

SECTION 1. EXECUTIVE DIGEST

1.1 INTRODUCTION

The U.S. Army Corps of Engineers, Engineering and Support Center, Huntsville (USAESCH) was established as the Mandatory Center of Excellence (CX) for the Ordnance and Explosive program within the U.S. Army Corps of Engineers. The mission is to safely eliminate or reduce risks from ordnance, explosives, a recovered chemical warfare materiel at current or formerly used defense sites. The Center of Expertise is responsible for Ordnance and Explosive (OE) activities in support of Defense Environmental Restoration Program for Formerly Used Defense Sites (DERP - FUDS), Installation Restoration (IR), Base Realignment and Closure (BRAC), and Services for Others (SFO) programs. These programs currently have over 2000 projects in inventory with normally 60-80 active projects at any given time.¹

1.2 BACKGROUND AND HISTORY

The U.S. Army Corps of Engineers is responsible for removing Ordnance and Explosives from approximately 14,000,000 acres at more than two thousand different DERP - FUDS and BRAC sites. Most of these sites were part of the military downsizing after World War II and the Korean War and are already turned over to the civilian population. Also, some of the more recent sites to be closed have not been involved in any ordnance firing activities since about 1960². The earlier sites, especially those near population centers, need to be restored (to an ordnance-free condition) as soon as feasible. This places particular emphasis on the ordnance and the vacuum tube fuzes used prior to about 1960 and their sensitivity to electromagnetic (EM) radiation from instruments used to detect or evaluate the unexploded ordnance (UXO).

By the end of World War II ordnance with vacuum tube fuzes had reached such a level of sophistication that, between the end of World War II (1945) and the end of the Korean War (1954), there was limited research and development in new conventional ordnance. This resulted in very little development of new types of electrical fuzes for the ordnance used during this time period.

The discovery of the transistor, by Walter H. Brattain and John Bardeen of Bell Laboratories, occurred on December 23, 1947⁴. In 1951 semiconductor materials were commercially available. In 1954 the first fully transistorized radio and computer were built. In 1955 transistors were available for the first time in production quantities. In 1956 investigations began into the use of transistors in fuze circuits. In 1959 the first integrated circuit microchip was made. The development of solid state transistors and microchip technology started new work to reduce the weight of mechanical fuzes and to replace the sometime unreliability vacuum tube proximity fuzes. Early vacuum tube fuzes would only withstand about a 4-ft drop due to the fragile capacitor and ampoule. The first electronic hybrid (transistors and vacuum tubes) fuze, the M532, was made in the early 1960s for a mortar round. The first fully transistorized fuze, the M429, was made in the

1965-1970 time period for a 2.75” rocket to use in the Vietnam War. The M514A1E1 (later named M728) was the first fully transistorized artillery fuze and was made in the late 1960s to early 1970s²⁹.

With development efforts, production, testing for safe fuze operation, and approval for military use, it was not until about 1968 that transistors were made in production quantities for Army fuzes and the mid-1970s for Navy units²⁸. There were some statistical field tests of pre-production items prior to production approval. Thus, before about 1960, electronic fuzes were all vacuum tube units. Indeed these miniature vacuum tube fuze units have such a long shelf life that some units are still in inventory. Since the initial fuze research and development activities were classified at the secret level and very closely guarded, all early dud items over land test sites were promptly recovered and evaluated. During statistical field firing testing of large numbers of fuzed ordnance, some with high explosives, some of the resulting duds may have been left on the test range(s). This effort addresses only ordnance fielded up to about 1960, and thus does not include the transistorized fuzes introduced in the 1960s, or more modern electronics containing integrated circuits.

1.3 TASK OBJECTIVES

The primary objective of this task is to catalog the commonly used U.S. fuzes up to about 1960, the type of EM energy to which these ordnance are most sensitive, and the amount of EM energy required to cause the fuze to function (a highly undesired effect during restoration). The second objective is to quantify and footprint the output energy of the primary geophysical instruments for the U.S. Army Corps of Engineers’ restoration program. This Electronic Fuze Evaluation effort is to provide a comparison of the EM signatures of the geophysical instruments with the sensitivity of the electronic fuze systems and identify circumstances most likely to cause problems. This report documents the first part of this effort by cataloging vacuum tube fuzes commonly used by the U.S. up to 1960, the type of EM energy to which these ordnance are most sensitive, and the amount of EM energy required to cause the fuze to function.

1.4 STUDY RESTRICTIONS

This study was restricted to assessing the potential hazard of buried ordnance to EM energy from geophysical instruments. Since the Corps of Engineers’ procedure of first doing a thorough visual walk-through examination and removal of any questionable items for a UXO site, prior to any site examination with instruments, only buried ordnance was addressed in this study.

Prior to 1942 fuze systems were entirely mechanical systems which are regarded as being inherently safe to low-level EM radiation. An example of a mechanical time fuze is shown in Figure 1-1. Early electrical fuze units, and even modern units, have continued to use clockwork mechanical subsystems. Figure 1-2 shows a Mark 45 fuze that used miniature vacuum tubes (nosetip), a short-term, wet-cell electrolytic battery (center), and

a mechanical safety and arming mechanism. (Initial research in thermal batteries²⁵ was conducted in the late 1950s and early 1960s.) The Mark 45 fuze and similar units were used extensively during World War II and the Korean War. Figure 1-3 shows a modern fuze system with a mechanical Safety and Arming Mechanism. This study was restricted to only the electrical/electronic fuzes, since these units may have a different sensitivity to the low-level EM energy of common geophysical instruments. This study task was further restricted to cataloging the electro-magnetically sensitive vacuum tube fuzes that were commonly used by the U. S. up to 1960 for US munitions only (no landmine, submarine, submunition, air-to-air, or seamine/torpedo fuzes). These generally include electronic fuzing systems developed and used between 1942 and 1960 for; US artillery and mortar rounds, US aerial bombs, US air-to-ground rockets and missiles, US ground-to-air missiles, and US ground-to-ground rockets and missiles. No laboratory or field testing of any fuze, ordnance, or geophysical instrument was conducted during this study. This report focuses on the vacuum tube electronic fuzes fielded prior to 1960.

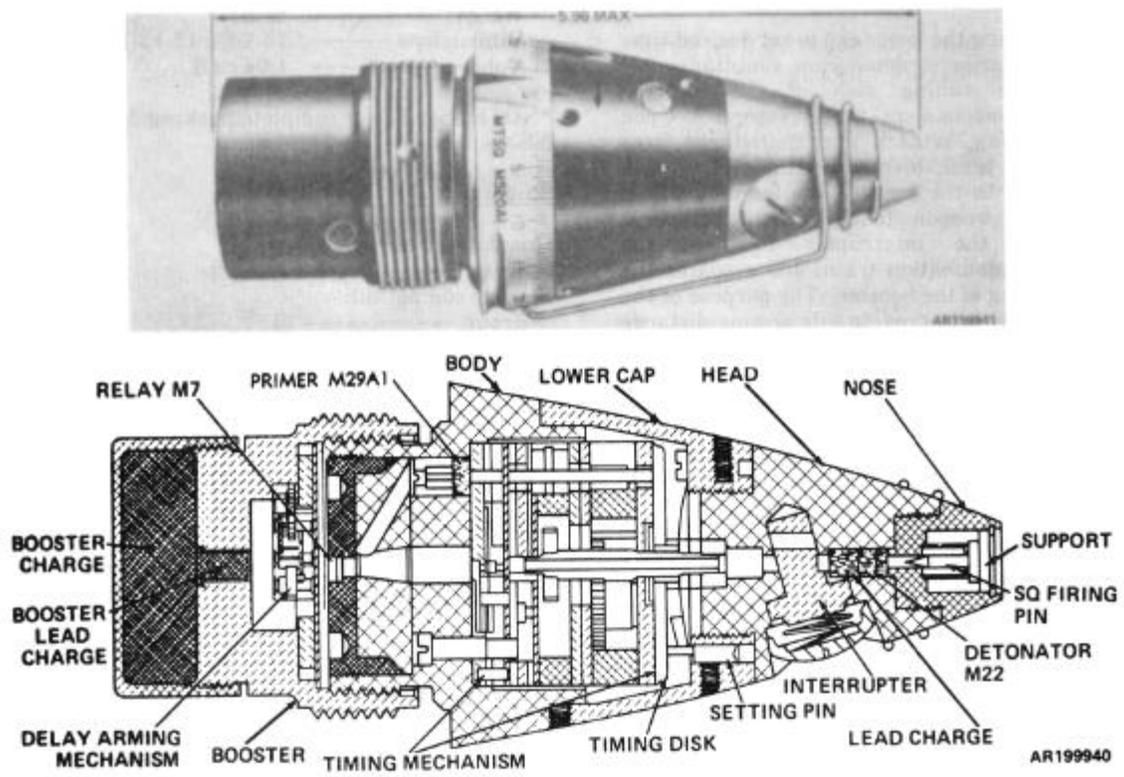


Figure 1-1. Mechanical-Time Fuze for Impact Detonation or Airburst.

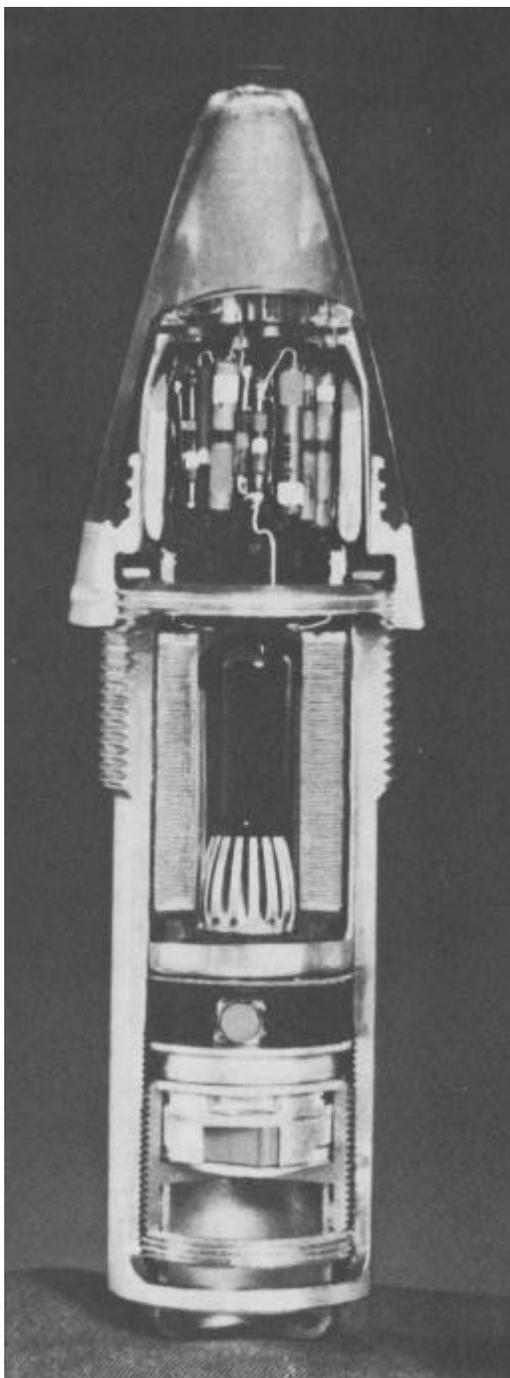


Figure 1-2. A Mark 45 Fuze made by Eastman Kodak Company.

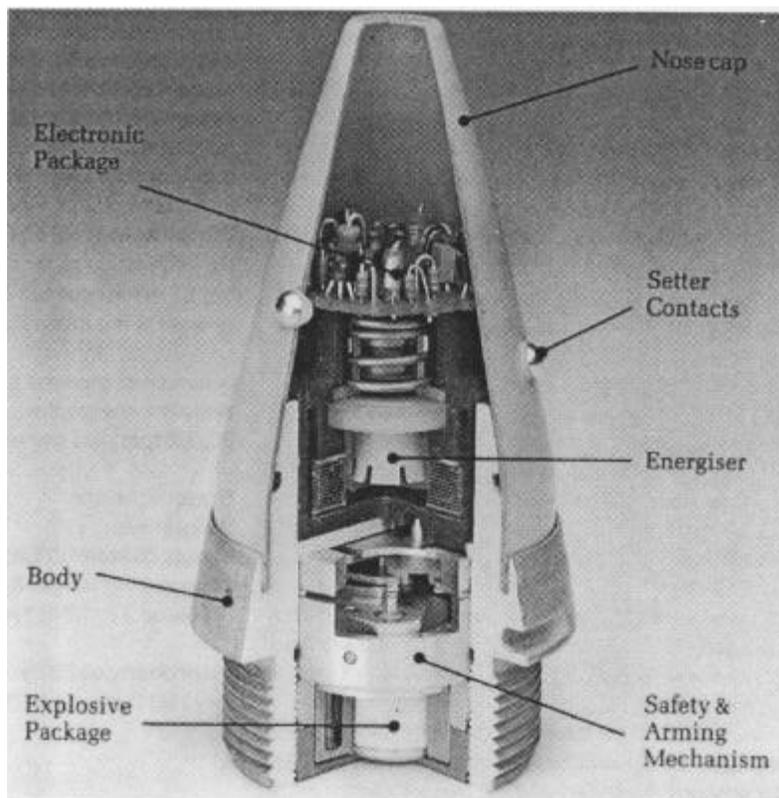


Figure 1-3. Example of a Modern Fuze with Electronic Initiator Package.

1.5 EXPLOSIVE TRAIN

The fuze part of the explosive train ignites or initiates the high explosives in the weapon. Fuzes are generally made separately and stored separately, due to their greater sensitivity to external stimuli, until the ordnance is to be readied for field use. The fuze unit has machined threads near its base for mounting in the ordnance shell containing the high explosive. From the standpoint of the explosive train, it is convenient to divide the explosives into three classes; primary explosives, priming mixtures, and high explosives²³. The electrical fuzes, called variable time (VT) fuzes during WWI and Korean War because of security reasons are commonly called proximity fuzes today, combined mechanical and electrical (vacuum tube) circuits for anti-aircraft and anti-personnel ammunition. These proximity fuzes were used extensively during WWII and the Korean War.

The distinguishing characteristic of primary explosives is their extreme sensitivity to heat and shock. They are the most sensitive of the explosives and occupy the “starting” position in the explosive train and are frequently called initiators. The more common primary explosives of this time period were; mercury fulminate, lead azide, lead styphnate, diazodinitrophenol, tetracene, and nitromannite. These materials can be easily and reliably ignited with minimal energy from a hot filament or exploding bridgewire (100 - 4,500 ergs), provided the energy is input in a relatively short period of time or the material is heated to its explosive temperature. The fundamental circuit for the electronic bridgewire

fuze is shown in Figure 1-4. The electronic bridgewire element is often referred to as an electronic blasting cap, as shown in Figure 1-5. For proximity fuzes the bridge element consisted of small metal wire or a thin strip of carbon film in parallel with a total resistance value of about 700 to 15,000 ohms.

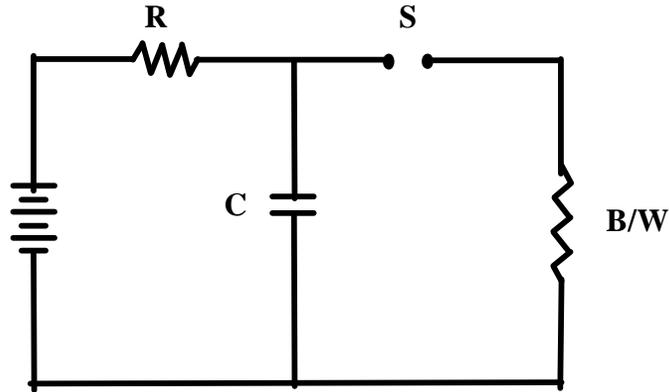


Figure 1-4. Fundamental Circuit of EBW Fuze.

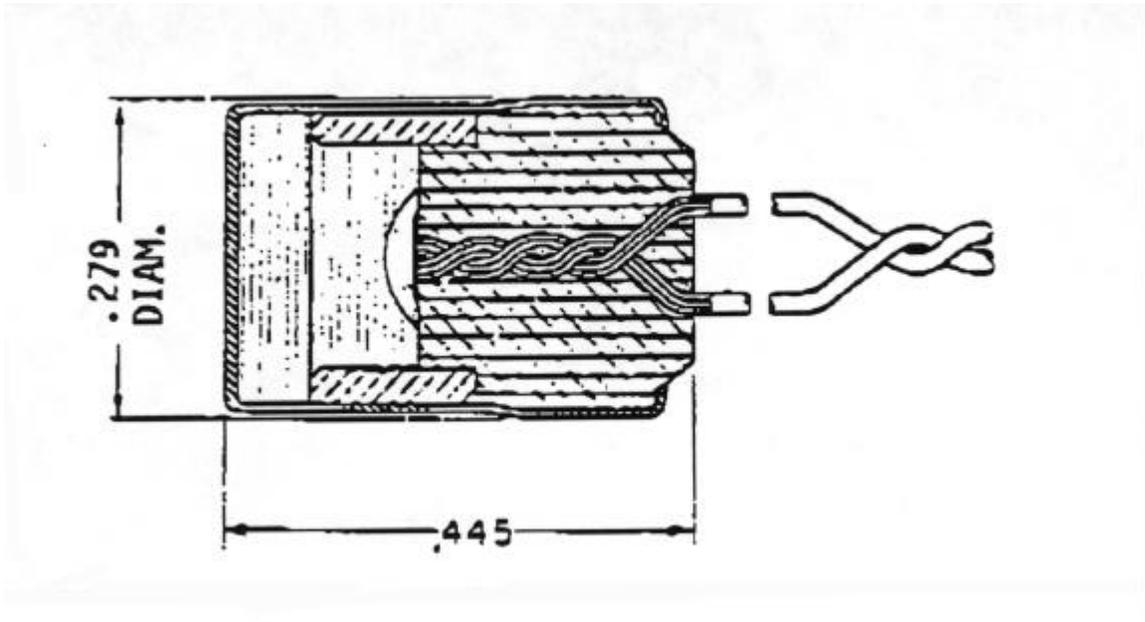


Figure 1-5. Electronic Blasting Cap.

Fuzes requiring as little as 10 ergs to initiate can be made, but this extremely high sensitivity creates a pronounced safety problem even for the designer! For safety reasons, fuze systems were generally designed for higher than minimal energy for initiation by proper selection of the primary explosive mixture and bridge circuit electrical properties. Early experimental fuzes were made and tested that required little more than 100 ergs to initiate the primary explosive, but these units were susceptible to initiation by static electricity. Later fuzes fielded during WWII required a minimum about 200 - 500 ergs for sure fire conditions. After WWII, high voltage circuits were used in some ordnance items to directly ignite the less sensitive priming mixtures and gave greater fuze safety.

Priming mixtures frequently contain mixtures of a primary explosive material, an oxidizing agent, fuels, and a binder material. Priming mixtures, sometimes called boosters, are ignited by the primary explosive and they in turn ignite the high explosives. Priming mixtures are generally less sensitive than the primary explosive, but more sensitive than the high explosives. Priming mixtures sometimes have additives to make them conductive, either for the purposes of electrical initiation by currents passed through the mixture or to decrease the sensitivity to static electric discharges. (After about 1980 when high voltage circuits were used to directly ignite the priming mixtures, reliable fuze systems requiring as much as 1.69 joules $\{= 1.69 \times 10^7 \text{ ergs}\}$ were commonly produced.)

High explosives have the characteristic of low sensitivity to heat or shock and function under the influence of the shock of the primary explosive or of another high explosive. Most high explosive, unlike primary explosives, when in an unconfined state will burn without exploding when ignited with a flame.

1.6 FUZE TYPES

Prior to the early 1960s, the types of fuzes fielded included; all mechanical systems and hybrid systems containing electrical timing systems (vacuum tube units and other electrical components). Fuzes are also categorized according to application and function. The hybrid systems were generally referred to as electrical fuzes and were used in artillery, bombs, mortars, and rockets. All fuze units have, as a result of government design requirements, multiple safety features to prevent accidental arming and firing. Although the primary explosive of the fuze is the most sensitive component in the explosive train, its sensitivity varies depending on the type of fuze system. Mechanical fuzes were commonly used for point detonation and detonation at a fixed mechanical time. (Mechanical fuzes are of a clockwork design and generally have many components as a result of extensive safety requirements.) From the beginning, all electronic fuzes were required to have multiple safety features and a self-destruct feature. Electrical circuits are generally required for the fuze to function as a precise proximity device.

During WWII slightly over 22,000,000 proximity fuzes were produced. Of these, about 1,500,000 were fired at the enemy, about 330,000 were used in testing and R&D. The large balance of fuzes and the general scale-back after WWII were the primary reasons why there was little fuze development between WWII and the Korean War. The

Radio Frequency (RF) proximity fuzes, commonly called variable time or VT fuze, developed during WWII commonly had 4 or 5 miniature vacuum tubes in the transmitter and receiver circuits, plus other electrical components for electrical signal conditioning. These units formed the basic designs for all vacuum tube units produced between WWII and their gradual replacement by transistorized units in the 1960s and 1970s. Appendix A lists the VT fuzes produced as of 15 August 1945 and some of those produced between 1945 and 1960. (Detailed production information for 1945 - 1960 has been hard to find.)

The all-mechanical fuze systems are of a clockwork design and generally require the high G's of launch to start the arming sequence and to activate a spring-loading device (to build up potential energy) which rotates and moves multiple mechanical components to align the firing train. It is then referred to as "an in-line explosive train" that is fully armed and ready to fire. Then the spring-loaded unit drives a firing pin into a small charge (the primary explosive) to start the detonation process (similar to conventional firearms). Fortunately, these all-mechanical fuze systems have no way to collect and store the EM energy from geophysical instruments to initiate any of the firing steps. The EM instruments can only couple energy to the mechanical fuze system by negligible heating and magnetization effects. Neither heating nor magnetization is used to move any of the components of an all-mechanical fuze design. The shock pulse from ground impact (or from thunder and lightning) would far exceed the forces on the firing pin of a buried and armed fuze than would be generated by heating or magnetization from geophysical instruments alone. For these reasons, an all-mechanical fuze is regarded as being inherently safe to the weak EM fields of geophysical instruments used to detect unexploded ordnance.

Electrical fuzes were designed to operate in the proximity of its intended target (aircraft, ground, water, or structures) and were called proximity fuzes, or variable time (VT) fuzes. Two types of proximity fuzes were developed during WWII, the radio and the photoelectric proximity fuzes. About 400,000 of each type were manufactured by 1943. The photoelectric fuze required light for operation and would sometimes function early when the sun moved into and out the field of view of the photoelectric lens. For these reasons, manufacture of photoelectric fuzes was cancelled in 1943 and the term proximity or VT fuze generally referred to the radio proximity fuze. The radio proximity fuze consisted of a diode detector arrangement that utilized the Doppler effect (frequency shift) between its transmitted waves and the reflected waves. The Doppler frequency was amplified and used to close the switch, discharging the capacitor and into the bridgewire.

Pre-1960 proximity fuzes, with their miniature vacuum tubes require high voltages for stable operation. Standard vacuum-tubes for commercial applications generally utilized 5 to 10 volts a-c for the tube filaments and d-c bias voltages over one hundred volts⁵. The miniature vacuum tubes used in early electronic fuzes operated with several d-c voltages²⁸: heater element at 1.5 - 3 V, bias at negative 5 - 10 V, screen at near 100 V, and the plate at about 170 V. The EM fields from geophysical instruments would not be sufficient for anything close to normal vacuum tube electrical operations, and especially so if the electrical circuit is enclosed inside the metal shell (Faraday cage) of a buried

ordnance. If the shell is ruptured, the EM fields could strike the electrical circuit and its components directly (after some attenuation by the soil). Depending on circuit design, at lower voltages there may be little or no current in the circuit. For ruptured and damaged ordnance, it may be feasible to couple energy into the electric detonator from one or more circuit loops.

1.7 GEOPHYSICAL INSTRUMENTS

The geophysical instruments evaluated during this study included: 1) the EM61 and EM31 made by Geonics, 2) total field magnetometers [or flux gate radiometers], 3) ground penetrating radars [GPR], 4) the GEM3 FDEM sensor made by Geophex, and 5) the AN/PSS-12 mine detector made by Schiebel Instruments. These are the primary instruments of interest with regards to a potential hazard from their EM fields initiating a fuze. These instruments are discussed in more detail in Section 2 and Appendix A.

Fluxgate gradiometers, such as the Schonstedts, Magna-Trak, and Foerster Mark 26 instruments were not considered in this study. Due to their design they produce EM emissions lower than, or at most comparable to, cesium vapor magnetometers.

1.8 CONCLUSIONS

The results of this study indicate that electronically initiated fuzes and fuzes with some electrical components are more sensitive to electromagnetic energy from geophysical instruments than the all-mechanical fuzes. The all-mechanical fuzes are regarded as being safe to the low-level electromagnetic fields produced by geophysical instruments. The hazard associated with electrical fuzes depends strongly on the condition of the explosive train and state of the fuze. If the ordnance did not fire because the fuze did not arm and the buried ordnance was not damaged on impact, then it should be insensitive to the fields produced by geophysical instruments. If the ordnance was properly armed but did not fire due to a malfunction or if it received significant damage on impact, then a detailed analysis of the possible configurations and operational states must be made to properly assess the hazards associated with the ordnance. If the ordnance shell was not ruptured on impact the sensitivity to EM fields will be much less than if the shell is ruptured. The likelihood of a detonation is a strong function of the strength of the EM field and thus the distance between the instrument and the ordnance. Our analysis indicates that if the instruments are carried at one meter above the ground, the risk of UXO detonation is low. However, instruments at ground level can pose a serious detonation risk for an armed fuze immediately below the surface.

1.9 RECOMMENDATIONS

It is recommended that additional study of the sensitivity of electrical proximity fuzes made before 1960 be conducted. Specifically, it is recommended that all geophysical instruments used for detection and evaluation of pre-1960 UXO be tested prior to field

use to determine whether they will activate unshielded primary explosives. The testing should be performed for any fielded instrument configuration at close distances (~1 cm) most likely to start the detonation process. In addition to the instrument manufacturer’s analysis to support a claim for safe operation, laboratory and field tests of the instruments should be conducted with unshielded primary explosives of representative highly sensitive fuzes in various “damaged states” to verify safety.

Specific recommendations for pre-1960 UXO detection include:

- a) Never place any operating geophysical instrument, its electronics, data processor, or battery pack on the ground in an area of UXO. (The dependence of the energy coupled to the initiator with the instrument magnetic field and its height above ground are addressed in subsection 2.4.3, equations 7 and 8, and in Tables 2-3 and 2-4.)
- b) Current data indicates that Ground Penetrating Radar (GPR) units pulled across the ground should not be used for UXO activities until further notice.
- c) Do not use the EM61, EM31, or the GEM-3 units around trash piles.
- d) The GEM-3, EM31, and the EM61 are to be used at heights above ground of 1 meter. Do not allow these instruments, or their accessories, to come within 0.5 meters of the ground when they are turned on.
- e) For pre-1960 UXO work, use only geophysical instruments indicated in Table 1-1 to be safe for this activity. (A conservative criterion of no more than 1 erg per second of energy coupled to a fuze circuit of 50-cm² area was used as a safety cut-off limit.)
- f) Follow all safety regulations and operating procedures during UXO activities.
- g) **CAUTION:** In trash piles containing large quantities of wire, the magnetic coupling between any evaluated geophysical instrument and a damaged UXO may be sufficient to cause detonation. **THEREFORE, AVOID USE OF THE EVALUATED GEOPHYSICAL INSTRUMENTS WHEN A LARGE TRASH PILE CONDITION IS SUSPECTED.**

Table 1-1. Safety Summary for Geophysical Instruments

Type	Vendor/System	Safety Comments and Recommendations
TDEM	Geonics EM61	Safe when carted at 0.42 meter height (or carried at 1 meter height), <u>except at trash piles</u> . DO NOT OPERATE AT HEIGHTS LESS THAN 0.4 METERS!
FDEM (conductivity)	Geonics EM31	Safe when operated at 1 meter height, <u>except at trash piles</u> . DO NOT OPERATE AT HEIGHTS LESS THAN 0.3 METER!
Cesium Vapor Magnetometer	Geometrics G-858	Safe when operated at 1 meter height. DO NOT LET OPERATING INSTRUMENT CONTACT GROUND.
Cesium Vapor Magnetometer	Scintrex/ V-920	Safe when operated at 1 meter height. DO NOT LET OPERATING INSTRUMENT CONTACT GROUND.
Total Field Magnetometer	ADI/TM-4	Safe when operated at 1 meter height. DO NOT LET OPERATING INSTRUMENT CONTACT GROUND.
Flux Gate Gradiometer	Foerster/ Ferex 4.021	Safe when operated at 1 meter height. DO NOT LET OPERATING INSTRUMENT CONTACT GROUND.
GPR (Pulse, TD)	SSI/ Pulse EKKO IV/100	DO NOT USE FOR UXO ACTIVITIES! This is a ground contact instrument that might set off a low activation energy fuze.

GPR (Pulse, TD)	SSI/ Pulse EKKO 1000	DO NOT USE FOR UXO ACTIVITIES! This is a ground contact instrument that might set off a low activation energy fuze.
FDEM	Geophex Ltd./GEM-3	Safe when operated at 1 meter height, <u>except at trash piles</u> . DO NOT OPERATE AT HEIGHTS LESS THAN 0.5 meter!
Mine Detector	Schiebel/ AN/PSS-12	

NOTES: TDEM – time domain electromagnetic; FDEM – frequency domain electromagnetic; ADI – Australian Defense Industries; GPR – ground penetrating radar; SSI – Systems and Software, Inc.

SECTION 2. STUDY FINDINGS

2.1 FUZE FINDINGS

Prior to WWII, the ordnance fuzes were all mechanical systems. Electrical fuzes were developed during WWII for anti-aircraft weapons and then modified for anti-personnel and antitank use. The use of electrical fuzes prior to the 1960s were generally of a hybrid nature, part mechanical and part electrical. Some units had one or more capacitors, or one or more inductors, combined with resistors to function as a resonance circuit. Some units had RF electronics consisting vacuum tube circuits. Some units had a battery, or a piezoelectric material, to generate an initiation voltage under high G loading. The initial battery units used a dry-cell battery that had to be replaced about every six months. For later battery units, the high-G loading of launch was used to initiate a sequence of mechanical actions that would break an ampoule and release a reactive liquid onto the battery plates. This short-term battery would power the fuze circuits. Bending of the piezoelectric material would produce an electric pulse in a circuit to directly initiate the firing sequence. During WWII all proximity fuze designs and hardware were classified at the secret level, due to the increased efficiency from five to twenty times²⁷ to that of a standard contact fuze. The literature and technical experts state that very similar electrical components and circuits were used in all vacuum tube proximity fuzes for all munitions.

2.1.1 FIRING SEQUENCE INITIATION

The firing circuit for the MK 70-series tube-type fuze is shown Figure 2-1. The MK 70 series RF proximity fuzes dates from approximately 1947 to 1976 and is generally representative of earlier fuzes produced during WWII. When the MK 70 fuze is used in spinning ordnance the reed spin-switch opens at the high spin rates and removes the safety short across the firing capacitor. When the fuze clock reaches about 0.4 seconds the mechanical rotor is unlocked. This unbalanced rotor then rotates due to centrifugal force to align the transfer detonator with the electric detonator and lead. Just before full rotor alignment occurs, the shorting wire across the electric detonator is broken by a phenolic pin in the rotor. During this short time interval the high voltage supply charges the capacitor through the charging resistor. When the proper signal from the signal processor is received the thyatron becomes conductive and the firing capacitor is rapidly discharged through the electronic detonator. Similarly, when the impact switch is closed the capacitor is shorted through the electronic detonator, which is the most sensitive element of the explosive train.

The electronic detonator element is sometimes referred to as an electric blasting cap or squib, Figure 1-4. A current through this carbon bridge detonator can be used to rapidly heat the detonating charge to its explosive temperature. Alternately, a high current pulse through the element will cause it to explode and ignite the detonating charge. The primary explosive is normally initiated by a capacitor discharging through the carbon bridge of the detonator. The bridge of the electrical detonator typically has a resistance of

700 to 15,000 ohms. The minimum required energy input for bridge initiation, as indicated in Table 2-1 is about 200 - 500 ergs and is a critical safety factor.

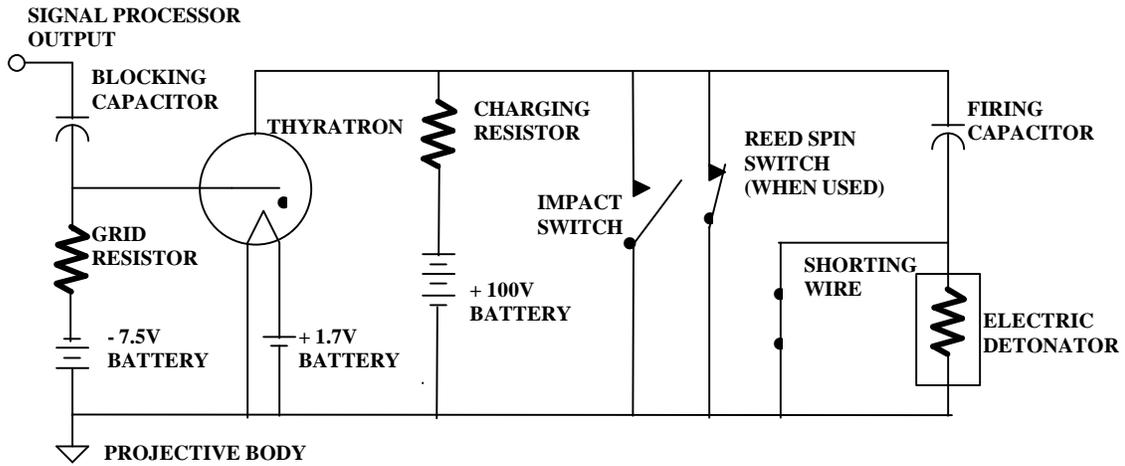


Figure 2-1. MK 70-Series Fuze Tube-Type Firing Circuit Schematic.

Two limiting threshold conditions⁸ for initiation apply to almost every system: (1) the condition in which the energy is delivered in a time so short that the losses are negligible during this time and (2) the condition in which the power is just sufficient to cause initiation eventually. In the first condition the energy required is at its minimum, whereas in the second the power is at its minimum. These two conditions are represented by the dashed asymptotes in Figure 2-2. The relation between the energy required for initiation and the rate at which it is applied can be represented by hyperbolas for different initiator compounds. When the primary explosive is initiated by a capacitor discharging through a carbon bridge, as is common in electronic detonators, the minimum required energy input for bridge initiation can be the critical safety factor.

Table 2-1. Electric Detonators for Fuzes³¹.

Detonator Number	Bridge	Capacitor Discharge		
		Microfarad	Volts	Ergs
M36A1	W	.7	75	20,000
M48	C	.0022	300	1,000
M51	C	.0022	300	1,000
M52 (same as T72)	C	.04	45	405
XM60	C	.02	100	1,000
XM64	W	16	2.5	500
XM65	C	.0022	300	1,000
XM66	W	1 amp all fire	1 amp all fire	25,000
XM67 (same as T76)	C	.004	100	200
XM70	W	4	200	800,000
XM72	EBW	.5	2,500	R&D (NA)
XM73	Special	.39	2.5	R&D (NA)
TX6025	W	4	200	800,000
T17E1	SG	.016	50	200
T20E1	W	.4	50	5,000
T21E1	C	.0022	300	1,000
T22E1	C	.004	100	200
T23E1	W	.4	50	5,000
T24E1	W	16	2.5	500
T25E1	C	.004	100	200
T29	C	.0022	300	1,000
T39E3	SG	.001	1,000	5,000
T40	C	.004	100	200
T44	W	16	2.5	500
T48	C	.0022	300	1,000
T50	C	.004	100	200
T60	C	.0022	300	1,000
T61	C	.004	100	200
T62	C	.0022	300	1,000
T63 (same as 62)	C	.004	100	200
T66	C	.004	100	200
T69	C	.004	100	200
T74	C	.0022	300	1,000
T75	W	.4	50	5,000
T76	C	.004	100	200
T77	W	16	2.5	500
T78E3	C	.05	100	2,500
T79	C	.04	45	405
T80	C	.04	75	1,125
T81	W	.68	38.5	5,040
T88	C	.002	700	4,900
T89 (same as M57)	C	.004	100	200
T90	C	.004	100	200
T105	C	.0022	300	1,000

Notes: W – wire (2 to 10 ohms), C – Carbon (1K to 10K ohms), SG-spark gap, EBW-Exploding Bridge Wire.

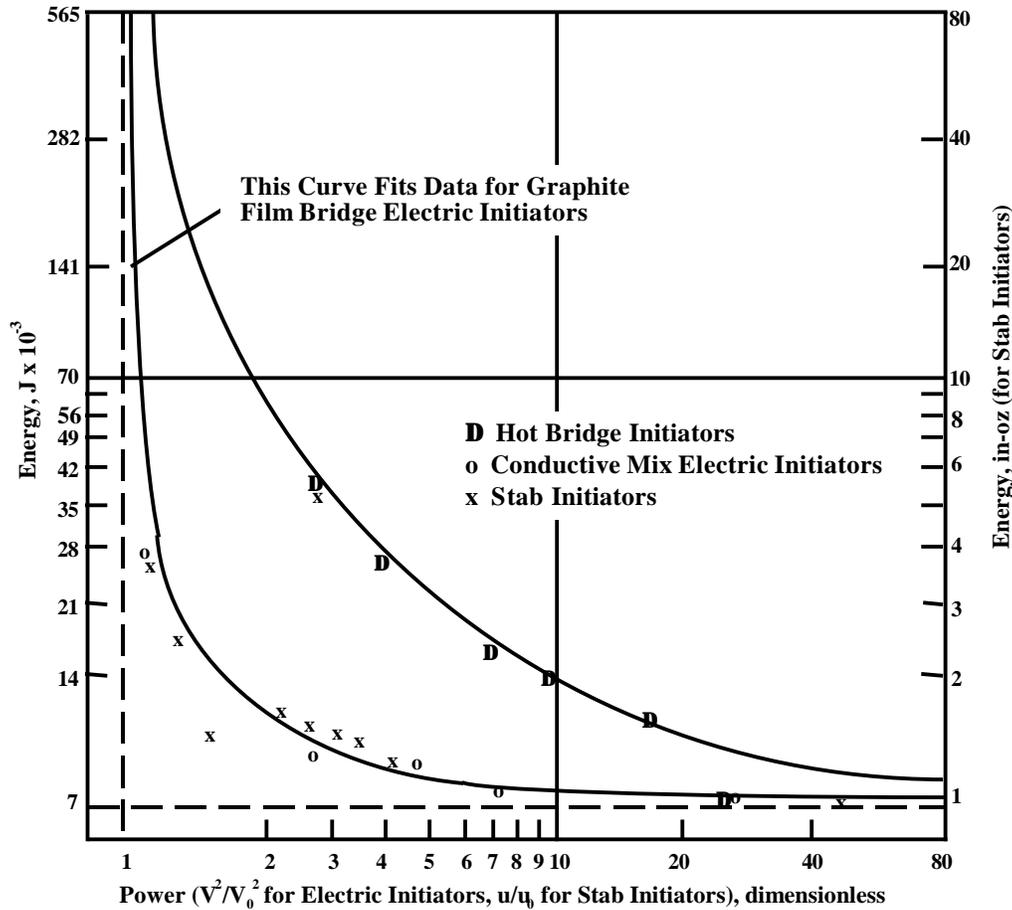


Figure 2-2. Energy Power Relationship for Various Initiators⁸.

2.1.2 ELECTRONIC FUZES AND DESIGN STABILITY

All electronic fuze designs have followed the redundant safety features requirement of earlier mechanical units. In addition to the multiple safety features of the mechanical subsystems of the fuze, the electronic subsystems (a hybrid with mechanical and electrical subsystems) have additional safety features. Electronic fuzes for artillery, bombs, mortars, and rockets have different design configurations and operational and safety requirements. For reliable operations, the as-made fuzes were potted and cemented together making repair difficult and often impractical. Thus, a single failure of any component meant loss of the complete unit. These factors influence the general stability and safety of the fielded units. Their design and operational features also influence the damage received upon ground impact and their sensitivity after being damaged. The degree of impact damage is a major factor in assessing fuze operation, stability with time, and the accuracy with which the fuze status can be determined.

All ammunitions, including fuzes, are assigned numbers or nomenclature based on their state of development, standardization, or modification. Specific fuze numbers and

production information, when available, are provided in Appendix A. The specific numbering system is as follows:

T number, assigned to an experimental item in process of development, and not standardized.

M number, assigned to an item standardized by action of the Ordnance Committee.

Mk number, standardized Navy item, or old Army item.

E suffix, denotes an experimental variation of either an experimental or standard item.

A suffix, denotes a standardized variation of a standard item, usually in design other than material (not applied to T numbers because an experimental variation of an original experimental design would simply be given a M number upon standardization).

B suffix, denotes a standardized variation of a standard item, usually method of manufacture or material.

AN prefix, denotes a standardized item, standard for use by both Army and Navy.

2.1.2.1. Artillery Fuzes

Artillery fuzes, which were developed for use against aircraft during WWII, were the first electronic fuzes developed. The small RF electronic fuze was screwed into the nose end of the artillery shell. The mechanical portion of these units were armed (put the explosive train in line) by the high-G forces of setback. Electrical timing circuits would complete the arming and initiate the detonation sequence, if the ordnance came close enough to the target to produce a strong enough RF return signal within the allotted time. All anti-aircraft fuzes were required to have a prompt self-destruct mechanism, to avoid a friendly-fire problem, if the target was not hit in the allotted time. Initially, artillery fuzes were approved for use over sea only to prevent enemy forces from obtaining duds and reverse engineering the fuze. After approval for use against land-based targets, the self-destruct feature was replaceable by an impact point detonation option.

2.1.2.2. Bomb Fuzes

Bombs dropped by aircraft, commonly used fuzes with a propeller vane that drove a small power generator, as neither dry nor wet-cell batteries were reliable at the sub-zero temperatures of high-altitude bomber flights. For these units the propeller vane must turn a minimum of about 100 to 1000 revolutions to arm the fuze. “Even after the fuze is fully armed, the electrical firing circuit cannot function unless the arming vane is rotating at a speed equivalent to that which would be induced by an air stream of 80 knots or more²⁶.” Although bomb fuzes were designed to be safe when the arming vane is not rotating, damaged bomb fuzes and other types of damaged fuzes can still be hazardous. Some early bomb fuzes were susceptible to vibrations. This susceptibility was reduced by making separate fuzes for small and large bombs and by tailoring their properties to the required performance.

2.1.2.3. Mortar Fuzes

Fuze design work for the eight-pound trench mortar projectile was started in 1944. The mortar fuze was required to withstand 10,000 times the force of gravity during launch and be no larger than 2.125" in diameter and 3" long. This is about one-third the volume of a bomb or rocket fuze. The electrical components; such as resistors, condensers, and their interconnects were manufactured by a new process involving the use of ceramics to save space. Mortar fuzes also had a small loop antenna instead of a projectile body antenna. Extensive field testing was performed from March through July 1945 at the National Bureau of Standards field station at Blossom Point, Maryland and at the University of Iowa field station at Clinton, Iowa. At the end of WWII, Army production had reached 100,000 mortar fuzes per month²⁷.

2.1.2.4. Rocket Fuzes

Fuze design work for the Navy 5" aircraft rocket (AR) began in September 1944. During WWII there were two types of ARs requiring VT fuzes, one type weighed about 85 lbs and reached a velocity of about 700 ft/sec, the other weighed about 140 lbs and reached a velocity of about 1300 ft/sec. The initial rocket fuze design started with the bomb fuze design and adapted it for air-to-air and air-to-ground use. The rocket fuze had an arming switch that was designed to be physically interchangeable with the gear train used in the bomb fuze. Rocket fuzes required an acceleration of 10 G's for 0.5 seconds and air travel of about 300 feet for arming. Rocket fuzes featured an enclosed turbine drive for the generator and gear train, self-destruction and variable arming time as field options, and a change-over switch for air-to-air or air-to-ground operation. Field testing of rocket fuzes was conducted at Blossom Point, Maryland and at the Naval Ordnance Test Station at Inyokern, California. Air-to-ground fuze production began in April 1945, while air-to-air fuze production began in July 1945.

2.2 DESCRIPTION OF GEOPHYSICAL INSTRUMENTS

The geophysical instruments examined during this study included: 1) the EM61 and EM31 made by Geonics, 2) total field magnetometers [or flux gate radiometers], 3) ground penetrating radars [GPR], 4) the GEM3 FDEM sensor made by Geophex Ltd., and 5) the AN/PSS-12 mine detector made by Schiebel. The requested information obtained to date for each instrument is given in Table 2-2 below. Additional information obtained from manufacturers, distributors, and the Internet is given in Appendix A.

There are a few common geophysical instruments for UXO detection activities. The Geonics EM61 portable instrument, Figure 2-2, is commonly used for UXO detection. The Geonics EM31, Figure 2-3, is also a portable instrument sometimes used for UXO detection. It is currently used primarily for pits and trenches. GPR units of one variety or another are also sometimes used in UXO detection. Figure 2-4 shows an example of a ground-based GPR unit.

Geophysical instruments can couple energy into a fuze element by electric and/or magnetic fields. The electric fields produced by geophysical instruments can apply an electrical potential across the leads of an exposed fuze. The electric potential applied to fuze leads will be reduced by the soil and any air gaps. For geophysical instruments not in contact with the ground, the resistance of the air gap may be the dominant source of the potential (voltage) drop. Geophysical instruments on the ground just above shallowly buried ordnance will be the worst case for the electric field coupling.

The magnetic field produced by a geophysical instrument can couple with a fuze circuit and generate an induced electromotive force (emf) that depends on the time rate of change in flux across the area bounded by the circuit. (See Faraday's Law in most standard electronic textbooks.) The change in flux may be due to instrument movement (motional emf), or a change in the magnitude of the magnetic field (stationary circuits).

Table 2-2. Properties of Geophysical Instruments

Type	Vendor/ System	Freq.	Pulse Dura- tion	Pulse Rep Rate	Rise (fall) Time	Mag. Mom. A-m ²	Peak Cur. (amps)	Peak Power (W)	Ave. Power (W)	Foot- print (dia.)
TDEM	Geonics EM61		3.3 ms	75 Hz	90 μs	256	8	95	15	8 m
FDEM (conductivity)	Geonics EM31	9.8 kHz			25 μs (fall)	1	0.1	1.4	1	8 m
Cesium Vapor Magnetometer	Geometrics G-858	Variable 1-10 Hz	N/A	N/A	N/A	"0"	2.5	70	15-20	NA
Cesium Vapor Magnetometer	Scintrex/ V-920	200 kHz			(Sine Wave)	"0"	1.5-surge 0.5 ave.	1.5A x 24V=36	2	0.75
Total Field Magnetometer	ADI/TM-4 (~ G-858)	(Var. 1-10 Hz)	N/A	N/A	N/A	"0"	(2.5)	(70)	(15-20)	NA
Flux Gate Gradiometer	Foerster/ Ferex 4.021	10 kHz one axis	N/A	N/A	N/A	27x10 ⁻⁶	N/A	"0", no peaks	<1x10 ⁻⁶	<8 m
GPR (Pulse, TD)	SSI/ Pulse EKKO IV/100 (MHz units)	12.5 M, (25, 50, 100, 200 M)	120 ns, (60, 30, 15, 7.5 ns)		40 ns, (20, 10, 7.5, 2.5 ns)			~10	560mW 280mW 140mW 70mW 35mW	24 m (12, 6, 3, 1.5 m)
GPR (Pulse, TD)	SSI/ Pulse EKKO 1000 (MHz units)	110 M, (225, 450, 900, & 1200 M)	14 ns, (7, 3.3, 1.7, 1.3 ns)		4.7 ns, (2.3, 1.1, 0.6, 0.4 ns)			~10	70mW 30mW 15mW <10m W <10m W	2.8 m (1.4, 0.8, 0.4, 0.3 m)
FDEM	Geophex Ltd./GEM-3	300 Hz - 23 kHz	NA	NA	(Sine wave)	15	5.5	50	4W	0.6 m
Mine Detector	Schiebel/ AN/PSS-12									

NOTES: TDEM – time domain electromagnetic; FDEM – frequency domain electromagnetic; ADI – Australian Defense Industries; GPR – ground penetrating radar; SSI – Systems and Software, Inc.



Figure 2-3. Geonics EM61 Magnetometer.



Figure 2-4. Geonics EM31 Magnetometer.



Figure 2-5. Ground-Based Monostatic GPR (GeoRadar) Example.

2.3 SENSITIVITY TO NATURAL ELECTROMAGNETIC RADIATION

The sensitivity of ordnance to EM radiation is addressed in two parts; that due to natural sources and that due to geophysical instruments. Sensitivity due to EM radiation from natural sources is briefly discussed below, as it relates to current status of fuzes fielded before 1960. Some additional discussion of the sensitivity to EM radiation from geophysical instruments is included in ECG Report No. H-0003 "Electronic Fuze Evaluation; Sensitivity to Radiation from Geophysical Instruments", Interim Study Report, 16 July 1997.

The sensitivity of electronic and electrical fuzes used in the US prior to 1960 to EM radiation is believed to be different from modern fuzes being used today. Part of the sensitivity difference is due to the change from high-voltage vacuum tube technology to low-voltage transistor systems, to low-power integrated circuits, and the use of post-destruct systems. However with the increased understanding of electronics and the greater design restrictions for enhanced fuze safety requirements, modern electronic fuze systems must now meet very demanding Government standards before being approved for military use.

Since some electronic fuze systems used prior to 1960 had low activation energies, they are perceived as being more sensitive to EM fields from geophysical instruments. There is limited information which suggest the sensitivity of electrical fuzes to EM fields may not be as bad as perceived. There is not a documented case of an unintentional detonation of a UXO by any geophysical instrument used for detecting or evaluating UXOs. Pueblo Army Depot⁴⁴ had a pad of 75mm, M-48's that was hit by lightning in the late 1940's. It resulted in the detonation of several hundred items of ordnance. (At 1 km ordinary lightning can produce electric fields of a few KV/m as measured at ground level.) Considering the large number of UXOs (both buried and on top of the ground) on test ranges and the time since use/firing, it is very likely that some of these items have received direct lightning strikes after being fired/misfired. Even though UXOs used/fired prior to 1960 have been exposed several times to EM fields from distant lightning, there is no record of detonation of any fired UXO, but then these ranges are generally not monitored. Other than the Pueblo incident, other documented cases of accidental detonation of UXOs have resulted from rough handling (i.e., cutting the casing with a blowtorch, struck with a backhoe, or hitting with a hammer and chisel, etc).

Some geophysical instruments used for UXO detection are also used in the mining industry. The mining industry was very concerned that these instruments could activate an electronic blasting cap. The mining industry has tested geophysical instruments by holding them over a blasting cap and verified that it was not ignited prior to approval for field use. The blasting caps used in mining explosives are similar to the higher activation energy electronic detonators used in some modern fuzes³⁰. The basic design of the detonator electronic (or blasting cap) has changed little since initial development during WWII. However, the threshold energy for initiation has changed with time and application.

If the explosive materials within an UXO were exposed, dry, and received a direct lightning strike, it would most likely detonate or burn. However, the metal case of the ordnance and the fuze surrounds the explosive materials and provides excellent electromagnetic shielding (a Faraday cage). J. D. Robb and J. R. Stahmann²² computed the internal electrical field of an airplane struck by a 100,000-amp bolt of lightning for different metal wall thickness of the aircraft. They modeled the airplane shell as a 7' diameter closed thin wall shell (aluminum or copper) with thickness of 0.03", 0.06", and 0.09" and computed that the electric field inside the aircraft never exceeded 1 V/m and decreased with increasing frequency according to the expression:

$$E = (I \times [2]^{1/2}) / [(2 \times \pi \times R \times \sigma \times \delta) \{e^{2b/\delta} - 2e^{b/\delta} \cos(b/\delta) + 1\}^{1/2}] \quad (1)$$

where; I = current of lightning pulse (100,000 amps used in lightning calculation)
R = mean radius of the tube (3.5 feet use for aircraft)
 σ = conductivity of the tube material
 δ = skin depth of the tube material = $1/(\pi \times f \times \mu \times \sigma)^{1/2}$
b = thickness of the wall
f = frequency

Performing a simple scaling calculation assuming ordnance diameter of 0.7' (~8") and wall thickness of 0.09", it can be seen that the electric field internal to a non-ruptured ordnance would be less than 10 V/m from a direct lightning strike of 100,000 amps. Obviously, the internal electric fields from low-power level geophysical instruments would be several orders of magnitude less, as the current pulse would be orders of magnitude less and the wall thickness of the fuze, shell, or bomb is also greater.

However, if the casing of the ordnance has been ruptured (by impact or erosion), the ruptured casing would provide very little electromagnetic shielding. The condition of the ruptured ordnance depends very strongly on how long it has been since the ordnance was exposed and the environment to which it has been exposed. For ordnance in which the fuze was ruptured on impact (prior to 1960), the fuze unit would probably be damaged or filled with dirt and debris, such that the explosive train has a low probability of functioning. For ordnance in which the high explosive shell was ruptured on impact (prior to 1960), the high explosive material may have leached out or degraded, such that an activated fuze would not initiate a high pressure explosion. (The remaining high explosive material in a rupture shell may burn or produce a low-order explosion, and thus pose a reduced hazard.) For those ordnance that were ruptured on impact (prior to 1960), the explosive material, fuze components, and wiring circuits have probably degraded beyond normal functioning and less likely to be initiated by the weak EM fields of geophysical instruments. If the fuze survived impact fully intact and armed, any ordnance that had been recently ruptured by excavation or a nearby intentional detonation could pose the highest risk when exposed to electromagnetic fields.

2.4 SENSITIVITY TO INSTRUMENT EM RADIATION

When the primary explosive contains a carbon film electronic detonator, the minimum required energy input for detonator initiation is a critical safety factor. To determine the lowest sensitivity value for all types of fuzes potentially left at test sites, will require a detailed comparison of the energy that a geophysical instrument can couple to this critical electrical circuit. Table 2-3 summarizes our deposited energy analysis.

The first five rows (for the EM61 magnetometer) indicate the strong dependence of the magnetic field coupling on the fuze circuit loop area and height of the instrument above the ordnance. The energy coupled to the detonator goes as the square of this loop area. A more detailed analysis must address all feasible configurations (or at least the worst cases) of the electrical circuit, as the fuze may be severely damaged from impact.

2.4.1 ASSUMPTIONS OF ANALYSIS

Since the proximity fuzes addressed in this analysis were fired, or misfired, prior to about 1960 and probably have been buried a few centimeters to a few meters below the ground surface ever since, we made a few assumptions based on age and impact effects. First, all dry-cell batteries and wet-cell batteries that properly activated no longer maintain a voltage. Wet-cell batteries that properly activated in fuzes that did not detonate could be reactivated and then generate operational voltages by a simple rotation of the fuze, if the electrolytic solution was not lost on impact. When the ordnance impacted the ground, some received no damage, some received little damage, some received major damage, and some received severe damage that rendered it nonfunctional. Ordnance that impacted soft soils is expected to have received less damage than those impacting hard rocky soils. However, the degree of damage for an individual UXO can not be assigned based on soil type or condition, as soft topsoil or loose sand may have large rocks, or other objects, buried within a few meters of the surface.

The electromagnetic emission data provided by the manufacturers and distributors of the geophysical instruments is used directly in the analysis whenever available. If the requested data was only partially obtained, we have made “conservative engineering estimates” for the remaining information needed if feasible. Some vendors claim to have the requested data and have promised to send it, but have yet to provide it. There are some vendors that seem vague as to whether they have the requested data or not. Perhaps they have the data, but they have low confidence in it. One vendor was vague about his data and expressed a serious lack of confidence in the data from other vendors. He wanted the Government to perform a standardized measurement of the electromagnetic radiation emitted from all geophysical instruments considered for UXO use prior to performing any comparison analysis or down-selection of any instruments.

A large part of the geophysical instrument community seems to be only casually interested in the UXO problem and has limited knowledgeable about the EM fields generated by their instruments. This suggests that the accuracy of the data obtained on these instruments may be less than desired. Unless otherwise noted we have used the data

as obtained. The uncertainty in obtained data indicates that our calculations should not be regarded as absolute, but that a large margin of safety may be needed.

The EM fields we computed are normally based on the properties provided for the geophysical instruments. These computed EM fields were considered as being applied to the electrical circuits of the fuze. We expect the magnetic fields produced by the geophysical instruments to be varied by the magnetically susceptible materials of the ordnance. (The magnetic field enhancement could vary from a few percent to perhaps four orders of magnitude increase!) The larger the ordnance and the higher the iron content, the greater the enhancement potential. However, we did not compute the change in the applied magnetic fields due to a lack of information on the ferromagnetic, antiferromagnetic, diamagnetic, and paramagnetic materials in the ordnance (fuze and shell). We do not have adequate quantitative information on; the original metallic concentrations of the ordnance, the degree of oxidation or other chemical changes that have occurred since initial ordnance burial, the approximate geometry and orientation of a damaged ordnance, or the contributions from the local ordnance site. Even if we had all the needed theoretical information, it would probably be more productive to address the problem through testing with removed and certify safe UXO than by analysis.

As indicated earlier, the resistance of the electrical detonators varies from 700 ohms to 15,000 ohms. We have used a detonator resistance of 700 ohms for all calculations, as this represents the worst case for sensitivity to the EM fields of the geophysical instruments. This resistance value is also common for production detonators as it increases the sure-fire performance. For the instruments that produce a sine wave output, the rise (and fall) time corresponding to approximately 1/2 cycle was assumed.

2.4.2 ANALYSIS OF SENSITIVITY TO ELECTRIC FIELDS

The four or five vacuum tubes used in proximity fuzes have different functions and different operating voltages for their elements. The thyratron, see Figure 2-1, normally functions as a hot gas diode. A thyratron is a hot-cathode, triode or pentode, electronic tube containing low-pressure gas or metal vapor in which one or more electrodes start the current flow to the anode but exercise no further control over its flow. Gas diodes can be either hot or cold operational devices. The ionization potential for typical diode gases are: 10.4 V for mercury, 15.7 V for argon, 21.5 V for neon, and 24.0 V for helium. For hot gas diodes, the diode fires at the ionization potential plus a few tenths of a volt. However, the heating element must be heated to produce thermionic emission. For cold gas diodes, the diode does not fire until its firing potential of about 150 volts is exceeded, then the current changes from a few microamps to milliamps. A 1 microamp current through a 700-ohm electronic detonator corresponds to only about 7×10^{-3} ergs of energy during each second of operation, or about 24 ergs in an hour of operation, which is too low for detonator activation. With no functioning battery and thus no heater current, a "cold gas" thyratron would not conduct significant currents until external voltages of about 150 volts are applied.

The electric fields from geophysical instruments that are operated above the ground do not generate large enough voltages to activate the vacuum tubes in buried fuzes. Most of the electric potential from a geophysical instrument operated above the ground would be applied to the high resistance air-gap between the instrument and the ground. (A geophysical instrument with sufficient high voltage to conduct across a large air gap [several thousands of volts] would be dangerous for the operator who carried it.)

Geophysical instruments in direct contact with the ground can have a relatively low resistance conduction path, especially if the soil is moist. If the metal fuze shell were not ruptured on impact, it would provide a low resistance (few ohms) path and reduce the possible hazardous current flow inside a normal or damaged fuze circuit, as the electrical detonator resistance values are typically 700 ohms or more. If the metal fuze shell were ruptured, application of a voltage directly with ground penetrating spikes (contacts) to the electrical circuits may be sufficient to activate the detonator. If the spikes made direct contact with the fuze electrical circuits, two cases exist. Either portions of the fuze circuits would be external to the fuze making it highly damaged and probably inoperable; or the rupture is to the fuze top side such that it probably is filled with dirt, debris, or moisture that would reduce the probability of it functioning. Any geophysical instrument that directly applies roughly 100 volts or more to ground contacts could potentially activate the detonator of a near-surface damaged fuze or may pose a hazard to the instrument operator. The effects of such geophysical instruments (with high voltage electrical contacts) on a fuze should be examined carefully both analytically and experimentally, prior to used in any area possibly containing UXO.

Of the geophysical instruments evaluated (Table 2-2 above) only the ground penetrating radar (GPR) units are in direct contact with the ground during normal field operations. Neither of the GPR units, or the other instruments evaluated in this study, apply a direct voltage across electrical contacts driven into the ground (stakes) for data measurements. The electrical voltages from the geophysical instruments evaluated do not pose a serious risk in their normal operation mode. However, as with any ordnance, be certain to avoid making direct contact with any electrical instruments, especially any power source that may result in a large current short. All geophysical instruments evaluated do have one or more electrical current loops to their sensors, which generates a magnetic field.

2.4.3 ANALYSIS OF SENSITIVITY TO MAGNETIC FIELDS

In addition to direct application of an electric field, a geophysical instrument can also generate a magnetic field that can induce strong electric fields in electrical circuits by rapid changes in the applied magnetic field. This change in applied magnetic field may be due to instrument motion or changes in magnetic field strength. The applied magnetic field from the instrument induces eddy currents on the surface of the ordnance. If the ordnance shell were very thick and had no holes, cracks, or seams, the shielding of the shell would be complete, such that no magnetic field is induced internal to the ordnance. For small holes or cracks in thin-shelled ordnance, the strength of the induced magnetic

field varies with shell thickness, the maximum length of the opening, and the frequency of the EM wave. In general, thicker enclosures are better and metal enclosures with lower resistance than the electronic circuit are better shields. Small openings can be viewed as aperture or slot antennas for which the transmitted fields at low frequencies tend to fall off inversely proportional to the cube of the distance from the aperture. At higher frequencies, the shield effectiveness is limited by resonant penetration and skin-depth effect⁴⁰. For relatively large openings (worst case), the applied field can couple directly with the electrical circuit(s) of a damaged, or exposed, fuze by the magnetic flux through the fuze electrical circuit loop(s) area and applies an induced potential to the charges within the circuit. (See induced electromotive force³⁶ in most standard physics or electronics textbook addressing Electricity and Magnetism.) The following calculations are based on the fuze circuits being directly exposed to a changing magnetic field.

The magnetic field B, produced by a current in a coil is given by;

$$B = k' (2m)/(h^3). \quad (2)$$

k' is a constant equal 10^{-7} newtons/ampere², m is the magnet moment of the coil, and h is the height of the coil (instrument) about the article (fuze). The area of the fuze loop that this magnetic field can intersect is given by;

$$A_1 = \pi (r_1)^2 \quad (3)$$

r₁ is the radius of the loop. For a worst case orientation, the fuze loop is oriented perpendicular to the direction of the magnetic field. In this case the flux, Φ, through the loop is given by;

$$\Phi = B \times A_1 \quad (4)$$

The maximum electromotive force ξ on the electrons in the fuze loop is given by;

$$\xi = (B \times A_1)/dt \quad (5)$$

The term, dt, is the time interval associated with the change in flux through the loop, due either to turning the pulse on or off (rise or fall time), or due to moving the magnetic field (sensor) across (over) the fuze loop. The induced current in the fuze loop is given by;

$$I = (\xi/R) \quad (6)$$

R is the resistance of the fuze loop, which equals the resistance of the electrical detonator (about 700 ohms or more) plus the equivalent resistance of the rest of the loop path. If the resistance of the detonator is much greater than that of the rest of the loop, worst case, the energy from each change in magnetic field will be essentially deposited in the electrical detonator. This deposited energy per change in magnetic field (a rise or fall) is given by;

$$E = I \times \xi \times dt = (\xi^2/R) \times dt = (B^2 \times A_1^2)/(R \times dt), \text{ or} \quad (7)$$

$$E = 4(\pi^2 \times k'^2 \text{ m}^2 \times r_1^4)/(R \times dt \times h^6) \quad (8)$$

Note the very strong dependence, $(1/h^6)$, on the height of the instrument above the ordnance and a strong dependence, r_1^4 , on the radius of the loop.

The magnetic field computed for the fuze loop was based only on the geophysical instrument properties. (In short, we assumed free-space between the instrument and the fuze.) We also assumed the magnetic field of the geophysical instrument is essentially uniform over its footprint, which for our basic calculations should be adequate. (We have not requested two-dimensional profiles of the magnetic field across the footprint as a function of distance from the instrument needed for precise calculations. Accurate profile data probably has not been measured for these instruments.) Normally, the instruments are carried at waist height (~1 meter), or in a cart at about 05 meters above the ground. We have assumed an instrument height of only 0.3m above the ordnance as a worst case. This condition may occur with the instrument turned on while traveling over rugged terrain, or if the operator becomes careless due to fatigue or distraction.

2.4.3.1 Fuze Sensitivity to Magnetic Field from EM61

The first row of Table 2-3 corresponds to the normal height (0.42 m) for the instrument transmitter coil. As the volume for a large bomb fuze is only about three times that of mortar fuze, a 50-cm² fuze loop area is an estimate of an average value. The bomb and mortar circuit loop areas could differ by about a factor of two. A factor of two increase in the loop area gives a factor of two increase in the flux and electromotive force, with a corresponding factor of four increase in the energy values. The 50-cm² fuze loop area is representative of having both sides (one side is grounded to the fuze shell) of the electronic detonator connected to the fuze shell (a damaged fuze). The 50-cm² area is roughly the geometrical area of the entire fuze electrical circuit. The electronic detonator has twisted wires to minimize the loop area, which should be roughly the same loop area for all pre-1960 UXO fuzes. The 5-cm² area in the second line is roughly the geometrical area of the electrical detonator loop and representative of the electrical detonator still being shorted by the shorting wire. The third row with a 50-cm² fuze loop area corresponds to the instrument being 30-cm above a damaged fuze (too low). The fourth row corresponds to the approximate height for the instrument transmitter coil, if the coil unit was carried and shows the strong dependence on height. The 50-m² fuze loop area (fifth row) corresponds to the instrument footprint area and corresponds to the detonator being connecting directly to a large loop or multiple loops (such as a spool of discarded wire) as a result of the impact damage received. If the fuze was fully armed, aligned, and the detonator was somehow connected (unlikely except in a trash pile) to such an external loop, a single pulse (change in magnetic field) could result in activation.

2.4.3.2 Fuze Sensitivity to Magnetic Field from EM31

The analysis of the EM31 is similar to that of the EM61, except the rise time and the magnetic moment are both less for the EM31. The EM 31 is also normally carried at 1-meter height. The net result is lower energy coupling to the electrical detonator, due to

the much lower magnetic moment. The resulting low energy values indicate a moderate margin of safety.

2.4.3.3 Fuze Sensitivity to Magnetic Field from the G-858 and the V-920

The cesium vapor magnetometers require low instrument magnetic moment to correctly operate. Both instrument vendors claim to have “zero” magnetic moment. The instruments use “all twisted wiring” and counteracting magnetic loops to eliminate their magnetic moments as much as possible. If this were precisely true, these instruments pose absolutely no risk due to their magnetic field. Nonetheless, as a conservative calculation, a worst case scenario for these instruments was evaluated. The instruments were assumed to have an effective loop area of 1 cm^2 , be momentarily defective, with the maximum current pulsed at the instruments operating frequency for up to 1 second. The magnetic moment due to a single loop is the product of its area (assumed to be 1 cm^2) and its current (peak current used for each instrument). This gives a “one-time” magnetic moment of $2.5 \times 10^{-4} \text{ A-m}^2$ for the G-858 and a value of $1.5 \times 10^{-4} \text{ A-m}^2$ for the V-920. The vendor indicated that the magnetic field from the G-858 battery pack and sensor electronics package is kept below 1 Gamma (10^{-9} w/m^2) at 4 feet to prevent interference with the sensor. This magnetic field corresponds to a magnetic moment of $9.1 \times 10^{-3} \text{ amp-m}^2$, which is a factor of about 40 higher than the sensor’s magnetic moment indicated (approximated) in Table 2-3. The electronics package could couple about 1600 times more energy to the fuze, but this level would still be well below the hazard level. (A similar statement could be said about the V-920 Cesium Vapor magnetometer, but the margin of safety would be somewhat less due to the higher operating frequency.)

2.4.3.4 Fuze Sensitivity to Magnetic Field from the ADI/TM-4

The ADI/TM-4 instrument uses the same Cesium Vapor magnetometer sensor as the G-858. The TM-4 system operates at a magnetic noise threshold is about 0.2 nT (equals $0.2 \times 10^{-9} \text{ w/m}^2$) and thus should be comparable to other Cesium Vapor magnetometers in terms of its magnetic field. The resulting energy values were also comparatively low, and provide a wide safety margin.

2.4.3.5 Fuze Sensitivity to Magnetic Field from FEREX 4.021

The magnetic field from the FEREX 4.021 instrument is very low. The vendor gave a value of $27 \times 10^{-6} \text{ A-m}^2$ for the magnetic moment and a value of 1×10^{-6} watts for the average power. In normal operations this instruments should not produce any surge peaks, thus he indicated “0” for the peak power and no corresponding peak current. For conservative calculations, the instrument was also treated as having malfunctioned by pulsing (at the operating frequency) the power on and off for up to 1 second. A peak power of up to 5×10^{-6} watts and a corresponding current of 1×10^{-3} amps were assumed for these worst case calculations. These resulted in very low energy values and similar wide safety margins.

2.4.3.6 Fuze Sensitivity to Magnetic Field from EKKO IV/100 and EKKO 1000

These radar units emit electromagnetic waves that can be coupled to ordnance and thus the fuze by different methods. The Air Force Manual 91-201, 7 October 1994, page

143, provides a nomogram of the “Recommended Safe Separation Distances for EEDs in Exposed Conditions” in terms of frequency and radiated power. Using this nomogram and the frequency and power from Table 2-2, the safe separation distances of Table 2-4 were computed for the EKKO IV/100 and EKKO 1000. As seen in Table 2-4, all safe distances are ≥ 1 centimeter. However, these GPR units are pulled along on the ground. **If buried ordnance is within 1 centimeter of the surface, then the safe separation distances are violated for both units at all operating frequencies.**

Additional calculations of the radar energy coupled to the ordnance by considering the ordnance as a receiving radar antenna were performed using a series of nomograms found in Reference 38 for standard high-powered radar systems and extrapolation information provided by Ron Lewis³⁹. The approximate energy coupled to the ordnance at a distance of 1 centimeter varied from about 1 to 50 ergs, depending of frequency and transmitted power. These values are close enough the detonation levels (~200 ergs) that safe operation for potentially damaged ordnance can not be assured. If on impact the ordnance connects to a conductor that functioned as a (quarter-wave) loop or rod antenna, then significantly more energy could be coupled to the ordnance.

Thermal calculations were also performed assuming the transmitted power to be uniform from the ground-contact surface of the GPR transmitter. For a GPR transmitting 70 mW at roughly 100 MHz with a transmitter surface area of 92 x 46 cm and a detonator area of 0.152 x 0.254 cm, the ratio of receiver to transmitter area is 0.09. For a uniform plane wave, approximate 9% of the transmitter energy (6.3mW) could directly strike an exposed detonator. If 0.1% of this radar energy is absorbed by the detonator during a one second transmission, then about 5 to 100 ergs would be deposited in the detonator. These values are close enough to the detonation levels that a safe operation can not be assured.

2.4.3.7 Fuze Sensitivity to Magnetic Field from GEM-3

The Geophex broadband frequency-domain GEM-3 sensor has a moderately high magnetic moment and a relative short rise time. These contribute the relative strong magnetic coupling and the resulting energy potentially transferable to the fuze. Except for the sensor emitting a continuous sinusoidal wave, the calculations were made the same manner as for the EM magnetometers. (A rise time of one-half the period was used in the calculations.) The energy values for this instrument are also close enough to the detonation levels that a safe operation can not be assured.

2.4.3.8 Fuze Sensitivity to Magnetic Field from the Schiebel AN/PSS-12

The Schiebel AN/PSS-12 instrument is a German sensor used for metallic mine detection. To date no information has been obtained from Schiebel Instruments.

Table 2-3. Fuze Sensitivity per Geophysical Instruments

Geophysical Instrument	Height Of Instru.	Rise (fall) Time	Magnetic Moment (A-m ²)	Mag. Field (w/m ²)	Fuze Loop Area	Emf (V)	Bridge ¹ Energy (ergs)	Rep. Rate (Hz)	Bridge ² Energy (ergs/sec)
Geonics EM61	0.42 m*	90 μs	256	6.7x10 ⁻⁴	50 cm ²	0.37	1.8x10 ⁻³	75	0.26
Geonics EM61	0.3 m	90 μs	256	0.0019	5 cm ²	0.01	1.4x10 ⁻⁴	75	2.1x10 ⁻²
Geonics EM61	0.3 m	90 μs	256	0.0019	50 cm ²	0.1	1.4x10 ⁻²	75	2.1
Geonics EM61	1.0 m	90 μs	256	5.1x10 ⁻⁵	50 cm ²	0.003	1.0x10 ⁻⁵	75	1.6x10 ⁻³
Geonics EM61	0.3 m**	90 μs	256	0.0019	50 m ²	1040	1.4x10 ⁶	75	2.1x10 ⁸
Geonics EM31	1.0 m*	(25 μs)	1	2.0x10 ⁻⁷	50 cm ²	4.0x10 ⁻⁵	5.7x10 ⁻¹⁰	9.8x10 ³	1.1x10 ⁻⁵
Geonics EM31	0.3 m	(25 μs)	1	7.4x10 ⁻⁶	5 cm ²	1.5x10 ⁻⁴	7.8x10 ⁻⁹	9.8x10 ³	1.5x10 ⁻⁴
Geonics EM31	0.3 m	(25 μs)	1	7.4x10 ⁻⁶	50 cm ²	1.5x10 ⁻³	7.8x10 ⁻⁷	9.8x10 ³	1.5x10 ⁻²
Geometrics G-858	0.3 m	0.02 sec	“none” [2.5x10 ⁻⁴]	---	---	---	---	---	---
Geometrics G-858	1.0 m	0.02 sec	“none” [2.5x10 ⁻⁴]	---	---	---	---	---	---
Scintrex/V-920	0.3 m	[2.5 μs] note3	“none” [1.5x10 ⁻⁴]	---	---	---	---	---	---
Scintrex/V-920	1.0 m	[2.5 μs] note3	“none” [1.5x10 ⁻⁴]	---	---	---	---	---	---
ADI/TM-4 (note4)	0.3 m	0.02 sec	“none” [2.5x10 ⁻⁴]	---	---	---	---	---	---
ADI/TM-4 (note4)	1.0 m	0.02 sec	“none” [2.5x10 ⁻⁴]	---	---	---	---	---	---
Foerster/ Ferex 4.021	0.3 m (1-axis)	5x10 ⁻⁵	27x10 ⁻⁶	2x10 ⁻¹⁰	50 cm ²	2x10 ⁻⁸	2.9x10 ⁻¹⁶	1x10 ⁴	5.7x10 ⁻¹²
Foerster/ Ferex 4.021	1.0 m (1-axis)	5x10 ⁻⁵	27x10 ⁻⁶	5.4x10 ⁻¹²	50 cm ²	5.4x10 ⁻¹⁰	2.1x10 ⁻¹⁹	1x10 ⁴	4.2x10 ⁻¹⁵
SSI/ Pulse EKKO IV/100	0.01 m	40 ns, (20, 10, 7.5, 2.5 ns)	See text above.						
SSI/ Pulse EKKO 1000	0.01 m	4.7 ns, (2.3, 1.1, 0.6, 0.4 ns)	See text above.						
Geophex Ltd./GEM-3	0.3 m	[2x10 ⁻⁵]	15	1.1x10 ⁻⁴	50 cm ²	2.8x10 ⁻²	2.2x10 ⁻⁴	2.3x10 ⁴	10.1
Geophex Ltd./GEM-3	1.0 m	2x10 ⁻⁵]	15	3x10 ⁻⁶	50 cm ²	7.5x10 ⁻⁴	1.6x10 ⁻⁷	2.3x10 ⁴	7.4x10 ⁻³
Schiebel AN/PSS-12									

NOTES: (* Denotes operational heights. Non-operational heights are shown for comparison to emphasize to the operators how strongly safety depends on the height above ground of the instrument.)

[** Included to address trash piles, which may contain large bundles of wire.]

1. This computed detonator bridge energy is for a single change (rise or fall of a single pulse) in the magnetic field.
2. This is the bridge energy for the total number of rises and falls in one second.
3. The V-920 has a RF signature of 2 watts (constant) RF sinusoidal wave at 200 kHz. The rise from -90 to +90 degrees occurs in 2.5 microsecond.
4. The TM-4 uses the same Cesium Vapor Magnetometer sensor as the G-858.

Table 2-4. Safe Separation Distances for GPR units

Geophysical Instrument	Frequency (MHz)	Average Power (W)	Safe Separation Distance (ft)	Safe Separation Distance (cm)
EKKO IV/100	12.5	0.56	4.7	143
EKKO IV/100	25	0.28	3.6	110
EKKO IV/100	50	0.14	2.6	79
EKKO IV/100	100	0.07	1.0	30
EKKO IV/100	200	0.035	0.42	13
EKKO 1000	110	0.07	0.95	29
EKKO 1000	225	0.03	0.37	11
EKKO 1000	450	0.015	0.13	4.0
EKKO 1000	900	0.01	0.045	1.4
EKKO 1000	1200	0.01	0.032	1.0

2.4.4 DISCUSSION OF ANALYSIS RESULTS

Our analysis results indicate that some of the evaluated geophysical instruments (see Table 1-1) are generally safe to operate for detection and discrimination of UXO and pose limited risks for detonation of UXO, provided the instruments are ALWAYS carried at safe heights. No geophysical instrument should be operated on the ground in an ordnance area until proven safe. Geophysical instruments with low magnetic moments pose less risk than instruments with large magnetic moments. Instruments carried at a meter, or more, heights above ground pose considerably less risk than instruments on or near the ground. Instruments that have low magnetic moments and are carried at one-meter height, or more, will couple less energy to the fuze, and thus present lower detonation risks. The GPRs evaluated here are pulled along on the ground and could pose a serious risk if damaged ordnance were buried at or just below the surface.

2.5 SOURCES OF INFORMATION

The key documents used for this report are found in the references of Appendix C. In addition to these references, significant guidance and historical points were obtained from different experts knowledgeable in fuze and ordnance technology. The geophysical instrumentation information was obtained from the manufacturers, distributors, and from the Internet. The majority of the geophysical instrument information obtained is provided in Appendix B. The key points of contact are indicated in Appendix E.

APPENDIX A

FUZE DATA

FUZE DATA

A.1 Variable Time (VT) Fuzes

The different VT fuzes made by the U.S. prior to 15 August 1945 are listed in Table A-1 through Table A-4. Table A-5 list fuzes made during the Korean War. Information on other fuzes noted in the literature is provided in Tables A-6 to A-9, but production numbers through 1960 have not yet been obtained. Table A-10 provides information on electronic detonators.

Table A-1. VT Fuze Production for U.S. Navy as of 15 August 1945

Types	No. Produced	Shipped for Use	Shipped for Test
<i>U.S. Navy</i>			
Mk 32 (5"/38)	2,055,132	2,008,407	46,725
Mk 40 (5"/38)	339,616	333,000	6,616
Mk 45 (3"/50 Mod 11)	79,186	75,852	3,334
Mk 47 (6"/47)	27,205	26,532	673
Mk 53 (5"/38)	1,280,407	1,259,358	21,049
Mk 58 (3"/50)	743,594	729,883	13,711
Mk 59 (5"/54)	32,414	31,635	779
Mk 173 (5" rocket)	11,076	10,000	1,076
Total U.S. Navy	4,568,630	4,474,667	93,963

Table A-2. VT Fuze Production for British Navy as of 15 August 1945

Types	No. Produced	Shipped for Use	Shipped for Test
<i>British Navy</i>			
Mk 33	340,710	307,760	32,850
Mk 41	212,042	199,700	12,342
Mk 56	121,610	119,624	1,986
Mk 60	216,389	213,021	3,368
Total British Navy	890,751	840,105	50,546

Table A-3. VT Fuze Production for U.S. Army as of 15 August 1945

Types	No. Produced	Shipped for Use	Shipped for Test
<i>U.S. Army</i> (Mk 45 Type)			
T73 (75-mm AC)	1,000	1,000	0
T74 (90-mm AA)	1,499,750	1,468,472	31,278
T75 (120-mm AA)	621	333	288
T76 (Lg. How.)	840,515	820,870	19,645
T76 (Lg. How. RB6)	952,594	940,950	11,644
T76 (Lg. How. RB12)	532	0	532
T80 (Sm. How.)	6,961,665	6,858,053	103,612
T80 (Sm. How. RB2)	92,668	90,000	2,668
T80 (Sm. How. RB6)	3,787,110	3,747,622	37,488
T80 (Sm. How. RB12)	118,575	116,712	1,863
T152 (90-mm AA Short SD)	780,284	770,636	9,648
T31 (Mk 170 4.5" rocket)	3,071	2,648	423
Total U.S. Army	15,038,385	14,819,296	219,089

Table A-4. VT Fuze Production for British Army as of 15 August 1945

Types	No. Produced	Shipped for Use	Shipped for Test
<i>British Army</i> (Mk 45 Type)			
T 97 (Brit. Sm. How.)	105,721	102,624	3,097
T 97 (Brit. Sm. How. RB6)	568,049	563,739	4,310
T98 (Brit. 3.7" AA)	628,068	615,574	12,494
T100 (Brit. Lg. How.)	82,558	80,460	2,098
T100 (Brit. Lg. How. RB6)	67,081	66,000	1,081
T149 (Brit. 3.7" AA Short RD)	124,238	122,592	1,646
Total British Army	1,575,715	1,550,989	24,726

Table A-5. Fuze Production During Korean War (1951-1957)²⁸.

Fuze Type	Kodak	RCA	Baldwin	McQuay Norris	Crosley	Westing -house	Wells- Gardner	Admiral
T226*	3,029K	2,092K	2,578K	1,658K	1,173K	603K		
T227*	1,564K	996K		1,127K	1,205K	1,618K		233K
MK71	546K					826K		250K
MK72	1,005K	425K	653K	501K	200K		705K	
MK73	60K							
MK174	39K							
MK74	4K							
MK75	23K							
TOTALS	6,270K	3,513K	3,231K	3,286K	2,578K	3,047K	705K	483K
GRAND TOTAL							23,151K	

NOTE: T226 and T227 became M-513 and M-514, and associated with MK15 Rear fitting.

Table A-6. VT Bomb Fuzes²⁶.

VT Bomb Fuze Types	No. Produced	Shipped for Use	Shipped for Test
AN-M168, (T91E1)			
AN-M168E1, (T161E1)			
M166E1 (bar type)			
An-M166 (M166) (T51E1)			
MK 172 Mods 0, 1, 2			
T50E1 (Ring)			
T50E3 (Ring)			
T50E4 (Ring)			
T82 (Bar)			
T89 (Ring)			
T90 (Ring)			
T91 (Ring)			
T92 (Ring)			

Table A-7. Rocket Fuzes^{26,32}.

Rocket Fuze Types	No. Produced	Shipped for Use	Shipped for Test
T2061			
M404A1			
XM431			

Table A-8. Mortar Fuzes^{33, 42}.

Mortar Fuze Types	No. Produced	Shipped for Use	Shipped for Test
M3A1			
M329			
M362			
M513 (T226)			
M513A1 (T226E2)			
M513B1 (T226B1)			
M517 (T178E3)			

Table A-9. VT Fuzes^{28, 43}.

VT Fuze Types	No. Produced	Shipped for Use	Shipped for Test
Mk 12			
Mk 13			
Mk 122			
Mk 15			
M728			
Mk 71			
Mk 72			
Mk 73			
Mk 90			
Mk 91			
Mk 92			
M504 (T75E6)			
M504A1 (T75E7)			
M504A2			
M514 (T227)			
M514A1 (T227E2)			
M514B1 (T227B1)			
M515 (T225)			
M516 (T73E12)			
M516A1 (T73E10)			
M516B1 (T73E13)			
M516B2 (T73E14)			
M517 (T178E3)			
M532			

APPENDIX C
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