COP820CJ,COP840CJ,COP880C,COP884BC, COP888CF,COP888CL,COP888EK,COP888FH, COP888GW,COP8ACC5,COP8AME9,COP8CBE9, COP8CBR9,COP8CCE9,COP8CCR9,COP8CDR9, COP8SAA7,COP8SAC7,COP8SBR9,COP8SCR9, COP8SDR9,COP8SGE5,COP8SGE7,COP8SGG5, COP8SGH5,COP8SGK5,COP8SGR5,COP8SGR7, COP912C

AN-761 Electronic Fuzing

TEXAS INSTRUMENTS

Electronic Fuzing

1.0 INTRODUCTION

Fuzing mechanisms are devices used to ''safe'', ''arm'' and detonate explosive military munitions (such as missiles, mines, demolition charges, explosive shells ranging in size from 20 mm to 16 inches, unguided bombs and various sub-munitions).

Early electronic fuzes developed for 5-inch naval air defense projectiles during World War II used a CW Doppler RF technique to detonate the projectile when it reached its closest proximity to a target aircraft. More advanced electronics were used to initiate nuclear devices. Today, most missiles and bombs use electronic fuzes of varying levels of complexity.

The largest current growth in electronic fuze usage will occur in U.S. Army applications. Until very recently, most large caliber projectile fuzes were mechanical devices. The Army's M-762 program has set the stage for a rapid conversion to electronic fuzing.

The primary military specification for fuzing and safing is MIL-STD-1316, which has as its main thrust fuzing safety. The main tenet of fuzing safety is that there must be two independent mechanisms or processes involved in arming the fuze. Examples will be provided later.

2.0 BASIC FUZING TERMINOLOGY

Ammunition (Autonomous Munition): a projectile which is deployed from a weapon barrel.

Bomb: a non-self-propelled projectile, typically unguided, that is dropped from an aircraft.

Mine or emplaced munition: an explosive device that is detonated subsequent to a pre-determined target recognition process.

Missile: a self-propelled weapon, typically guided.

Rocket: a self-propelled weapon, typically unguided.

Submunition: a small, explosive device dispensed from a larger delivery system (such as a missile, a bomb cannister, a large artillery shell, a cluster mine or the like).

3.0 BASIC ELEMENTS OF A FUZE

3.1 Safing and Arming

Fuze safing and arming (S & A) is the primary concern in any fuze design. MIL-STD-1316 dictates the use of two independent operations and/or mechanisms to ensure that the detonator cannot accidently initiate the explosive train. Historically, S & A has been accomplished mechanically even when an electronic detonator has been used. The trend now is toward total electronic solutions.

There are numerous ways to implement mechanical S & A. One example of a mechanically safed fuze is one where the detonator or priming device (which may be electronic) is mounted in an assembly in which it is rotated 90 mechanical degrees out of line with the explosive train. If it fires in that configuration, the pressure wave generated cannot initiate the explosive train, and the fuze is thus ''safed''. In many designs, acceleration of the projectile will cause the mechanism to travel through a 90 degree rotation and thus align the detonator with the explosive train. This is one of the two independent processes.

A second independent process is the application of power to the detonator (or electro-explosive device). The detonators of interest in electronic fuzing are ''microdetonators'' (micro-dets) which require only a few milli-Joules of energy to detonate. Two methods are commonly employed to provide power to the detonator. The first is the installation in the nose of the projectile of a piezoelectric device whose leads are routed back to the detonator. When the projectile strikes a surface with sufficient force, the impact will generate the energy needed to fire the detonator, which will then trigger the primary explosive charge. The second method is the use of a pre-set timing device whose counter will not begin to operate until the 90 degree detent has occurred.

This approach (''out-of-line'' safing) is used in the majority of fuzes. One reason that this is widely employed is that micro-dets tend to be extremely sensitive, and are thus more easily fired accidently.

The ''slapper'' detonator is the most common example of another class of fuze which places the detonator permanently ''in-line'' with the explosive train. A slapper detonator employs plasma physics in its operation. Its simplest configuration uses a very thin layer of dielectric (frequently kapton) on top of a wide copper conductor. When an extremely large electrical current is passed through a narrowing of the conductor, it literally explodes, converting the copper to a plasma state with an energy density second in magnitude only to nuclear detonations. If the copper/dielectric sandwich is placed in a housing with an opening on one side, the expansion of the copper plasma will vent in the direction of the opening and a disk of dielectric (called a ''flyer'') will be perforated and made to ''fly'' into the explosive train with a ''slap'' of enormous dynamic pressures. Slapper technology is very commonly used in underwater demolitions.

Slapper detonators require very high voltage to generate the required currents. Gas arc tubes are common in many designs, but one fuze manufacturer has designed and patented a Slapper Integrated Fuze which integrated the slapper and the explosive lead into a single monolithic chip. Currently popular with many fuze developers, slapper technology is particularly attractive to bomb fuze developers since it permits usage of insensitive explosives.

3.2 Energy Storage

Most electronic fuze designs rely on batteries for energy storage. Since many programs require 20 year storage life, most batteries have historically used electrolytic liquid chemicals stored within the battery in glass ampules. In a projectile fuze, gun launch acceleration shatters the ampule, thus wetting the battery plates with the electrolyte. In mines and bombs, small explosive charges (called primers) are used to break the glass.

Some bombs and missiles use wind powered generators to develop electricity. Other systems use the heat from a small pyrotechnic charge to operate a thermoelectric generator. One electric generator developed for a tank-fired round uses the force of gun launch to shear the supports on a magnet, thus allowing the magnet to pass out of the coil assembly. This generates a high voltage which is then stored in a capacitor. Most generators used, however, charge capacitors which are subsequently discharged into the detonator through mechanical or semiconductor switches. A good switch carries high currents with very low resistance. In almost all fuzes, the energy management structure is part of the detonator firing circuit.

3.3 Event Sensing

Event sensing is the determination that the optimal point of detonation has been achieved. This can range from closing to within a predetermined distance of the target to delaying to a preset time after firing or after impact with the target.

Event sensing elements can be as simple as an impact switch (which, when closed, dumps a charged capacitor into the detonator) on the nose of the fuze or as complex as that of the SADARM (Search and Destroy Armor) missile, whose sensing element contains both a passive infrared (IR) imaging system and an active millimeter wave FM-CW radar with autonomous DSP (digital signal processing) capabilities. Regardless of complexity, all event sensing systems either close a switch or deliver a discrete logic signal to the firing element.

3.4 Detonator Element

TNT is no longer used as a military explosive because the tendency of nitroglycerin to leach out of the filler materials and pool in the sticks. This creates over time a level of instability that can lead to unplanned detonation as the result of minimal levels of shock. The end explosive elements in modern projectiles and bombs use stable explosives (such as C-4) in order to ensure safe handling. These explosives are detonated by using a more energetic compound to generate intense pressure waves (105 psi and up) which will cause the end explosive to detonate. To accomplish this, the fuze designer employs an explosive ''amplifier'' in which small amounts of very energetic explosive are detonated ''in series'' with less energetic materials to produce the desired level. Generally, the fuze will contain the very energetic material, and the main body of the weapon will contain the less energetic material.

4.0 COMMON TYPES OF FUZES

4.1 Time Fuze
(time to arm/time to detonate)

This device arms after a set period of time and explodes at the end of a set delay from the time of arming. Either or both time increments can be setable prior to firing or fixed within the design of the device. These fuzes are typically used in ammunition and missiles.

One current example of a time fuze is the U.S. Army's M762, now transitioning to production after close to ten years in development. Another example is MOFA (multi-optional fuze for artillery), which is detailed in Appendix A.

4.2 Impact Fuze
(time to arm/impact to detonate)

The device arms after a set period of time and detonates on impact. This type of fuze is typically used in ammunition, bombs and missiles.

4.3 Delay Fuzes

The device arms after a set period of time and detonates a set period of time after impact. This type of fuze is used on ammunition, bombs and missiles.

4.4 Proximity Fuzes

The device arms after a set period of time and detonates when at the closet point of approach to a target. This type of fuze is typically on ammunition, rockets and missiles.

5.0 DESIGN CRITERIA FOR FUZES

5.1 Cost

Fuze designs are constrained by several factors. The most obvious is that the cost of a fuze must be realistic relative to the cost of the weapon system within which it is to be used or to the value of the target against which it is to be employed. At one end of the scale, the fuze for a 20 mm artillery round must be extremely inexpensive. At the other end of the scale, the fuze for a nuclear device, because it must provide maximum safety and reliability, may be very expensive. Large numbers of 20 mm rounds are produced annually, while the production rate for nuclear weapons is extremely small.

One example of the low end of this cost curve was the M42 submunition fuze which had been considered for upgrade several years ago. 88 M42 submunitions were packed into each M483 artillery round. With an inventory of approximately one million M483 rounds to be upgraded, at a cost of $1.00 per fuze (the M42 cost about $.35 each), the program would have cost $88,000,000. The program was terminated because no electronic solution could meet the $1.00 (including the battery) target at that time.

5.2 Twenty Year Storage Life

The government has always bought ordnance and placed it in storage until it is needed. For example, many of the artillery rounds used in Vietnam had been manufactured during the Korean War. Shells fired in Korea were largely manufactured during World War II. Ordnance therefore requires very stable fuzes and explosives with at least a 20 year shelf life. For electronics, this has long meant the use of hermetic ceramic packages, but improvements in molding processes and compounds have led to a recent renewed interest in molded packages (which do offer superior resistance to gun launch and shock).

While program managers can waive those requirements, programs are constrained by mandates which direct them to use packages and screening techniques compatible with the MIL-SPEC system administered by DESC (Defense Electronics Supply Center). To date, that specification system does not accommodate molded packages. Some programs have developed assembly techniques and encapsulation methodologies that minimize the effects of severe mechanical shock on ceramic packages used within their systems, but these successes appear to be the exception rather than the norm.

Many laboratories and programs are actively investigating techniques that would allow the use of molded packages. The 20 year storage requirement has clearly made hermeticity an issue, and one approach being evaluated is the development of a hermetic housing around the entire electronic assembly within which individual devices would be installed.

5.3 Shock and Acceleration

Shock is a serious concern. A 155 mm artillery shell fired with a maximum charge will experience an acceleration force (called ''setback'') in the longitudinal axis of over 16,000 Gs over a period of about 16 milliseconds. Side-to-side movement of the projectile as it traverses the barrel will subject it to short duration lateral acceleration (''balloting'') of up to 30,000 Gs.

A 120 mm tank round can experience approximately 60,000 Gs of setback, and a 40 mm projectile will endure over 100,000 Gs. The power spectral density of gun shock is such that its energy content will usually be concentrated at high audio frequencies.

The fuze generally does not have to operate during the launch process (although it obviously must survive that operation). In fact, having it operational during that process would present severe safety hazards.

The fuse is operating, however, when it is subjected to the second major source of shock, impact with the target. The amount of shock a delay fuze experiences upon impact with the target varies depending upon the target, but the forces ecountered can be of the same magnitude as the setback noted above. It is also important to note that the primary force vector will be in the opposite direction of that encountered during launch. What this says is that a good fuze design will contain no unsupported structures.

That argues for molded packages, since the leads in hermetic packages cannot be supported. Devices utilizing gold bond wires can be particularly problematic because the gold wires are both significantly heavier than aluminum and much more malleable.

5.4 Size and Weight

The size and weight of a projectile are typically fixed by its application. For example, a fired round cannot have a greater diameter than the barrel through which it is fired. Its length is somewhat inflexible, particularly where automated handlers are used for loading the round into the firing chamber of the weapon. Bombs and missiles face similar (albeit less rigid) constraints.

It should be obvious that a smaller and lighter fuse frees valuable space for more explosives in the warhead, or for additional sensing or guidance circuitry in the case of a ''smart'' round. To some extent, this constraint works against the cost constraint. In many applications, the trade-off may be between a number of inexpensive ''off-the-shelf'' components (at a weight of x and a cost of y) or a single complex device (also costing y, but with a weight of $0.3x$). In many cases, cost concerns may seem to exclude the complex device because of the NRE (non-recurring engineering) charges associated with configuring it for the design in question. What should be understood is that the chip-level NRE is not an additional charge, but rather design costs that are transferred from the fuze board to a component on the board. The bottom line cost may prove to be less.

Understanding of that cost trade-off has led many fuze designers to the use of ROM-programmable microcontrollers as a key to weight saving in the fuze design.

6.0 PARTS SELECTION FOR FUZE DESIGNS

As Table I illustrates, the components required for a fuze will vary based upon the type of sensor, weapon and the like. There are, however, some common threads and some trade-offs. Not all of the components shown are required for a design. For example, discrete devices, logic and amplifiers can be incorporated into digital or analog Application Specific Integrated Circuits (ASIC) devices. ASIC devices have been used on fuzes because of their integration and because the custom digital circuit was believed to be better behaved than a microcontroller under harsh environments. The major disadvantage to the ASIC fuze was Built-In Selt-Test (BIST). DoD studies have shown a tremendous production cost advantage as well as a more reliable fuze when proper software techniques are employed (Self checking/ healing code). The complexities of different microcontroller or microprocessor designs present an obvious cost trade-off, and the use of a single 8-bit microprocessor for safing, arming and detonation may be more cost-effective than the use of separate less-expensive 4-bit microprocessors for each function.

Given the range of designs in question, it will prove more useful to the designer to examine what each of the possible candidate devices or device families offers and allow him to determine how each best fits his particular application.

6.1 Microcontrollers

Except for extremely sophisticated applications (such as nuclear weapons), a microcontroller will typically offer distinct advantages over a microprocessor. For the most part, the software instruction set used to control fuze operation is fairly small. What is required is a device that will execute that instruction set rapidly and efficiently.

Microcontrollers also better satisfy cost constraints. Because microprocessors receive both their data and execution instructions from external sources, they must devote a significant portion of their circuitry to memory interface. That makes them larger (hence more expensive) devices. In addition, a microprocessor solution is normally a multi-chip solution, while microcontroller solutions can often be implemented without additional external circuitry (on chip counters/timers, interrupt, watchdog, etc.).

National Semiconductor offers a variety of microcontroller options which can be utilized in almost the entire range of fuzing applications. All utilize high performance CMOS processes to provide solutions which do not require high levels of current or voltage, particularly during stand-by mode.

The microcontroller most suited to the high volume, low cost designs is the **COP400 family.** Members of this family offer from 500 to 2000 bytes of ROM and up to 128 nibbles of RAM. From 16 to 23 serial I/O ports are available.

Most low-end designs, however, now focus on the **COP800 family,** whose use in a number of recent designs has clearly demonstrated its advantages. The COP822, for example, has been used in prototype designs for the M732A2 and the XM773 (MOFA-Multi-Option Fuze). These designs have been evaluated by various DoD laboratories, which are actively pursuing its use in new designs.

One of the key advantages offered by the COP800 family is that it has been shown to operate at 2.3V, making it ideal for battery operation. The CMOS process utilized offers high noise immunity (which is of particular value in low voltage operation), and on board timer elements allow these devices to be true single-chip microcomputers.

The third microcontroller family offered by National is the **HPC family.** These devices are better suited for higher performance fuze applications. Various mine fuzes, for example, because they must accurately recognize the signature of a potential target, require FFTs (Fast Fourier Transformations), which in turn depend upon fast multiply capabilities. With the HPC, this has been accomplished using a 54ACT1016 as a co-processor. The HPC16100 (HPC$^+$) has an on board Multiply Accumulate circuit which can be used for these DSP functions.

7.0 APPLICATION EXAMPLES
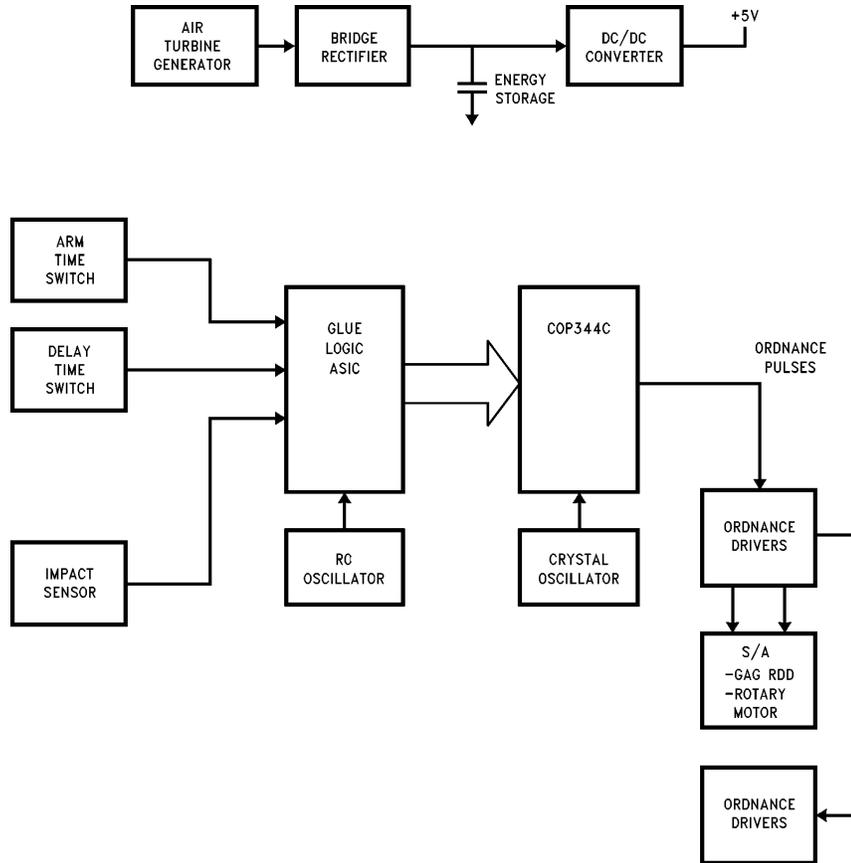
FIGURE 1. Bomb Fuze

TL/L/11182–1

7.1 Bomb Fuze Description

Figure 1 is a block diagram of a common arial drop bomb fuze. The fuze can be used on a variety of bombs ranging from 500 lbs to 2000 lbs which can be dropped from a number of different airplanes. The main function of the fuze is to provide maximum safety to handling personnel and to optimize detonation timing in the operational mode.

During loading and transit time, the bomb is unarmed and there is an extremely low probability of inadvertent detonation because the detonator is "out of line" and there is no power applied to the fuze. When the bomb is dropped, a small wind driven generator produces a regulated AC voltage supply for the operation of the fuze.

At the start of the operational phase, the microcontroller reads two rotary switches which have been manually set to the "arm time" and "delay time" for the fuze. When the arm time expires, the fuze will arm itself by firing a squib, which removes a safing pin. It then fires a piston actuator, which

causes the detonator to rotate "in line". The fuze is now fully armed and the next meaningful event in the firing sequence is impact. At impact, the fuze counts the delay time, then detonates.

These operational specifications are easily implemented using a 4-bit microcontroller (COP344C) and a small gate array that contains an RC Oscillator and some glue logic. The gate array's main function is to act as a high reliability timer that is used to measure the delay time (between impact and detonation). In addition, the gate array is used to route signals to and from the microprocessor, which is I/O limited for this application. The microcontroller's main function is to measure the arm time (bomb release to fully armed) and to control a number of safety checks conducted during this time. The microprocessor also fires the squibs.

The fuze also contains a number of discrete components which are needed to interface the Safe and Arm device, impact switch and squibs.

Military Design Example Fuze

TL/L/11182–2

FIGURE 2. Artillery Fuze

5
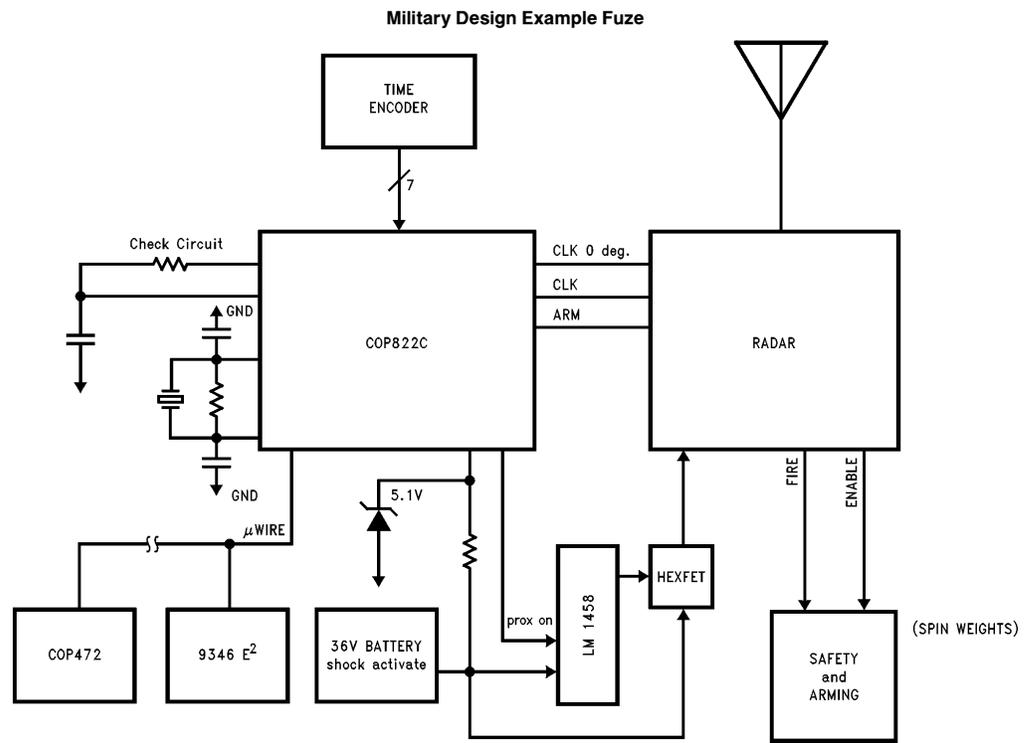
7.2 Multi Option Fuze Assembly (MOFA)

Figure 2 is an example of a MOFA design. The example shown is broken into three main sections. The RADAR section is an RF Proximity Detector, which tends to be a discrete and MMIC design. The RADAR section is planned to be included to be in a MOFA design though it is used in only about 25% of the applications.

The Safe and Arm section can be an electronic (ESA) or a traditional mechanical design. Because of the wide variation in the ESA designs, this will be discussed in a separate paper.

The Control circuit utilizes a COP822 microcontroller to interpret and drive all peripheral circuitry. The controller runs off of a crystal oscillator that is verified by a separate check circuit. In this example an RC is used by having a timer expire and cause a service routine to discharge the capacitor and enable an interrupt to be triggered when a threshold is reached. The number of clock cycles it takes to charge the RC will be captured using a built in capture feature and compared using a known reference count. This comparison will determine if the oscillator is running at a normal frequency. The decision to continue or disable is based on this comparison.

The COP822 utilizes 1 Kbytes of masked ROM to hold its Program Memory. This has been found to be sufficient for this application (larger ROMs are available) even when writing code using self checking, fault tolerant techniques.

The LCD display is controlled by a Serial Display Driver. The microcontroller employs a serial port (called Microwire Plus™) to communicate to peripheral devices. As shown, the Microwire Plus can also be used to interface to other peripherals such as an EEPROM.

The decoder switches are scanned, debounced and read directly by the controller. The microcontroller allows the fuze to employ diagnostic features used to greatly reduce test time and increase safety and reliability. Diagnostics are initiated by the encoder and response is received on the LCD Display. Lack of this feature was a major deficiency in earlier fuze designs.

8.0 SUMMARY

Fuzing and Safing and Arming (S & A) have historically been accomplished using mechanical means. Development of new, high tech weapons often times exceed the capability of the mechanical fuze to respond. The electronic solution will also be developed to the point where it is much more cost effective that the mechanical. This conversion is in progress and is gaining momentum. Electronic fuzing and S & A is a rapidly growing market which will require that the fuze makers and electronic suppliers work very closely together to define and implement the new electronic solutions.

Lit. # 100761

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