1 μs. This provided a total energy output of 100 J. Up to five each of the 36 devices were tested with only three of them approaching failure. The three ac power-line protection devices experienced excessive internal arcing, although they did not fail completely. All of the other devices survived the 10 pulses and suppressed the voltage transient voltage without failure.

Conclusions

Of the 56 devices tested, there are many that have acceptable transient-voltage suppression capabilities and can be used for the protection of Amateur Radio equipment. These include ready-made units for direct connection to the ac power lines and coaxial antenna lines as well as smaller devices that can be used alone (varistors) or in combinations (gas-discharge tube/varistor) to protect other points.

[Editor's Note: This series of articles is condensed from the National Communications System report (NCS TIB 85-10) *Electromagnetic Pulse/Transient Threat Testing of Protection Devices for Amateur/Military Affiliate Radio System Equipment.* A copy of the unabridged report is available from the NCS. Write (no SASE required) to Mr Dennis Bodson, Acting Assistant Manager, Office of Technology and Standards, National Communications System, Washington, DC 20305-2010, or call 202-692-2124 between the hours of 8:30 AM and 5 PM Eastern.]

Notes

[4]The published clamping voltage of a device is the average voltage level where the device will change from a nonconducting state to a conducting state.

[5]Varistors are voltage-dependent devices that behave in a nonlinear electrical manner similar to back-to-back Zener diodes. When subjected to high-voltage transients, the varistor's impedance changes over a large range from a near open circuit to a highly conductive circuit, thereby switching the transient voltage to ground or some other point. Varistors are designed for a large assortment of switching (clamping) voltages.

[6]The tubes tested are sealed gas-discharge tubes consisting of two or three electrodes properly separated by insulators and filled with a rare gas. These tubes are designed to switch rapidly at a specific voltage level from a nonconductive to a conductive state (arc mode) when subjected to a fast-rising voltage transient. When the voltage across the tube's electrodes is increased, ionization of the inert gas occurs and the tube conducts across the electrode gap. The breakdown-voltage level is determined by the design of the tube's electrode spacing and the gas pressure.

Electromagnetic Pulse and the Radio Amateur

Part 3: In Part 2, we told how the EMP transient-protection devices were tested individually under isolated conditions. Now, the protectors are connected to Amateur Radio equipment and retested.†

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The tests described in the previous installment subjected 56 selected protection devices to several different injection pulses that simulated the waveforms and energies associated with EMP and lightning discharges. Those protective devices found acceptable during the first test program were then connected to several types of radio equipment and tested for their effectiveness in a typical Amateur Radio installation.

Since there is a large number of possible combinations of protection devices and radio equipment, low-cost devices were evaluated first. If they were found unacceptable, higher-cost protection devices were installed and tested until an acceptable protection scheme was developed. After completing the testing of the low-cost commercial devices (see Table 6), several homemade units, assembled from previously tested components (see Table 7), were checked. This was done with an eye toward finding a very low-cost protection device that could be built by the radio amateur. Six of these units will be described in the next installment of this series.

Sixteen system configurations (see Table 8) were tested at frequencies from 1.8 to 435 MHz. These systems included both new and old gear (some no longer manufactured, but available on the used-equipment market), and tube-type and transistorized radios. The equipment tested was manufactured by Drake, ICOM, Kenwood, Swan and Yaesu.

Measurements were taken of the radio system's performance before and after each pulse or pulse series to compare the radio's

Table 6
Commercial Protection Devices Tested

Manufacturer	*Part Number*	*Description*
Fischer	FCC-250-300-UHF	Coaxial line suppressor
Fischer	FCC-250-350-UHF	Coaxial line suppressor
Fischer	FCC-250-150-UHF	Coaxial line suppressor
Fischer	FCC-250-120-UHF	Coaxial line suppressor
Fischer	FCC-450-120-UHF	Coaxial line suppressor
Joslyn	2031-35-B	Miniature gas-tube surge protector (MSP)
General Electric	V36ZA80	Metal oxide varistor (GE-MOV)
Polyphaser Corp	IS-NEMP	Coaxial line protector
Polyphaser Corp	IS-NEMP-1	Coaxial line protector
Polyphaser Corp	IS-NEMP-2	Coaxial line protector
TII	Model 428	Plug-in power line protector
Siemens	S14K130	Metal oxide varistor (SIOV)
Siemens	B1-A350	Button type surge voltage protector
Alpha Delta	Transi-Trap R-T	Coaxial line protector
Archer	61-2785	Three-outlet ac power strip/protector

Table 7
Homemade Transient Protection Devices Tested

Device Name	*Description*
SIOV ac test box	Three Siemens MOVs (S14K130) installed in an ac receptacle box. One MOV wired from hot to ground, one from neutral to ground and one between hot and neutral
GE MOV	One GE MOV (V36ZA80) installed across the 12-V dc power line between hot and ground.
SIOV RF test box	The Siemens MOV (S14K130) installed in a metal box. The box had UHF connectors attached to both ends and a wire connected between the center conductors of the two connectors. The MOV was connected to the wire on one side and to the box on the other side.
Siemens UHF test box	Two Siemens gas-gap tubes (BI-A350) installed in the UHF connector box described above. The tubes were wired in series from the center conductor to the side of the box.
Joslyn UHF test box	Two Joslyn gas-gap tubes (2031-35B) installed in the UHF connector box in series from the center conductor to ground.
UHF coaxial T	Two Siemens gas-gap tubes (BI-A350) installed in series between the center conductor and case, on one leg of a coaxial T connector.

†Parts 1 and 2 appear in the Aug and Sep issues of *QST*, respectively. Part 4 will appear in a subsequent issue.

Table 8

Amateur Radio System Configurations and Ancillary Equipment Tested

System 1
Yaesu FP-757HF power supply
FT-757GX all-mode transceiver
FC-757AT antenna matching network

System 2
Yaesu FP-757HF
FT-757GX

System 3
Yaesu FT-726 VHF/UHF all-mode transceiver

System 4
ICOM IC-745 HF Transceiver
IC-PS35 internal power supply
IC-SM6 desk microphone
IC-AT100 antenna matching network
IC-SP3 external speaker

System 5
ICOM IC-745 HF transceiver
IC-PS35 internal power supply

System 6
ICOM IC-27A 2-m mobile transceiver

System 7
ICOM IC-02AT 2-m hand-held transceiver

System 8
ICOM IC-271A 2-m transceiver

System 9
ICOM IC-471A 430- to 450-MHz transceiver

System 10
Kenwood TS-430S HF transceiver
PS-430 power supply
MC-80 desk microphone
AT-250 antenna matching network
ST-430 external speaker

System 11
Kenwood TS-430S HF transceiver
PS-430 power supply
MC-80 microphone

System 12
Kenwood TR-7930 2-m mobile transceiver

System 13
Kenwood TR-2600 2-m hand-held transceiver

System 14
Drake T-4XC HF transceiver
R-4C HF receiver
4B power supply

System 15 (Not tested)
Collins KWM-2A HF transceiver
KWM-2A power supply

System 16
Swan 250 HF transceiver
117Z power supply

Antennas
Mosley JRS TA33 3-element tribander
Cushcraft AV-5 80- to 10-m vertical

Other Items
Astron VS-35 power supply
Honda EG 650 generator

transmitter power output and receiver sensitivity. First, stand-alone (equipment unwired) radio systems were subjected to a field-pulse wave. This disclosed any inherent design weaknesses and identified the internal areas that required protection. Damaged equipment was repaired and returned for further testing. After a series of field-only pulse tests, the simultaneous field and injection pulse tests were made.

Test Program

Threat Definition

The peak values used in these tests were:

EMP simulator pulse field:	50 kV/m
RF drive pulse:	275 A, 13.75 kV
Ac drive pulse:	130 A, 6.5 kV

In the *Simulator Field Tests,* the radio system was placed in the working volume of a large parallel-plate EMP simulator. The simulator's Marx pulse generator was discharged into the pulser wire elements with sufficient energy to produce a 50 kV/m field strength with a 10-nanosecond pulse rise time. For the *Simultaneous Field and Injection Pulse Tests,* the radios were kept in the same environment and two L-shaped wires were attached to the equipment.

Transient Injection Methods

The working volume of the parallel-plate simulator used for these tests, while large, was not sufficient to house an entire radio station including an antenna and residential power-line drop. Therefore, the station equipment was placed in the chamber, and pulses were injected that simulated the stresses carried to the equipment by the power lines and antenna. The maximum transient expected from the power line was about 6 kV since household wiring should limit the transient to this level. Antenna connections, however, are limited only by the spark-over levels of the installed antenna cabling.

Power-Source Transient Injection

Power for the systems in the test chamber was provided by an isolated generator that would prevent interaction with the pulser and data links used in the experiment. To simulate the connection of a typical residential supply, the neutral and ground leads of the isolated system were grounded to the pulser ground plane at a single supply box within the transient field. A transient injection pulse was generated by an L-shaped wire antenna within the test chamber. The antenna was connected to the hot lead of a power plug inserted close to the protective device under test. When a commercial plug-in device was used, the transient was injected into the same receptacle into which the device was plugged. If a fabricated protection device was used, the transient was injected into the device receptacle alongside the equipment power plug. This maximized the stress on the equipment while offering an opportunity for the free-field transient to couple with the equipment power cord after the protection device. The dimensions of the L-shaped antenna were adjusted until a current of 130 A was produced in a 50-ohm load.

Antenna Transient Injection

A larger L-shaped antenna was constructed within the test chamber for evaluation as an injection pulse generator for the antenna port of the equipment under test. Current, measured through a 50-ohm load resistor, was limited to about 80 A when two short lengths of coaxial cable were used between the antenna and load. Results of the removal of the cable from the transient path led to the conclusion that the coaxial cable and connectors greatly limit the magnitude of the transient imposed on radio equipment. The L antenna used in this test was considered adequate to stress any antenna connection terminal (at the equipment end) with a pulse as large as the coaxial cable could transmit. A possibility exists in a real transient situation that the coaxial cable itself may be damaged if not protected at the antenna end, but this condition could not be tested by the configuration used here.

Test Equipment

A parallel-plate EMP simulator 24 feet long, 20 feet wide and 11 feet high (Fig 11) was used. The Marx generator was charged by a high-power dc power supply and discharged through a spark-gap bank and output capacitor into the simulator's wire elements. These wire elements extended from the Marx generator through a 16-foot-long transitional section to a bank of copper-sulfate load resistors, which provided a termination load resistance (110-130 ohms) for the pulser. A 30-kV charge to the Marx generator was sufficient to provide a 50-kV/m field strength with a pulse rise time near 10 ns inside the working volume. The 30-kV charge to the Marx generator produced a 240-kV charge on the pulser elements.

A round and a square H-field sensor were used to provide daily calibration of the simulator and to measure the field strength during each test. Normally, only one sensor was used during the actual test. Four current sensors measured the output of Amateur Radio antennas erected in the

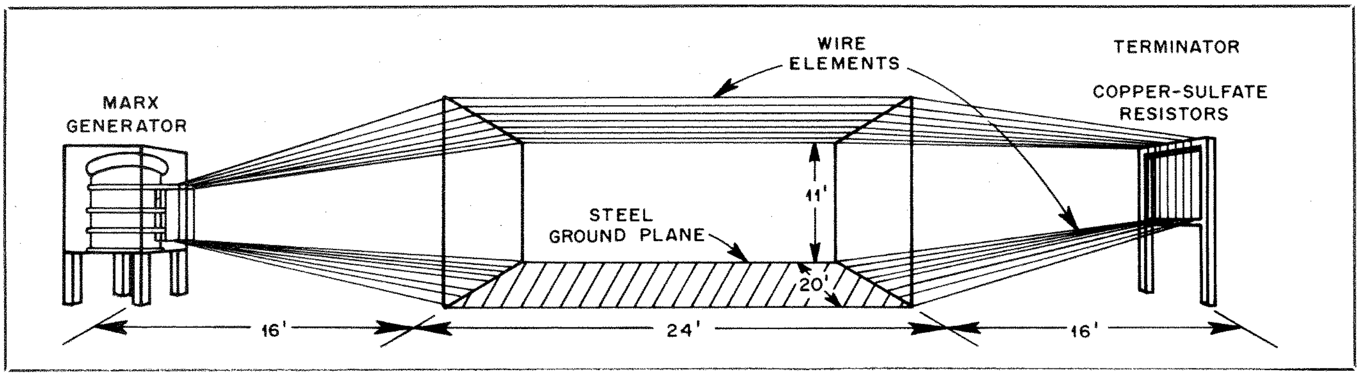

Fig 11—A drawing of the large parallel-plate EMP simulator used in the tests. The Marx generator is a high-voltage pulse generator in which several capacitors are charged in parallel through a high-resistance network. When the charge reaches a critical value, discharge occurs through spark gaps.

pulser field. The sensors also measured the output of the L-shaped wire antennas that were used to drive the ac power lines and antenna coaxial cables. A shielded coaxial probe and a fiber-optic system with a battery-powered, shielded transmitter took H- and E-field measurements. Sensor measurements were recorded on an oscilloscope. Photographs of the oscilloscope display were taken for each simulator pulse. Other test equipment included four signal generators and a wattmeter.

Radio System Tests

Each radio system was checked before and after each pulse. Transmitter power output was measured in the CW mode. This was done with and without any transient-protection devices in the feed line. That provided an evaluation of the protection device's suitability for that particular radio system, by showing its ability to pass the transmitted signal without clamping or without contributing a substantial loss of power output. Voice modulation was checked by observing the deflection of the wattmeter needle while speaking into the microphone. In some tests, the transmitter was monitored on a similar radio.

Receivers were placed on a set frequency in the USB mode with the RF amplifier on (if selectable) and the RF gain control set to maximum. The output of a signal generator was increased until the receiver's S meter read S5. (Receivers without an S meter were measured by listening for an audible signal in the speaker.)

Series A

For these tests, the radio equipment was placed on wooden carts 34 inches above the simulator floor. No interconnecting wires were attached to the equipment. All permanently attached external wires (such as power cords) were coiled and placed under the case of the radio equipment. This test evaluated the susceptibility of the radio's internal wiring and components to self-generated transient pulses resulting from exposure to a field pulse. All radios (with the exception of one, System 15, that was dropped from the test for prolonged maintenance problems) passed these tests with no measurable degradation.

Series B

Again, the radios were placed on the wooden carts. They were unpowered and ungrounded, but this time the interconnecting wiring and power cords were in place. This second test was designed to evaluate the radio's susceptibility to transient pulses generated by the internal wiring, and any external wires including microphone and power cords. All radios passed this test except for two, Systems 3 and 8. The receivers in these two systems exhibited decreased sensitivity: that of System 3 by 26 dBm and 8 dBm for System 8. Since a strong signal was still audible, the two systems were considered not to be seriously degraded and were accepted for further testing.

Series C

Only System 2 was used for this test. The transceiver was placed on the pulser floor and grounded to the pulser ground plane. All wiring was attached except for the coaxial feed line to the antenna. Tests were performed first with no ac power applied, then with power on. No degradation of the transceiver performance was measured.

Series D

This was a power-on test of the equipment with all external wiring and peripherals in place, including the coaxial antenna cable. Commercial transient-protection devices were installed in the ac power and antenna feed lines. Then, the ac power line and coaxial antenna cable were driven by an injected signal at the threat levels described earlier. All the devices, except one, provided adequate protection. System 2 sustained some internal damage during a test when the Alpha Delta R-T Transi-Trap was in the circuit. The Transi-Trap devices had performed satisfactorily during the first test program. [Note: As a result of this report, Alpha Delta has a new "EMP series" R-T and LT design. The new version has a clamping level three times lower than previous designs for maximum safety—Ed.]

Another protective device failed a post-test check. The Fischer FCC 450-120-UHF would not pass RF signal power. It was replaced.

Series E

Now, five assembled (experimental) transient-protection devices were tested (see Table 7). Of these five, one was an ac-line unit and four were RF assemblies. These tests were designed to find a low-cost solution to the transient-protection requirements of the radio systems under test. All of the units provided adequate protection of the radio equipment during the test pulse. Further testing revealed that three of the devices blocked the transmitted signal. The Siemens Metal Oxide Varistor (SIOV) RF Test Box containing a large-capacitance varistor blocked the signal over a wide frequency range. The Siemens UHF Test Box and Joslyn UHF Test Box containing the gas gaps were adequate at HF, but blocked the signal at higher frequency ranges. Although these three devices are adequate for receiver use, they are not recommended for use with a transmitter.

The UHF coaxial T was the best assembled device; it provided transient protection and could pass the transmitted signal over the full range of test frequencies. Also, the SIOV AC Test Box repeatedly provided necessary power protection required by the radio equipment. These two devices will be discussed in more detail in the next installment.

Series F

This series of field and injection tests had three configurations. First, the radio systems were fully protected. Then, transient protection was removed from the coaxial feed line. Finally, protection was removed from the ac power line as well. As expected, some equipment damage was experienced. However, the most surprising result of this test series was that only one radio system (System 2) experienced significant, permanent performance degradation. The other radios suffered various amounts of lowered transmitter power output and receiver sensitivity, but were still operational in their damaged state. A contributing factor in the survivability of the equipment was the influence the RG-8 coaxial cable had on the RF injection pulse (discussed later).

Antenna Tests

Measurements were taken of the response of two amateur antennas to the simulator pulse field in several different configurations. These included measurements taken with a 75-foot length of RG/8 cable attached and with a connection to the pulser ground plane directly through a 50-ohm resistor. The Mosley JRS TA33 Jr antenna generated a maximum of 152 A through 50 ohms for a 7.6 kV pulse level. The Cushcraft AV-5 produced a maximum output of 170 A through the 50-ohm resistor for an 8.67 kV pulse level.

An L-shaped wire antenna was placed in the pulser field to generate a drive current that could be injected into the coaxial cable attached to the radio equipment under test. The maximum measured output of this antenna was 175 A through a 50-ohm resistor for a maximum pulse level of 13.75 kV.

Two "rubber ducks" were tested. The maximum measured current was 8 A producing 400 V through 50 ohms. This low current was not sufficient to cause any degradation of the hand-held transceivers.

Coaxial Cable Effects

Measurements were made to determine the response of RG/8 coaxial cable in the pulse field alone and when attached to three different antennas: two amateur antennas and the RF-drive antenna. At the antenna side of the cable, large currents (250-290 A) could be found, but at the opposite end—with the 50-ohm resistor connected to ground—only 50-110 A was measured. We suspected that the coaxial cable was arcing. To test this, a piece of RG/8 cable was connected to a high-voltage dc supply and the supply voltage was slowly increased. Arcing between the center conductor and the coaxial connector began at a potential of 4 kV; the cable began arcing internally at 5.5 kV. We concluded that the RG/8 cable was acting as a spark-gap protector for the equipment under test. Given this condition, the protection devices installed in the feed line were needed only to suppress the approximate 4.4-kV pulse that would get through the cable.

Observations

Most of the solid-state, and all of the tube-type, radios were not susceptible to the simulator field pulses until long, external wires were attached. Short wires—microphone, power cord and internal wiring—did not generate sufficient transient pulse energy to produce observable damage to the radio equipment. When power lines and antennas are attached to radio equipment, however, protection must be provided. With long external wires attached and no protection provided, a single pulse could cause disruption of the microprocessor-controlled displays, cause frequency shifts and permanently damage the radio's internal components. Two notable exceptions are the handheld and mobile radios. Even with antennas attached, no equipment degradation was noted.

Other equipment used by the radio amateur can be damaged by transient pulses. A line-operated dc power supply (Astron VS-35) failed when pulsed with an unprotected power source. A hand-held transceiver's (ICOM IC-02AT) display was permanently damaged when the radio was plugged into its battery charger and then into an unprotected ac power source. The battery charger was also damaged. A Honda portable power generator was fully stressed with field and injection pulses and was unharmed. System 1 sustained damage to its antenna matching network, but the attached transceiver was unhurt. (In this case, the matching network may have protected the transceiver.) When System 4 was pulsed in an unprotected configuration, its matching network did not provide adequate protection for the transceiver; the transceiver's frequency display was temporarily disrupted.

Conclusions

Most Amateur Radio equipment should be protected from lightning and EMP to prevent damage that can degrade the equipment's performance. Adequate transient-pulse protection for most radio systems can be obtained by adding the proper protection devices to the ac power lines and the transmission line. Battery chargers for hand-held transceivers and line-operated dc power supplies should also be protected. With a minimum amount of protection, radio systems should survive transient pulses produced by lightning strikes and EMP. A direct lightning strike is another matter.

[Editor's Note: This series of articles is condensed from the National Communications System report (NCS TIB 85-10) *Electromagnetic Pulse/Transient Threat Testing of Protection Devices for Amateur/ Military Affiliate Radio System Equipment.* A copy of the unabridged report is available from the NCS. Write (no SASE required) to Mr Dennis Bodson, Acting Assistant Manager, Office of Technology and Standards, National Communications System, Washington, DC 20305-2010, or call 202-692-2124 between the hours of 8:30 AM and 5 PM Eastern.] QST

Electromagnetic Pulse and the Radio Amateur

Part 4: What can be done to protect an Amateur Radio station from lightning and EMP transients? Here are some ideas on procedures and protective devices.†

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The equipment test program described in the preceding three articles demonstrates that most Amateur Radio installations can be protected from lightning and EMP transients with a basic protection scheme. Most of the equipment is not susceptible to damage when all external cabling is removed. You can duplicate this stand-alone configuration simply by unplugging the ac power cord from the outlet, disconnecting the antenna feed line at the rear of the radio and isolating the radio gear from any other long metal conductors. Or, you can add two transient-protection devices to the interconnected system; that will also closely duplicate the stand-alone configuration.

The ac power line and antenna feed line are the two important points that should be outfitted with transient protection. This is the minimum basic protection scheme

†Parts 1-3 appear in Aug, Sep and Oct 1986 *QST*.

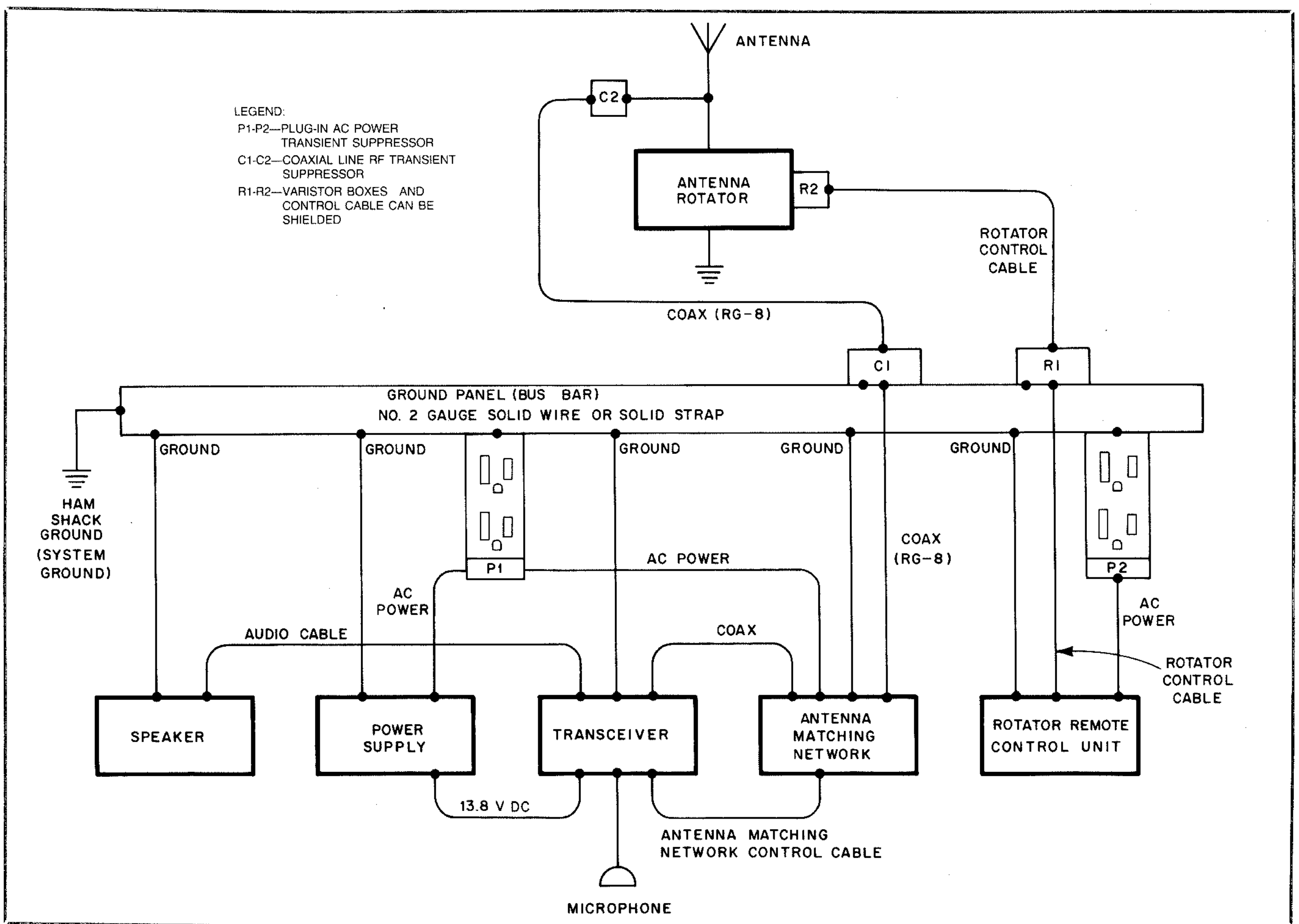

Fig 12—Transient suppression techniques applied to an Amateur Radio station.

recommended for all Amateur Radio installations. (For fixed installations, consideration should also be given to the antenna rotator connections—see Fig 12.) Hand-held radios equipped with a "rubber duck" require no protection at the antenna jack. If a larger antenna is used with the hand-held transceiver, however, a protection device should be installed.

General Considerations

Because of the unpredictable energy content of a nearby lightning strike or other large transient, it is possible for a metal-oxide varistor (MOV) to be subjected to an energy surge in excess of its rated capabilities. This may result in the destruction of the MOV and explosive rupture of the package. These fragments can cause damage to nearby components or operators and possibly ignite flammable material. Therefore, the MOV should be physically shielded.

A proper ground system is a key factor in achieving protection from lightning and EMP transients. A low-impedance ground system should be installed to eliminate transient paths through radio equipment and to provide a good physical ground for the transient-suppression devices. A single-point ground system is recommended (see Fig 13). Inside the station, single-point grounding can be had by installing a ground panel or bus bar. All external conductors going to the radio equipment should enter and exit the station through this panel. Install all transient-suppression devices directly on the panel. Use the shortest length(s) possible of no. 6 solid wire to connect the radio equipment case(s) to the ground bus.

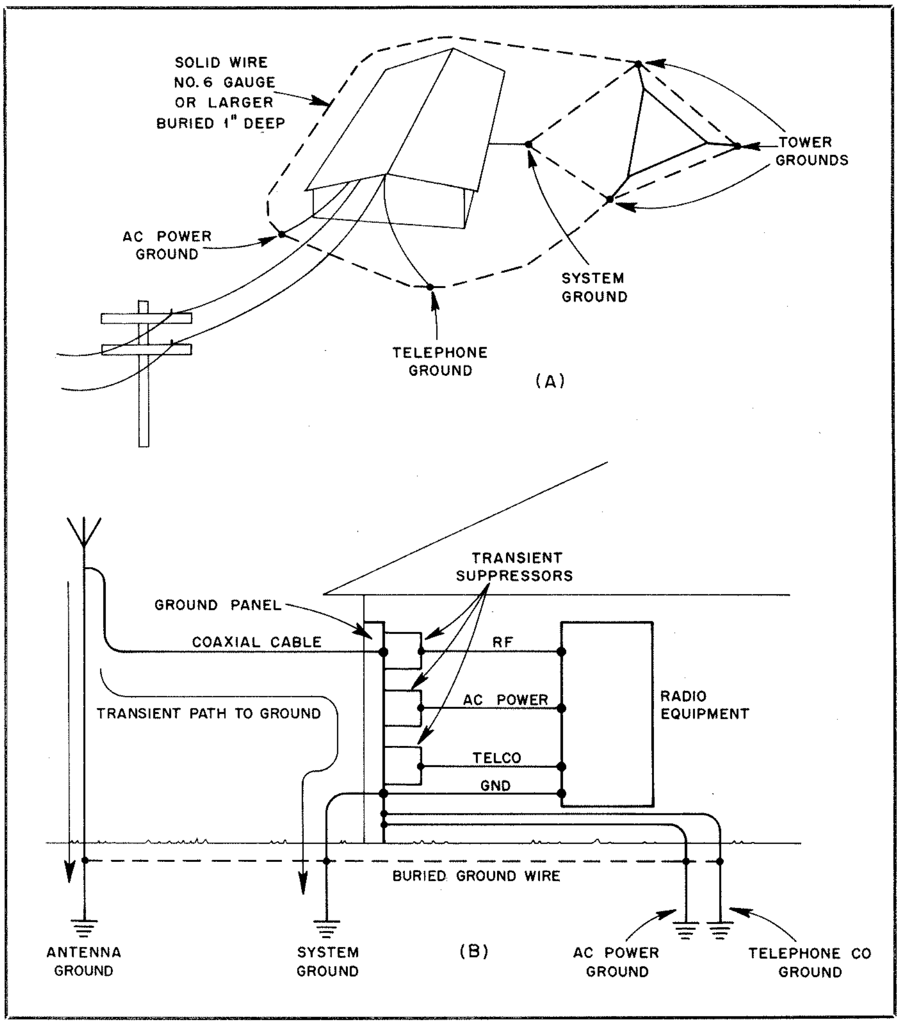

Fig 13—At A, the proper method of tying all ground points together. The transient path to ground with a single-point ground system and use of transient suppressors is shown at B.

Fixed Installations

Ac Power-Line Protection

Tests have indicated that household electrical wiring limits the maximum transient current that it will pass to approximately 120 A. Therefore, the amateur's station should, if possible, be installed away from the house ac entrance panel and breaker box to take advantage of these limiting effects.

Ac power-line protection can be provided with easy-to-install, plug-in transient protectors. Ten such devices were tested (see Table 9). Six of these can be plugged directly into an ac outlet. Four are modular devices that require more extensive installation and, in some cases, more than one module.

The plug-in-strip units are the best overall choice for the typical amateur installation. They provide the protection needed, they're simple to install and can be moved easily with the equipment to other operating locations. The modular devices are second choices because they all require some installation, and none of the units tested provided full EMP protection for all three wires of the ac power system.

Table 9
Ac Power-Line Protection Devices

Manufacturer	*Device*	*Approximate Cost (US Dollars)*	*Measured High-Z Clamping Voltage (Volts)*
	Modules		
Fischer	FCC-120F-P	55	420
Joslyn	1250-32	31	940
General Semiconductor	587B051	56	600
General Semiconductor	PHP 120	50	400
	Plug-Ins		
Joslyn	1270-02	49	600
TII	428	45	410
Electronic Protection Devices	Lemon	45	580
Electronic Protection Devices	Peach	60	1000
S L Waber	LG-10	13	600
Archer	61-2785	22	300

We consider the TII model 428 Plug-In Powerline Protector to be the best overall protector. It provides transient paths to ground from the hot and neutral lines (common mode) as well as a transient path between the hot and neutral lines (normal mode). The model 428 uses three MOVs and a 3-electrode gas-tube arrestor to provide fast operation and large power-dissipation capabilities. This unit was tested repeatedly and operated without failure.

Several other plug-in transient protectors provide 3-wire protection, but all operate at higher clamping voltages. Other low-cost plug-in devices either lack the 3-wire protection capability or have substantially higher clamping voltages. Some of these are the:

- Joslyn 1270-02. It provides full 3-wire (common and normal mode) transient-path protection, but at a slightly higher cost and at a higher clamping voltage.
- Lemon and Peach protection devices manufactured by Electronic Protection Devices, Inc. The Lemon provides full (command and normal mode) 3-wire protection, but at a higher clamping voltage; the Peach has a dangerously high (1000 V) clamping voltage.
- Archer (Radio Shack) 61-2785 [Replaced by a new model.—Ed.]. This unit provides excellent clamping performance at low cost, but it offers normal-mode protection only (a transient path between the hot and neutral leads). It will provide some protection for lightning transients, but not enough for EMP.
- S. L. Waber LG-10. The lowest-cost device does not provide full three-wire protection (normal mode only) and has a clamping voltage of 600. This unit can provide limited transient protection for lightning, but not the 3-wire protection recommended for EMP transients.

The transient suppressors require a 3-wire outlet; the outlet should be tested to ensure all wires are properly connected. In older houses, an ac ground may have to be installed by a qualified electrician. The ac ground must be available for the plug-in transient suppressor to function properly. The ac ground of the receptacle should be attached to the station ground bus, and the plug-in receptacle should be installed on the ground panel behind the radio equipment.

Emergency Power Generators

Emergency power generators provide two major transient-protection advantages. First, the station is disconnected from the commercial ac power system. This isolates the radio equipment from a major source of damaging transients. Second, tests have shown that the emergency power generator may not be susceptible to EMP transients.

When the radio equipment is plugged directly into the generator's outlets, transient protection may not be needed. If an extension cord or household wiring is used, transient protection should be employed.

An emergency power generator should be wired into the household circuit only by a qualified electrician. When so connected, a switch is used to disconnect the commercial ac power source from the house lines before the generator is connected to them. This keeps the generator output from feeding back into the commercial power system. If this is not done, death or injury to unsuspecting linemen can result.

Feed-Line Protection

Coaxial cable is recommended for use as the transmission line because it provides a certain amount of transient surge protection for the attached equipment. The outer conductor shields the center conductor from the transient field. Also, the cable limits the maximum conducted transient voltage on the center by arcing the differential voltage from the center conductor to the grounded cable shield.

By providing a path to ground ahead of the radio equipment, the gear can be protected from the large currents impressed upon the antenna system by lightning and EMP. A single protection device installed at the radio's antenna port will protect the radio, but not the transmission line. To protect the transmission line, another transient protector must be installed between the antenna and the transmission line (see Fig 12).

RF transient-protection devices from three manufacturers were tested (see Table 10) using RG-8 cable equipped with UHF connectors. All of the devices shown can be installed in a coaxial transmission line. Recall that during the tests the RG-8 cable acted like a suppressor; damaging EMP energy arced from the center conductor to the cable shield when the voltage level approached 5.5 kV.

Low price and a low clamping-voltage rating have to be considered in the selection of an RF transient-protection device. However, the lower-cost devices have the higher clamping voltages, and the higher-cost devices have the lower clamping voltages. Because of this, we selected medium-priced devices manufactured by Fischer Custom Communications. The Fischer Spikeguard Suppressors (about $55) for coaxial lines can be made to order to operate at a specific clamping voltage. The Fischer devices satisfactorily suppressed the damaging transient pulses, passed the transmitter RF output power without interfering with the signal and operated effectively over a wide frequency range.

Polyphaser Corporation devices are also effective in providing the necessary transient protection. However, the available devices limited the transmitter RF output power to 100 W or less. These units cost approximately $83 each.

The Alpha Delta Transi-Traps tested were low-cost items, but not suitable for EMP suppression because of their high (over 700-V) clamping levels. [New Alpha Delta "EMP" units have clamping voltages about one-third that of the older units tested here.—Ed.]

RF coaxial protectors should be mounted on the station ground bus bar. If the Fischer device is used, it should be attached to a grounded UHF receptacle that will serve as a hold-down bracket. This creates a conductive path between the outer shield of the protector and the bus bar. The Polyphaser device can be mounted directly to the bus bar with the bracket provided.

Attach the transceiver or antenna matching network to the grounded protector with a short (6 foot or less) piece of coaxial cable. Although the cable provides a ground path to the bus bar from the radio equipment, it is not a satisfactory transient-protection ground path for the transceiver.

Table 10
RF Coaxial-Line Protectors

Manufacturer	*Device*	*Approximate Cost (US Dollars)*	*Measured High-Z Clamping Voltage (Volts)*
Fischer	FCC-250-300-UHF	55	393
Fischer	FCC-250-350-UHF	55	260
Fischer	FCC-250-150-UHF	55	220
Fischer	FCC-250-120-UHF	55	240
Fischer	FCC-450-120-UHF	55	120
Polyphaser	IS-NEMP	83	140
Polyphaser	IS-NEMP-1	83	150
Polyphaser	IS-NEMP-2	83	160
Alpha Delta	LT	20	700*
Alpha Delta	R-T	30	720*

Note: The transmitter output power, frequency of operation and transmission line SWR must be considered when selecting any of these devices.
*The newer Alpha Delta LT and R-T "EMP" models have clamping voltages one-third of those shown here.

Another ground should be installed between the transceiver case and the ground bus using solid no. 6 wire. The coaxial cable shield should be grounded to the antenna tower leg at the tower base. Each tower leg should have an earth ground connection and be connected to the single-point ground system as shown in Fig 13.

Antenna Rotators

Antenna rotators can be protected by plugging the control box into a protected ac power source and adding protection to the control lines to the antenna rotator. When the control lines are in a shielded cable, the shield must be grounded at both ends. MOVs of the proper size should be installed at both ends of the control cable. At the station end, terminate the control cable in a small metal box that is connected to the station ground bus. Attach MOVs from each conductor to ground inside the box. At the antenna end of the control cable, place the MOVs inside the rotator case or in a small metal box that is properly grounded.

For example, the Alliance HD73 antenna rotator uses a 6-conductor unshielded control cable with a maximum control voltage of 24.7. Select an MOV with a clamping voltage level 10% higher (27 V or more) so the MOV won't clamp the control signal to ground.

DC Power-Supply Protection

Mobile Installations

The mobile amateur station environment exposes radio equipment to other transient hazards in addition to those of lightning and EMP. Currents as high as 300 A are switched when starting the engine, and this can produce voltage spikes of over 200 V on the vehicle's electrical system. Lightning and EMP are not likely to impact the vehicle's electrical system as much as they would that of a fixed installation because the automobile chassis is not normally grounded. This would not be the case if the vehicle is inadvertently grounded; for example, when the vehicle is parked against a grounded metal conductor. The mobile radio system has two advantages over a fixed installation: Lightning is almost never a problem and the vehicle battery is a natural surge suppressor.

Mobile radio equipment should be installed in a way that takes advantage of the protection provided by the battery (see Fig 14). To do this, connect the radio's positive power lead directly to the positive battery post, not to intermediate points in the electrical system such as the fuse box or the auxiliary contacts on the ignition switch. To prevent equipment damage or fire, should the positive lead short to ground, an in-line fuse should be installed in the positive lead where it is attached to the battery post.

Connect the negative power lead to the chassis on the battery side of the quick-disconnect connector. Although it would help prevent alternator whine, connecting the negative power lead directly to the battery post is not recommended from an EMP standpoint.

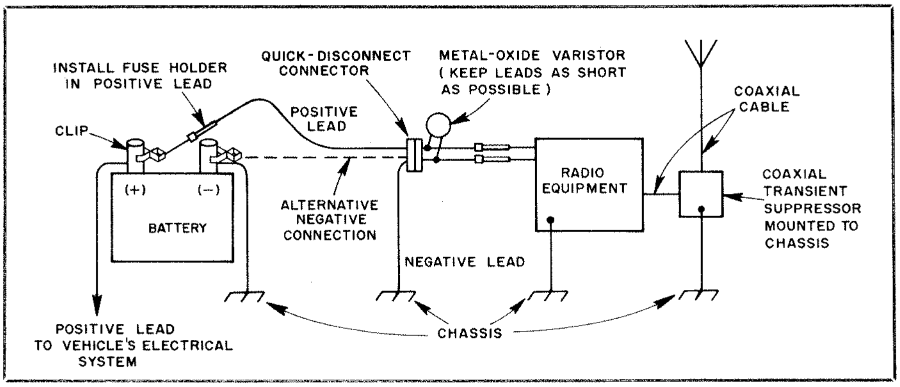

Fig 14—Recommended method of connecting mobile radio equipment to the vehicle battery and antenna.

An MOV should be installed between the two leads of the equipment power cord. A GE MOV (V36ZA80) is recommended for this application. This MOV provides the lowest measured clamping voltage (170 V) and is low in cost.

Mobile Antenna Installation

Although tests indicate that the mobile radios can survive an EMP transient without protection for the antenna system, protection from lightning transients is still required. A coaxial-line transient suppressor should be installed on the vehicle chassis between the antenna and the radio's antenna connector. A Fischer suppressor can be attached to a UHF receptacle that is mounted on, and grounded to, the vehicle chassis. The Polyphaser protector can be mounted on, and grounded to, the vehicle chassis with its flange. Use a short length of coaxial cable between the radio and the transient suppressor.

Clamping Voltage Calculation

When selecting any EMP-protection device to be used at the antenna port of a radio, several items must be considered. These include: transmitter RF power output, the SWR and the operating frequency. The protection device must allow the outgoing RF signal to pass without clamping. A clamping voltage calculation must be made for each amateur installation.

The RF-power input to a transmission line develops a corresponding voltage that becomes important when a voltage-surge arrestor is in the line. SWR is important because of its influence on the voltage level. The maximum voltage developed for a given power input is determined by:

$$V = \sqrt{P \times Z} \times SWR \qquad \text{(Eq 3)}$$

where

P = peak power in W
Z = impedance of the coaxial cable (ohms)
V = peak voltage across the cable

This equation should be used to determine the peak voltage present across the transmission line. Because the RF transient-protection devices use gas-discharge tubes, the voltage level at which they clamp is not fixed; a safety margin must be added to the calculated peak voltage. This is done by multiplying the calculated value by a factor of three. This added safety margin is required to ensure that the transmitter's RF output power will pass through the transient suppressor without causing the device to clamp the RF signal to ground. The final clamping voltage obtained is then high enough to allow normal operation of the transmitter while providing the lowest practical clamping voltage for the suppression device. This ensures the maximum possible protection for the radio system.

Here's how to determine the clamping voltage required. Let's assume the SWR is 1.5:1. The power output of the transceiver is 100 W PEP. RG/8 coaxial cable has an impedance of 52 ohms. Therefore

P = 100 W
Z = 52 ohms
SWR = 1.5

Substituting these values in Eq 3:

$$V = \sqrt{100 \times 52} \times 1.5 \qquad \text{(Eq 4)}$$

$$V = 108.17$$

Note that the voltage, V, is a peak value since the power was measured in peak watts. The final clamping voltage (FCV) is three times this value or 324.45 V. Therefore, a coaxial-line transient suppressor that clamps at or above 324 V should be used.

The cost of a two-point basic protection scheme is estimated to be $100 for each fixed amateur station. This includes the cost of one TII model 428 plug-in power-line protector ($45) and one Fischer coaxial-line protector ($55).

Inexpensive Transient-Protection Devices

Here are two low-cost protection devices you can assemble. They performed flawlessly in the tests.

SIOV AC Box

The SIOV (SIemens metal-Oxide Varistor) power-line protection device shown in Fig 15 is fabricated by installing a duplex receptacle in a metal electrical box. Power is brought into the box through a 6-foot-long, 3-conductor power cord. A fuse is installed in the incoming hot wire to guard against harmful effects if one of the protective devices shorts. MOVs (Siemens S14K130) are installed—with the shortest possible lead lengths—between the hot and neutral, hot and ground and neutral and ground leads. The estimated cost of this unit is $11.

UHF Coaxial T

The radio antenna connection can be protected by means of another simple device. As shown in Fig 16, two spark gaps (Siemens BI-A350) are installed in series at one end of a coaxial cable T connector. Use the shortest practical lead length (about ¼ in) between the two spark gaps. One lead is bent forward and forced between the split sections of the inner coaxial connector until the spark gaps approach the body of the connector. A short length of insulating material (we used Mylar®) is placed between the spark gaps and the connector shell. The other spark-gap lead is folded over the insulator, then conductive (metallic) tape is wrapped around the assembly. This construction method proved durable enough to allow many insertions and removals of the device during testing. Estimated cost of this assembly is $9. Similar devices can be built using components from Joslyn, General Electric, General Semiconductor or Siemens.

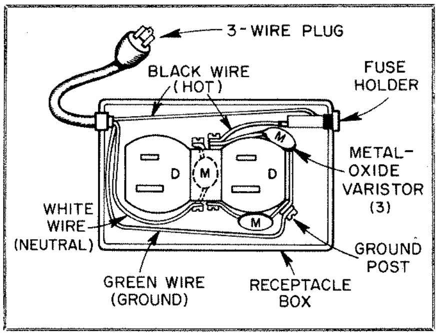

Fig 15—Pictorial diagram of an inexpensive, homemade ac power-line transient protector. This approach may be applied to multiple outlets; see text.

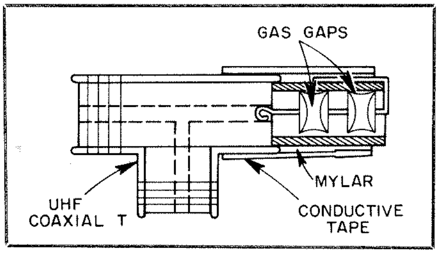

Fig 16—Pictorial diagram of an inexpensive, homemade transmission-line transient protector. See text for description of assembly.

Summary

Amateurs should be aware of which components in their radio system are most likely to be damaged by EMP. They should also know how to repair the damaged equipment. Amateurs should know how to reestablish communications after an EMP event, taking into consideration its adverse effects on the earth's atmosphere and radio equipment. One of the first things that would be noticed, providing the radio equipment is operative, is a sudden silence in radio transmissions across all frequencies below approximately 100 MHz. This silence would be due in part to the damage by the EMP transient to unprotected radio gear. Transmissions from one direction, the direction of the nuclear blast, would be completely out. RF signal loss by absorption and attenuation by the nuclear fireball are the reasons for this.

After an EMP event, the amateur should be prepared to operate CW. CW gives the most signal power under adverse conditions. It also provides a degree of message security from the general public.

Amateurs should develop the capability and flexibility to operate in more than one frequency band. The lower ground-wave frequencies should be useful for long-distance communications immediately after an EMP event. Line-of-sight (LOS) VHF would be of value for local communications purposes.

What can be done to increase the survivability of an Amateur Radio station? Here are some suggestions:

1) If you have spare equipment, keep it disconnected; use only the primary station gear. The spare equipment would then be available after an EMP event.

2) Keep equipment turned off and antenna and power lines disconnected when the equipment is not in use.

3) Connect only those external conductors necessary for the current mode of operation.

4) Tie all fixed equipment to a single-point earth ground to prevent closed loops through the ground.

5) Obtain schematic diagrams of your equipment and tools for repair of the equipment.

6) Have spare parts on hand for sensitive components of the radio equipment and antenna system.

7) Learn how to repair or replace the sensitive components of the radio equipment.

8) Use nonmetallic guy lines and antenna structural parts where possible.

9) Obtain an emergency power source and operate from it during periods of increased world political tension. The power source should be completely isolated from the commercial power lines.

10) Equipment power cords should be disconnected when the gear is idle. Or, the circuit breaker for the line feeding the equipment should be kept in the OFF position when the station is off the air.

11) Disconnect the antenna lead-in when the station is off the air. Or, use a grounding antenna switch and keep it in the GROUND position when the equipment is not in use.

12) Have a spare antenna and transmission line on hand to replace a damaged antenna system.

13) Install EMP surge arrestors and filters on all primary conductors attached to the equipment and antenna.

14) Retain tube type equipment and spare components; keep them in good working order.

15) Do not rely on a microprocessor to control the station after an EMP event. Be able to operate without microprocessor control.

Conclusion

The recommendations contained in this report were developed with low cost in mind; they are not intended to cover all possible combinations of equipment and installation methods found in the amateur community. Amateurs should examine their own requirements and use this report as a guideline in providing protection for the equipment.

[Editor's Note: This series of articles is condensed from the National Communications System report (NCS TIB 85-10) *Electromagnetic Pulse/Transient Threat Testing of Protection Devices for Amateur/Military Affiliate Radio System Equipment.* A copy of the unabridged report is available from the NCS. Write (no SASE required) to Mr Dennis Bodson, Acting Assistant Manager, Office of Technology and Standards, National Communications System, Washington, DC 20305-2010, or call 202-692-2124 between the hours of 8:30 AM and 5 PM Eastern.]