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 times[27] 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 spining 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 thyratron 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.

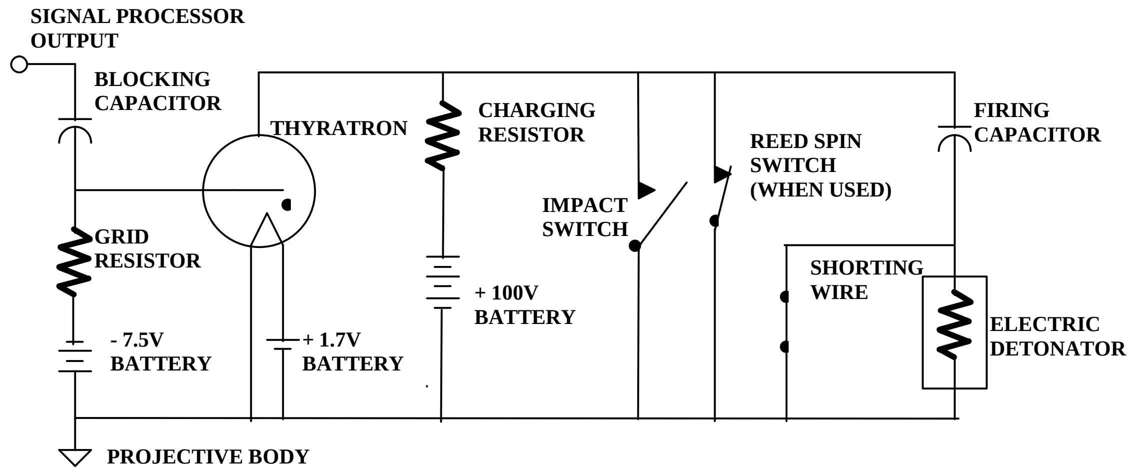

Figure 2-1. MK 70-Series Fuze Tube-Type Firing Circuit Schematic.

Two limiting threshold conditions[8] 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 Fuzes[31].

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	1amp all fire	1amp 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.

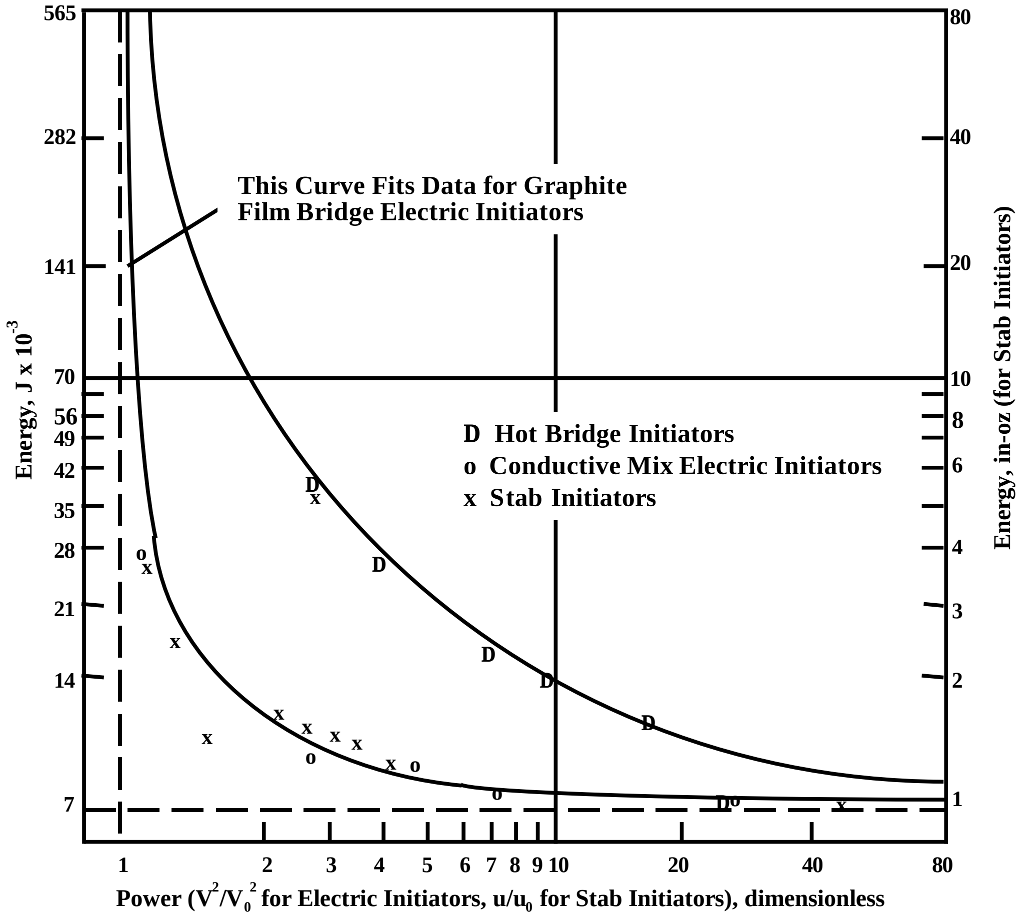

Figure 2-2. Energy Power Relationship for Various Initiators[8].

2.1.2 ELECTRONIC FUZES AND DESIGN STABILITY

All electronic fuze designs have followed the redundant safety features requirement of earlier mechanical units. In additional 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 more[26]." 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 filed station at Blossom Point, Maryland and at the University of Iowa filed station at Clinton, Iowa. At the end of WWII, Army production had reached 100,000 mortar fuzes per month[27].

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 Depot[44] 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 fuzes[30]. 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. Stahmann[22] 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 effect[40]. 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 force[36] 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;

$$B = k' (2m)/(h^3). \tag{2}$$

k' is a constant equal 10^{-7} newtons/ampere^2, 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;

$$A_l = \pi (r_l)^2 \tag{3}$$

r_l 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;

$$\Phi = B \times A_l \tag{4}$$

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

$$\xi = (B \times A_l)/dt \tag{5}$$

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;

$$I = (\xi/R) \tag{6}$$

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;

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

$$E = 4(\pi^2 \times k'^2\, m^2 \times r_l^4)/(R \times dt \times h^6) \quad (8)$$

Note the very strong dependence, $(1/h^6)$, on the height of the instrument above the ordnance and a strong dependence, r_l^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-cm^2 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-cm^2 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-cm^2 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-cm^2 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-cm^2 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-m^2 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 2.5×10^{-4} A-m^2 for the G-858 and a value of 1.5×10^{-4} 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 9.1×10^{-3} 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 0.2×10^{-9} 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 27×10^{-6} 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 $\geq$ 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 Lewis[39]. 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 sinusiodal 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}]	--- 1.9x10^{-9}	--- 50 cm^2	--- 4.6x10^{-10}	--- 6.1x10^{-17}	--- 10	--- 1.2x10^{-15}
Geometrics G-858	1.0 m	0.02 sec	“none” [2.5x10^{-4}]	--- 5x10^{-11}	--- 50 cm^2	--- 1.3x10^{-15}	--- 4.5x10^{-28}	--- 10	--- 9x10^{-27}
Scintrex/ V-920	0.3 m	[2.5 µs] note3	“none” [1.5x10^{-4}]	--- 1.1x10^{-9}	--- 50 cm^2	--- 2.2x10^{-6}	--- 1.8x10^{-13}	--- 2x10^{5}	--- 7.0x10^{-8}
Scintrex/ V-920	1.0 m	[2.5 µs] note3	“none” [1.5x10^{-4}]	--- 1.2x10^{-11}	--- 50 cm^2	--- 6x10^{-9}	--- 1.3x10^{-18}	--- 2x10^{5}	--- 5.2x10^{-13}
ADI/TM-4 (note4)	0.3 m	0.02 sec	“none” [2.5x10^{-4}]	--- 1.9x10^{-9}	--- 50 cm^2	--- 4.6x10^{-10}	--- 6.1x10^{-17}	--- 10	--- 1.2x10^{-15}
ADI/TM-4 (note4)	1.0 m	0.02 sec	“none” [2.5x10^{-4}]	--- 5x10^{-11}	--- 50 cm^2	--- 1.3x10^{-15}	--- 4.5x10^{-28}	--- 10	--- 9x10^{-27}
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 <u>single</u> change (rise or fall of a single pulse) in the magnetic field.
2. This is the bridge energy for the <u>total</u> number of rises and falls in <u>one second</u>.
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.