CHAPTER 7
ELECTRICAL ARMING, SELF-DESTRUCT, AND FIRING DEVICES

Advances in the state of the art of electronics have provided the fuze designer with many new, unique, and cost-effective means of performing accurate timing and numerous and complex fuzing control and logic functions. This chapter discusses the use of electronic, electrochemical, and micromechanical circuits and devices in present-day electronic fuzes. Typical applications of electrically operated components, such as switches and electroexplosive devices, are described and illustrated. The use of electronic logic to perform safety functions, e.g., fast-clock monitoring, sensor interrogation, and safety and arming (S&A) monitoring, is discussed. Examples of circuits and logic diagrams used to perform these functions are provided. The theory and current technology base for digital timers and for the components of a digital timing system (power supply, time base, and counter) are covered in detail. Numerous circuits and semiconductor devices are presented to illustrate the impact of state-of-the-art integrated circuits on fuze technology. The final output of most electronic fuzes is the firing of an electroexplosive device. Examples of high- and low-energy firing circuits, design guides, and equations for calculating the energy output of a capacitive discharge firing circuit are provided. Microcomputers are becoming more prevalent in complex fuzing systems that require multiple timing and safety logic functions. A general description and the operational characteristics of several microcomputers suitable for use with fuzing systems are discussed. Recent advances in the field of microelectronic chips have led to the development of micromechanical sensors of environmental factors, i.e., acceleration, pressure, and force. A micromechanical accelerometer design is described, and size, performance, and sensitivity data are presented. Electrochemical timers, capable of performing timing from seconds to months, are described, and their advantages for fuzing applications are discussed. Design techniques for achieving a reliable design in electronic fuzes are cited, and the relative merits of commercial vs military high-reliability electronic components are compared.

7-0 LIST OF SYMBOLS

C = capacitance, F or μF
C_T = capacitance across transistor, μF
C_o = output capacitance, μF
E = stored electrical energy, erg
f = frequency, Hz
f_{OUT} = output frequency of oscillation, MHz
g = acceleration due to gravity, m/s^2 (ft/s^2)
I_p = peak point current, μA
$I_p(MAX)$ = maximum value of I_p, μA
I_R = run current, A
I_s = stop current, A
I_v = valley current, μA
$K = \dfrac{R_S}{R}$, dimensionless
P' = average power dissipated by basic inverter, μW
R = resistance, Ω
R_A = resistance A, Ω
R_B = resistance B, Ω
$R_G = \dfrac{R_2R_1}{R_2+R_1}$, Ω
R_L = resistance L, Ω
R_S = resistance S, Ω
R_T = resistance T, Ω
R_1 = resistance 1, Ω
R_2 = resistance 2, Ω
R' = required bleed resistor, Ω
T = period of simplest RC multivibrator, μs
T_A = period of oscillation at pin 13, s
T_B = period of oscillation at pins 10 and 11, s
T_1 = period of modified RC multivibrator, μs
T' = period of oscillation, μs
t = time, s
V = supply voltage, V
$V_A = V_S + V_T$, V
V_{CAP} = EED no-fire voltage, V
V_{CC} = circuit positive voltage, V
V_D = diode forward voltage drop, V
V_{DD} = power supply voltage, V
V_{IN} = input voltage, V (See Fig. 7-20.)
$V_{NO-FIRE}$ = no-fire voltage across bleeder resistor, V
V_0 = output voltage, V
V_P = stop voltage, V
V_R = run voltage, V
V_S = set voltage determined by $R1/R2$ ratio, V
V_{SS} = circuit negative ground, V
V_T = offset voltage, typically 0.4 V
V_{TR} = transfer voltage at switching point of inverter, V
V_V = valley voltage, ≈ 0.6 V
V_s = stop voltage, V
η = duty cycle, dimensionless

7-1 INTRODUCTION

Since 1970, a wide variety of new electronic devices has become available to the electronic fuze designer. These new devices have made previously used electronic components obsolete, including vacuum tubes, cold cathode diodes, and square loop magnetic cores. The electronic fuzes of today heavily on the functional complexity available in standard and custom integrated circuits. The dominant integrated circuit (IC) technology used today is complementary metal oxide semiconductor (CMOS) because of its high-noise immunity and low-power consumption. Major advances have also been made in resistors, capacitors, crystals, inductors, and in the packaging of these components. They are now available in ultraminiature packages, which are attached to a substrate or to a printed circuit board by surface mount technology. These advances have led to extremely small, very rugged circuit designs.

Other IC technologies that might be considered by the fuze designer include

1. HCMOS—high-speed CMOS
2. TTL—transistor transistor logic
3. LSTTL—low-power Schottky TTL
4. ECL—emitter-coupled logic
5. I^2L—integrated injection logic
6. FAST—Fairchild advanced Schottky TTL
7. SOS—silicon-on-sapphire
8. GaAs—gallium arsenide.

CMOS originally could not compete with the speed of TTL logic, but today CMOS is able to match the speed. In fact, CMOS replacements for many TTL ICs are available in the HCMOS family group.

The influx of new information and technologies presents a problem to writing a handbook that is to contain the latest circuits and techniques because the electronic technologies of today will be superseded by newer ones in the very near future. The best that can be done is to give the designer background information and to impress upon him the need to review the current literature before selecting a circuit.

7-2 COMPONENTS

7-2.1 SWITCHES

Switches used in safety and arming devices (SAD) must be small and rugged, must close (or open) in a specified time, and must remain closed (or open) long enough to do their job. Switches can be operated by setback, centrifugal force, or impact.

A typical trembler switch, as illustrated in Fig. 7-1, is essentially a weight on a spring. When the velocity of a munition changes, inertial forces cause the weight to deflect the spring so that the weight makes contact with the case. The switch shown has a current rating of 100 mA and operates at accelerations of 40 to 100 *g*.

Ideally, the sensitivity of an impact switch should remain constant as the switch is rotated about its longitudinal axis, but tests on cantilevered switch designs, like those shown in Figs. 7-1 and 7-2, show wide variations in tolerances. The variations in switch sensitivity are generally due to eccentricities between the contact and contact housing and variations in the spring constant.

The design of the impact switch in Fig. 7-2 is less susceptible to tangential accelerations than the switch in Fig. 7-1

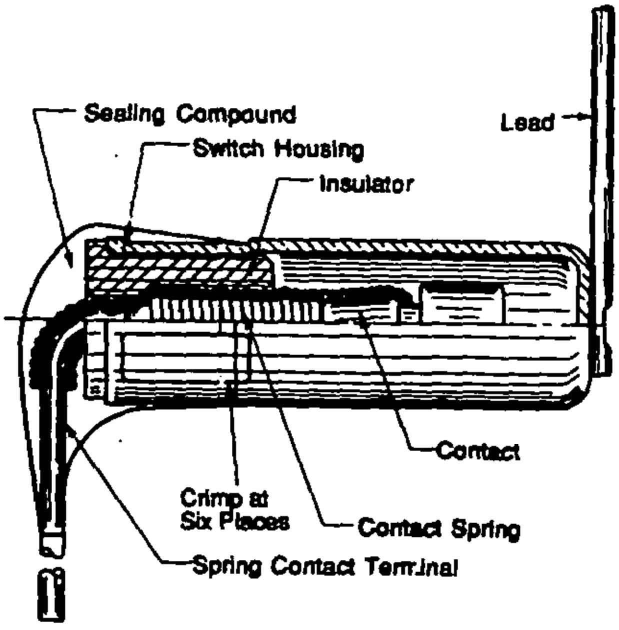


Figure 7-1. Trembler Switch

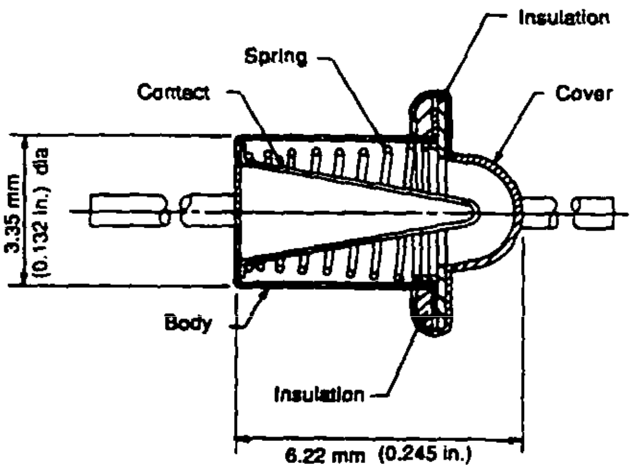


Figure 7-2. Low-Cost Biased Impact Switch (300-1000 *g*)

and has improved resonant resistance to in-flight vibrations and oscillations.

Switches that sense setback, spin, and impact are currently being developed as micromechanical cantilever beams of silicon, silicon dioxide, or photoetched metal with dimensions of a few microns.

Impact sensitivity and reliability can be improved by mounting two or more switches radially in spinning munitions or mutually perpendicular in nonspinning rounds, as shown in Fig. 7-3. If possible, electronic logic should be incorporated in fuzes employing impact-operated switches to prevent the fuze from functioning if closure is sensed prior to arming. Also to enhance overhead safety, the switch should be out of the detonator firing circuit as long as is

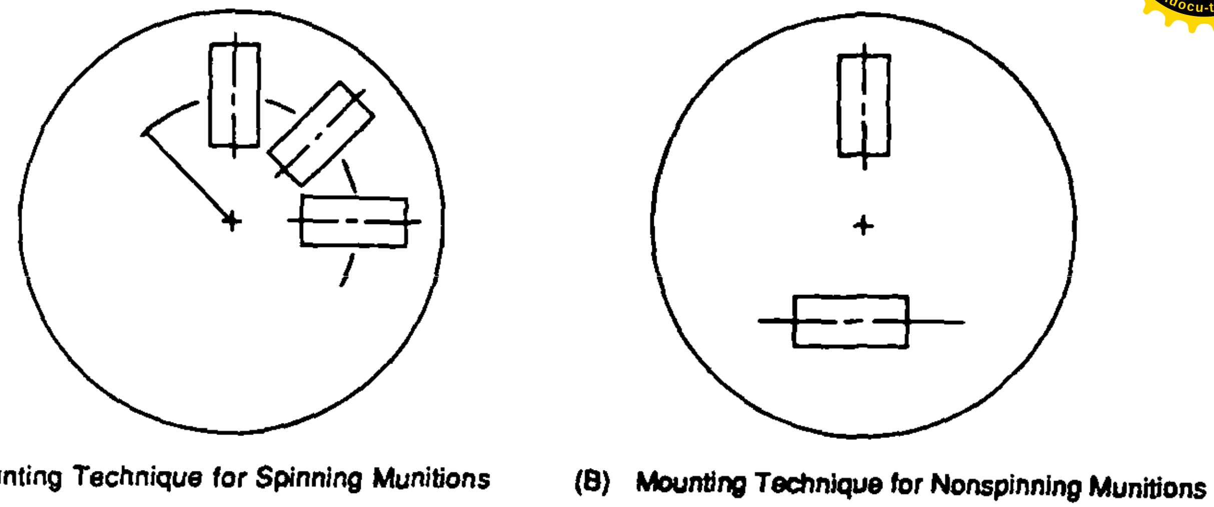


Figure 7-3. Mounting Techniques for Impact Switches for Spinning and Nonspinning Munitions (Ref. 1)

practicable, consistent with the operational requirements of the munition.

Fig. 7-4 shows a mercury-operated centrifugal switch. As the munition spins about its axis, mercury in the right compartment penetrates the porous barrier to open the circuit. The switch has an inherent arming delay that depends on the porosity of the barrier among other factors. Mercury switches should not be used at temperatures below −40°C (−40°F).

Heat generated in thermal batteries can be used to activate simple, reliable time-delay mechanisms that permanently close an electrical circuit at some specified temperature. Performance of these devices as delay elements depends upon close control of the rate of heat transfer from the battery to the thermal switch. Their application generally is limited to relatively short time delays (up to a few seconds) and to applications for which high accuracy is not required. Two switches of this type are shown in Figs. 7-5 and 7-6. These fusible-link thermal switches are used to provide the electrical arming delay and the self- destruction delay in the M217 Hand Grenade fuze. Both switches operate over an ambient temperature range of −40° to 52°C (−40° to 125°F).

The arming delay switch, shown in Fig. 7-5, closes within 1.0 to 2.4 s after initiation of the thermal battery. The switch contains a cadmium-lead-zinc alloy disk having a melting point of about 138°C (280°F). This disk is adjacent to a larger fiberglass disk, which is perforated with a number of small holes. When the metallic disk melts, the molten metal flows through the holes in the fiberglass, bridges the gap between the contacts, and closes the switch. Coating the fiberglass insulator with a wetting agent to improve the flow of the molten metal gives more uniform switch closure.

The self-destruction switch, shown in Fig. 7-6, has an average functioning time of 4 to 6 s. Closure times range from 3.5 s at 52°C (125°F) to 7.0 s at −40°C (−40°F). Its thermally activated element is a pressed pellet of mercuric iodide, which has insulating characteristics at normal temperatures but becomes a good electrical conductor at its

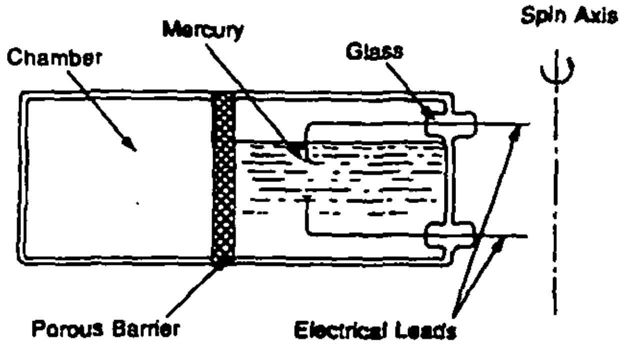


Figure 7-4. Switch for Rotated Fuzes

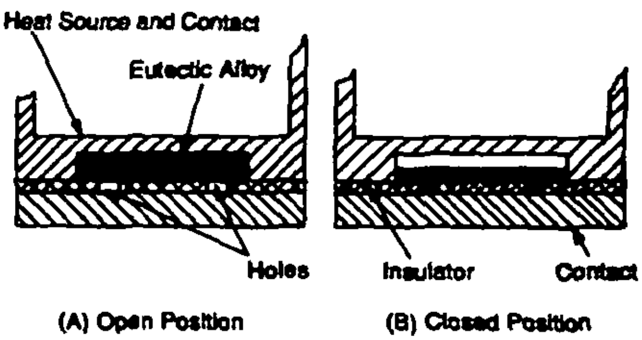


Figure 7-5. Thermal Delay Arming Switch (Ref. 2)

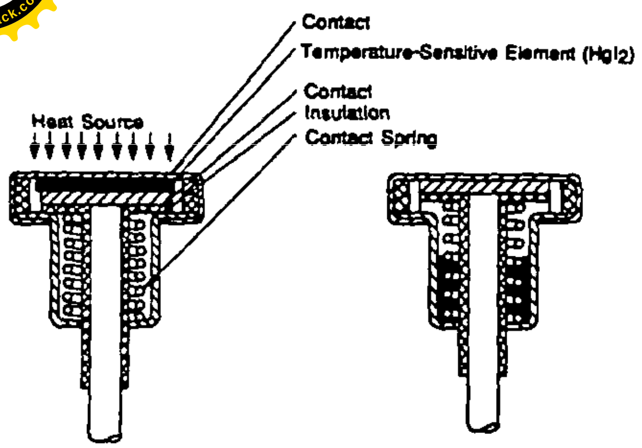


Figure 7-6. Thermal Delay Self-Destruction Switch (Ref. 2)

melting point, 260°C (500°F). More uniform switch closures are obtained by spring loading one of the switch contacts. This brings the contacting surfaces together sharply when the iodide pellet melts and reduces contact resistance in the closed switch to a few hundredths of an ohm.

Although other thermal-sensitive devices, such as bimetals, can be feasible for thermal switch applications, the fusible link appears to possess the advantages of simplicity, safety, and reliability. Its compactness and rugged design make it resistant to damage or malfunction caused by rough handling, shock, or vibration. Also there is little variation in the temperature at which the switch closes because the temperature is determined by the melting point of the fusible link. Bimetallic thermal switches often must be individually calibrated and adjusted and thereafter may be subject to deformation or premature closure. Cost and size also favor the fusible-link design. The primary disadvantage of fusible link switches is that they are one-shot devices that cannot be tested or reused.

Ambient temperature variation can greatly affect the function time of a thermal switch. Care should be taken to install the switches so that their ambient temperature is kept as nearly constant as possible. The following precautions will aid in reducing the adverse effects of variations in ambient temperature:

1. Place the thermal switch as close to the heat source as practicable.
2. Minimize the mass of thermal switch components and of any components interposed between the heat source and the thermal switch.
3. Use materials with low specific heat wherever possible.
4. Control the quantity and calorific value of the heat-producing material.
5. Control the thermal insulation of the assembly.
6. Control the manufacturing tolerance of components.
7. Control the uniformity of assembly, including assembly pressure of components and intimacy of contact between mating surfaces.

7-2.2 ELECTROEXPLOSIVE ARMING DEVICES

7-2.2.1 Explosive Motors

Explosive motors are devices that produce gas at high pressure in short periods of time in a closed volume for the purpose of doing work. They are small, reliable, one-shot devices well-suited to remote control of small movements, such as switch closures. Most explosive motors are electrically initiated. Hence their initiation mechanism and their input characteristics are the same as those of the electric initiators described in par. 4-3.1.4.

A dimple motor, as shown in Fig. 7-7, is similar in construction to an electric detonator, except that the bottom is concave and the explosive is a small gas-producing charge. The pressure of the gas liberated by the reaction inverts the concave end to a convex surface. A typical dimple motor imparts a 2.54-mm (0.10-in.) movement against a 35.6-N (8.00-lb) load. Careful design of the relatively complex curvature of the dimple and accurate control of the metal condition are necessary for reliable and satisfactory functioning (Ref. 3).

Bellows motors, as illustrated in Fig. 7-8, consist of a number of convolutions, which expand under the gas pressure produced by the motor charge. They are used where a longer (up to 25.4 mm (1.0 in.)) or angular stroke is required. They are capable of producing forces of up to 44.5 N (10 lb) or torques to 3.39 N·m (30 ft·lb).

Piston actuators, as shown in Fig. 7-9, are another form of explosive motor used in many modern munitions. The extendable version shown is capable of shearing a 1.27-mm (0.05-in.) pin over a minimum travel of 5.1 mm (0.20 in.). Other piston actuators are available with outputs up to 1335 N (300 lb). There are also retractable versions and a rotary version called a ROTAC.

Explosive motors may be used to move, lock, or unlock an arming device, or they may be used to operate a switch. Dimple motors are often used to close an electric contact, as described in par. 7-2.2.2.

7-2.2.2 Electroexplosive Switches

Explosive switches use a dimple motor or piston to drive a contact assembly to perform a mechanical switching operation. In the design shown in Fig. 7-10, the piston contact is displaced by a dimple motor; this displacement unshorts the two spring-loaded contacts and closes a second pair of contacts. The switching time for this device is less than 15 ms. Although this design is used in currently stockpiled fuzes, cheaper and more reliable switching methods are available in solid-state electronics.

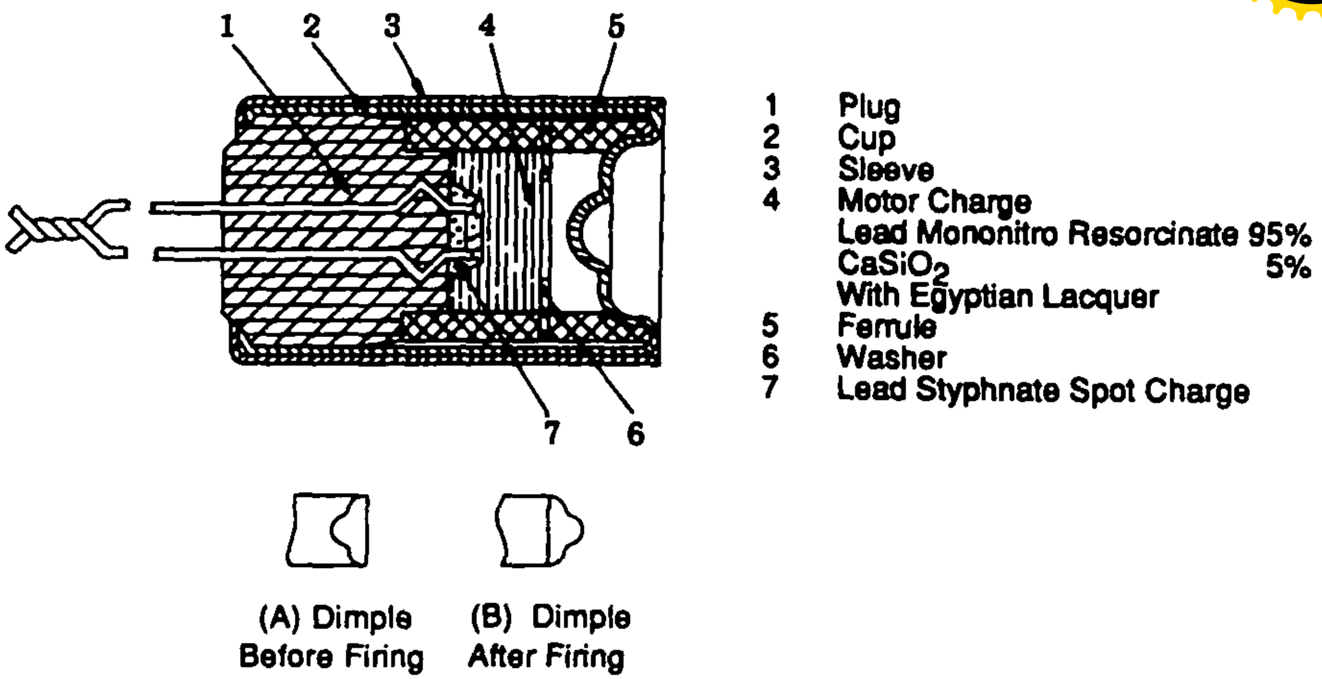


Figure 7-7. Dimple Motor T3E1

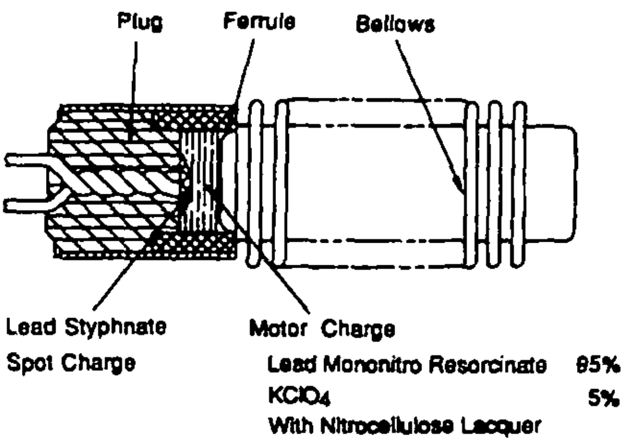


Figure 7-8. Bellows Motor, T5E1

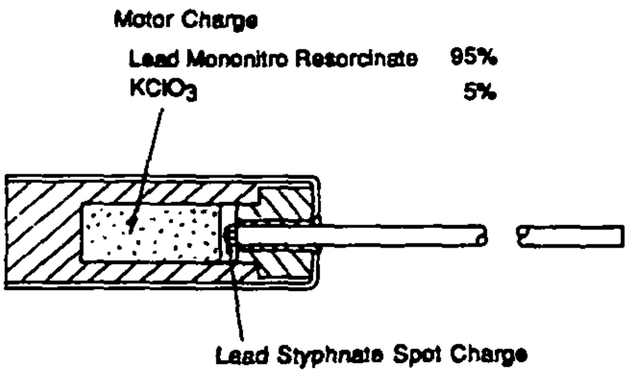


Figure 7-9. Piston Actuator Used in M762 Fuze (Ref. 4)

7-2.3 ELECTRONICALLY CONTROLLED FUZING FUNCTIONS

In electronic fuzes, the electronics section of the fuze may be required to

1. Arm the fuze after a selected time delay
2. Detonate the fuze after any of the following conditions: impact, delay after impact, after a preselected time delay, or after receipt of a signal from a target proximity sensor.
3. Perform functions such as time gating, switch status monitoring, AND/OR functions, and sequence monitoring.

It is critically important that the fuze not prematurely arm or detonate. To prevent premature arming or detonating, design safeguards are included in the electronic fuze design. Some typical safeguards are a fast-clock monitor to prevent premature arming and sensor interrogation to prevent premature detonation.

7-2.3.1 Electronic Logic Devices

Electronic logic devices can be used in conjunction with a system clock and some form of counter to perform a variety of logic and control functions. The technology most commonly used in ordnance applications is CMOS. The simplest CMOS logic element is the inverter, which contains two metal oxide semiconductor (MOS) transistors (a "P" type and an "N" type) connected in series, as shown in Fig. 7-11. The reason for its extremely low static, or quies-

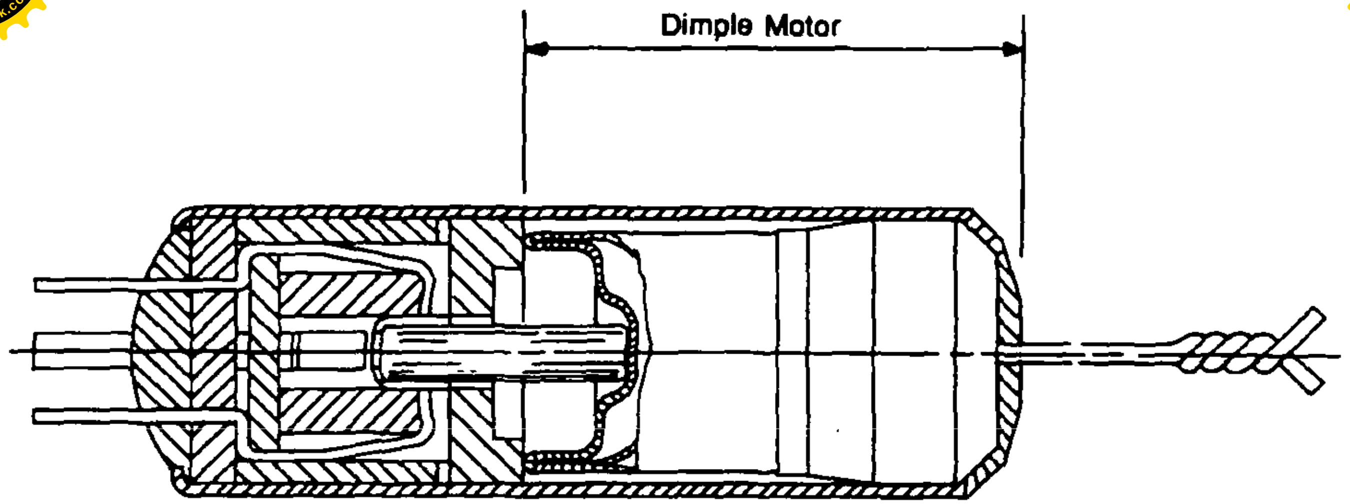


Figure 7-10. Switch, Electroexplosive, MK 127 MOD 0 (Ref. 4)

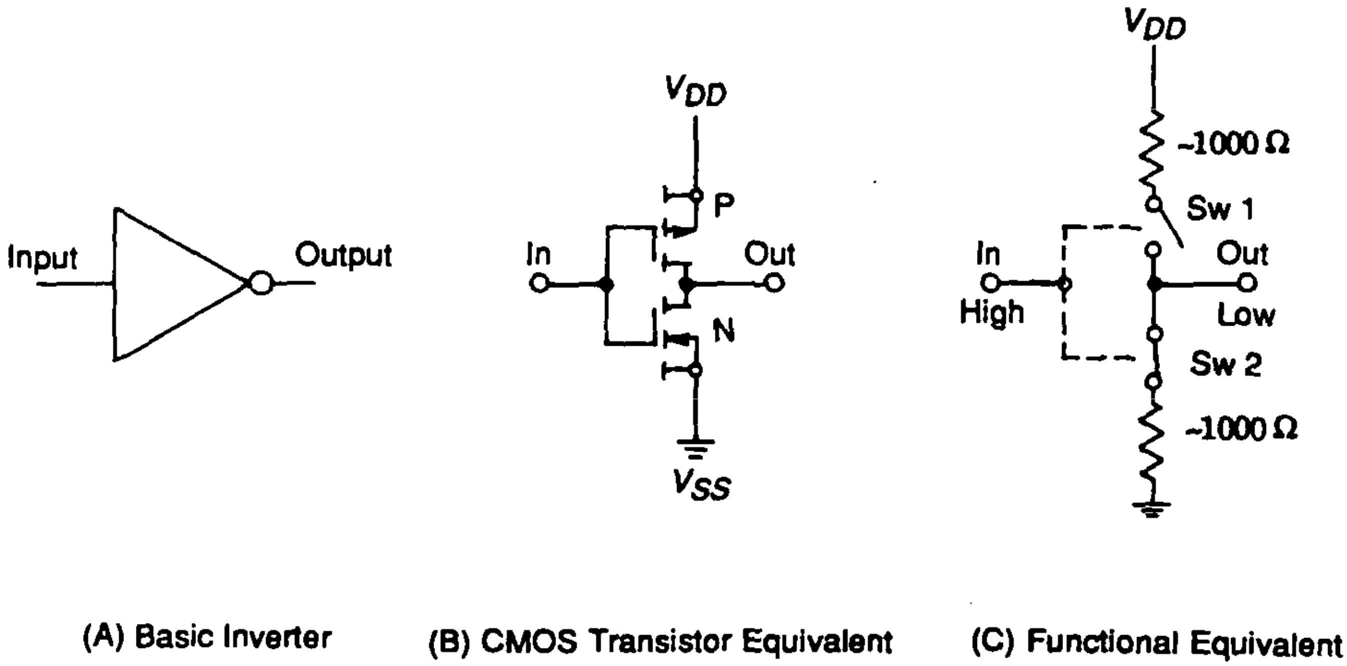


Figure 7-11. Basic Logic Inverter

cent. current drain is that for either logic level input (1 = +V or 0 = ground (GND)) to the inverter, one or the other MOS transistor is off. Therefore, virtually no current flows through the inverter. For example, the maximum input current for a CD 40100B (32-stage static left/right shift register) is specified as 100 nA at 18 Vdc and 25°C (77°F). The inverter changes states as the input signal rises and falls. The typical switching point is within 45 to 55% of positive dc power supply voltage V_{DD}. There is a momentary period during the switching process in which both the "P" and "N" transistors are simultaneously on, and this condition gives a make-before-break action. During this period a resistive load of approximately 2000 ohms is placed across the power supply. This load constitutes one of the elements that make up the dynamic current drain of the CMOS inverter. The other two elements that contribute to dynamic current drain are parasitic node capacitances and any load capacitance. For a capacitive load the average power P' dissipated by the basic inverter, if driven with a square wave input, is given by

$$P' = C_o V^2 f, \mu W \quad (7\text{-}1)$$

where

C_o = output capacitance, μF
V = supply voltage, V
f = frequency, Hz.

The basic *two-transistor inverter* can be used to construct more complicated logic devices (gates). For example, a *quad-two input NOR gate* is shown symbolically and schematically in Fig. 7-12. Sixteen "P" and "N" transistors are required to construct this device. A more complex device, such as a 64-bit static shift register, can contain more than 1000 transistors.

7-2.3.2 Typical Application of Electronic Logic

Fig. 7-13 presents a logic diagram of a generic bomb fuze. The generic fuze is for illustrative purposes only to show how a variety of logic devices can be combined to perform some of the functions listed in par. 7-2.3. The fuze provides three arming times:

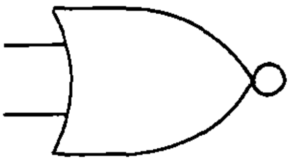
1. Retard—2.625 s
2. Dive—5.500 s
3. Level—10.000 s.

The fuze also provides four impact-delay times:

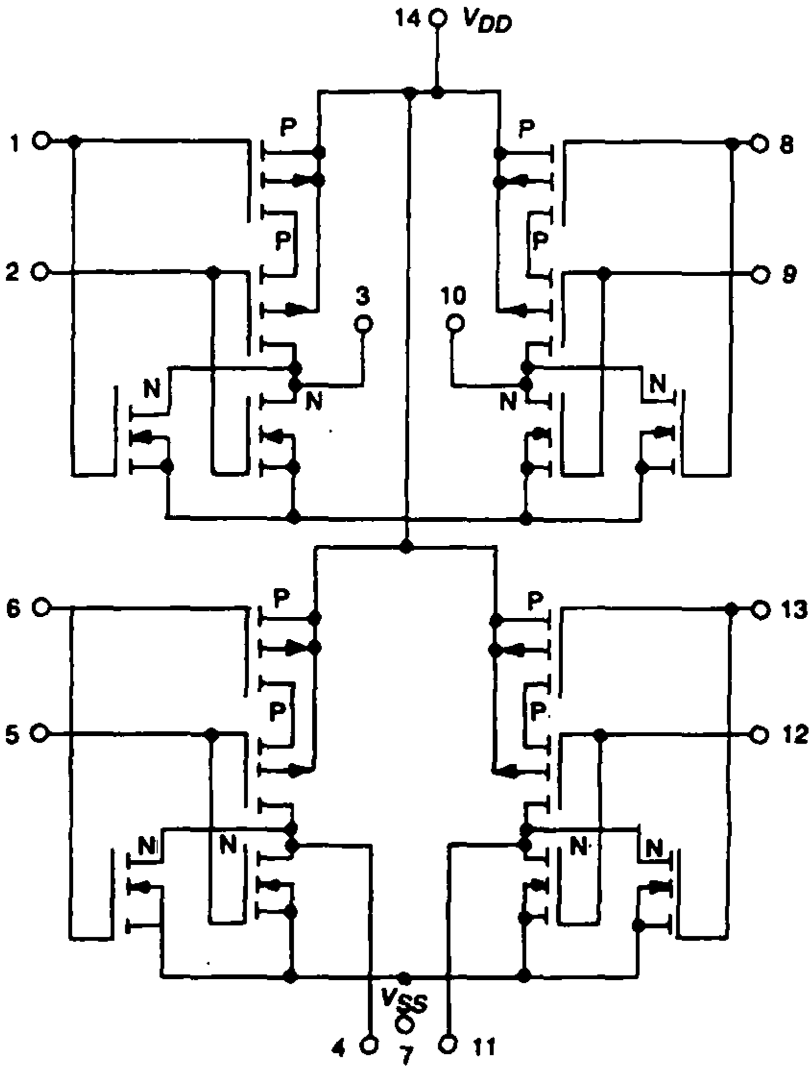
1. Instantaneous
2. Short—10 ms
3. Medium—25 ms
4. Long—60 ms.

The fuze contains

1. Fast-clock monitor
2. Arm switch monitor
3. Target-detecting device (TDD) monitor
4. Impact switch monitor.



(A) Single Two-Input NOR Gate



(B) Schematic Representation of CD 4001

Figure 7-12. Quad-Two Input NOR Gate

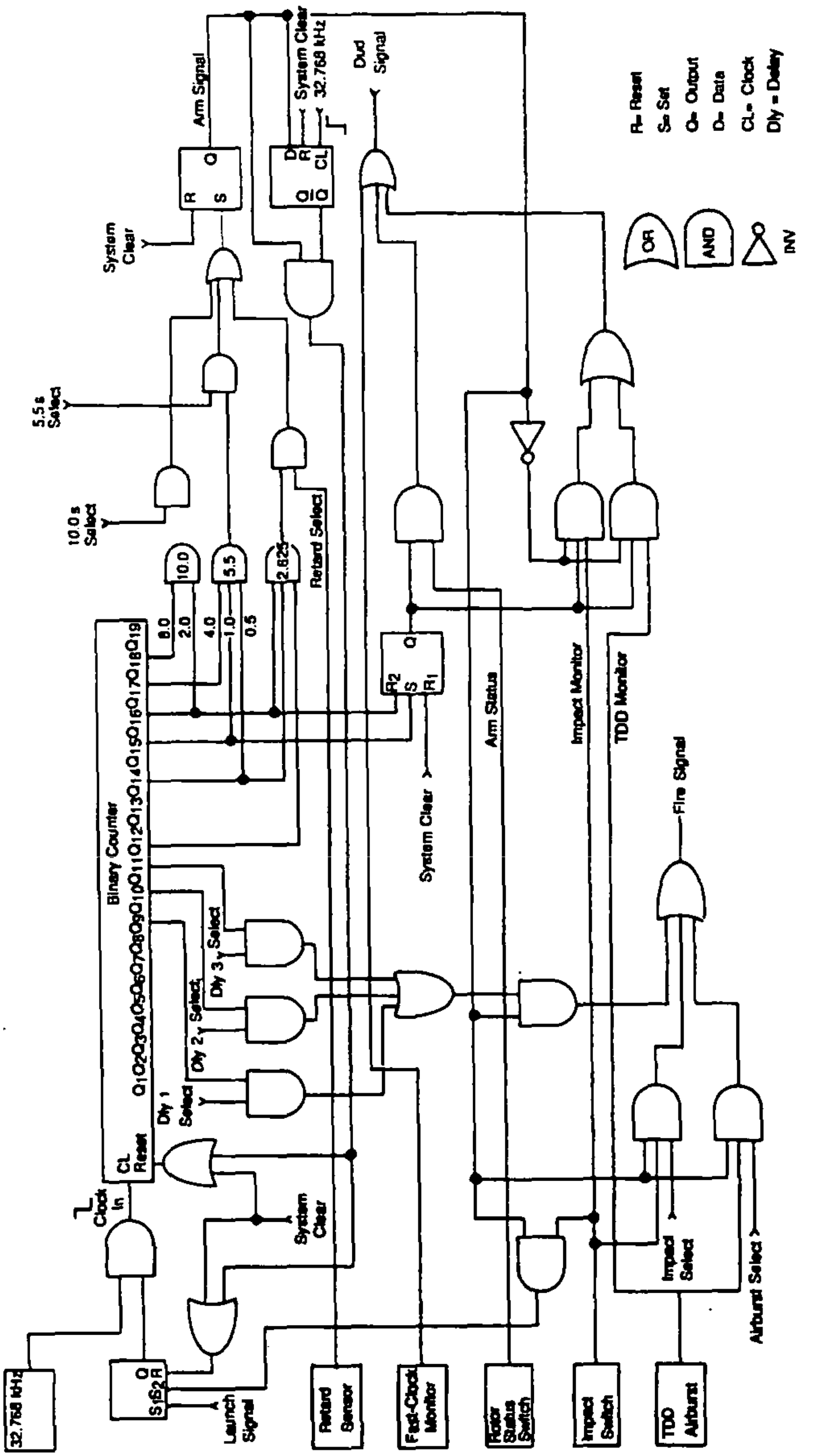


Figure 7-13. Generic Bomb Fuze Logic Diagram

A fast clock (defined in par. 7-2.3.3) or an improper TDD or impact switch output will cause a dud as will a fuze that is armed before 1.0 s after launch.

7-2.3.3 Fast-Clock Monitor

The fast-clock monitor is intended to safeguard against a system clock that has changed frequency so that it is running at a significantly higher frequency than desired. If the system arming time is being derived from a master clock, dangerously shortened arming times can result if the clock runs fast. Some techniques for safeguarding against the hazards created by a runaway system clock are

1. A narrow band phase lock loop (PLL), shown schematically in Fig. 7-14, which can be used to monitor the master clock. If the master clock frequency is outside the PLL lock range (high or low), the PLL will indicate this fact, and an appropriate logic decision can be made.

2. Two redundant timers running in parallel. If the outputs of both are not simultaneous at some point, the system will fail to function or will accept the clock that has the longer time period. The circuitry of these timers is shown in Fig. 7-15.

3. Use of a simple resistor capacitor (RC) network to determine whether the master clock frequency is proper.

7-2.3.3.1 Fast-Clock Monitor Circuits

The fast-clock monitor circuit of Fig. 7-16 operates as follows:

1. The system clock frequency of 32.768 kHz is gated after launch via AND gate 1 into the binary counter.

2. At launch, flip-flop (FF)1 is set and capacitor C charges via resistor R. After 3.7 ms, inverter (INV) goes low and disables AND gate 2.

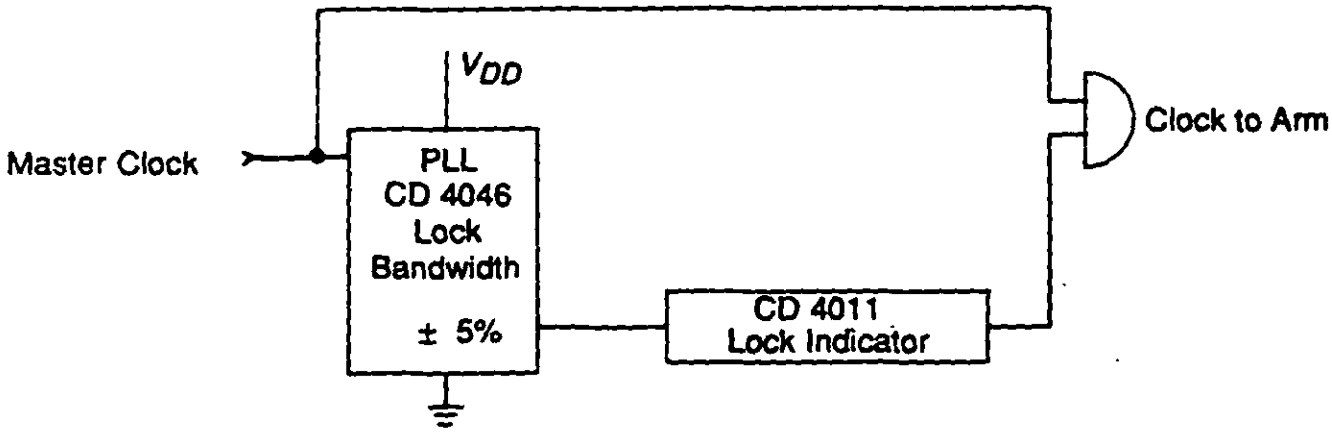


Figure 7-14. Phase Lock Loop Fast-Clock Monitor

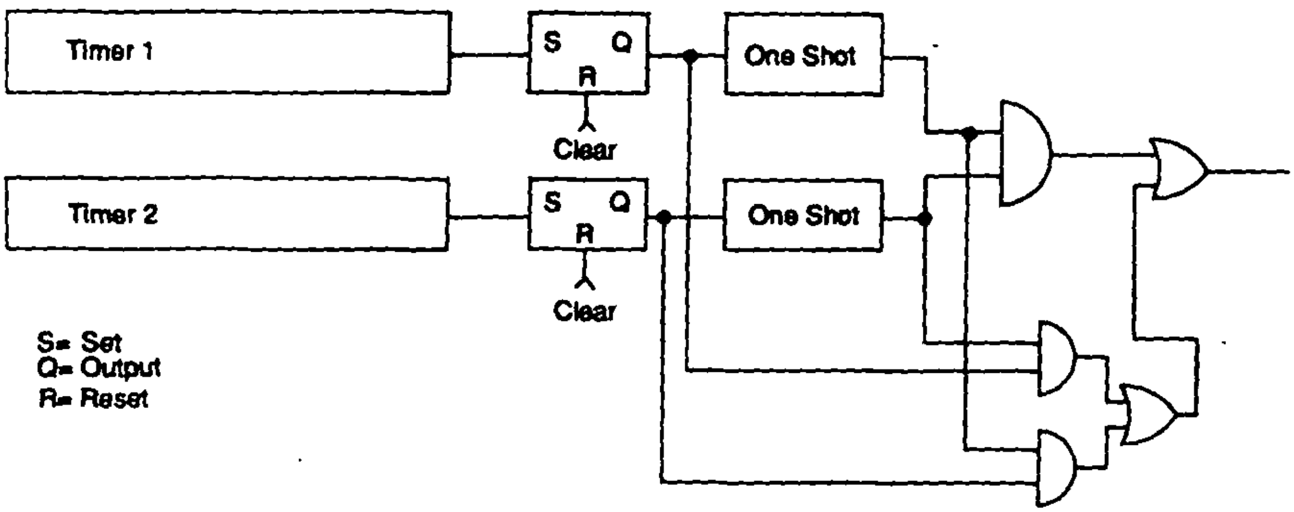
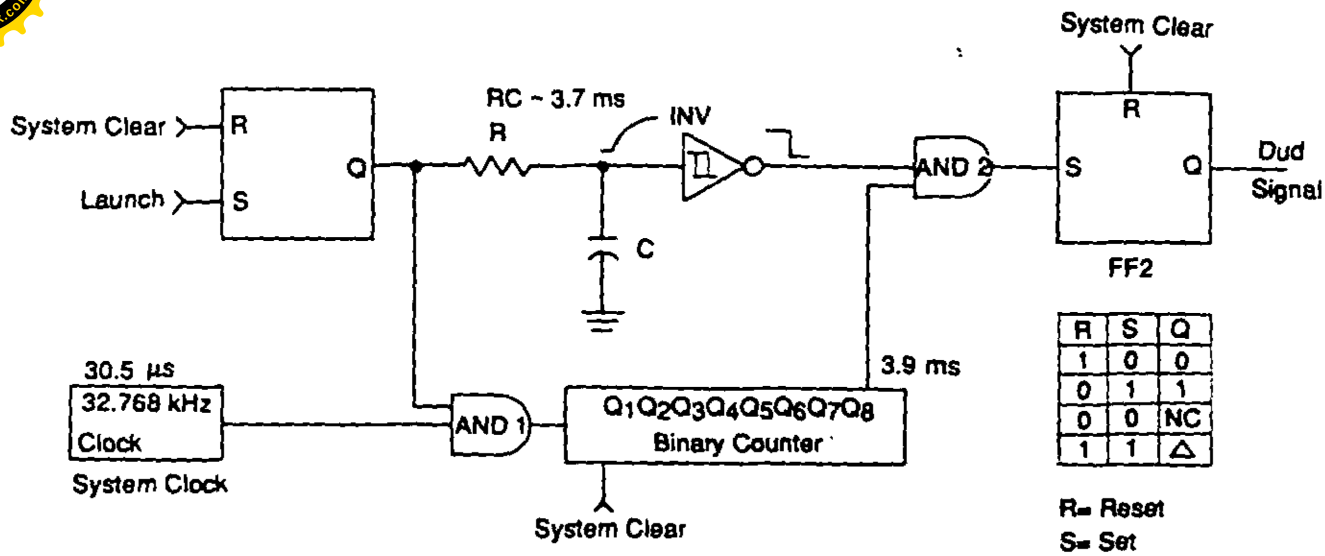


Figure 7-15. Redundant Timers



R	S	Q
1	0	0
0	1	1
0	0	NC
1	1	Δ

Figure 7-16. Fast-Clock RC Monitor Circuit

3. If the system clock is operating correctly, Q8 of the binary counter will go high 3.9 ms after launch, but it will not be able to pass through AND gate 2 because AND gate 2 was disabled at 3.7 ms by the RC circuit. However, if the system clock runs fast enough to cause Q8 to go high before 3.7 ms, then the output of AND gate 2 will go high, set FF2, and result in a dud signal.

The fast-clock monitor circuit of Fig. 7-17 operates as follows. An independent RC multivibrator running at 35 kHz is used to monitor the 32.768-kHz, crystal-based system clock. At launch AND gates 1 and 2 are enabled permitting the 35-kHz and 32.768-kHz clocks to drive binary counters 1 and 2. If the crystal clock is operating correctly, Q8 of counter 2 will go high before Q8 of counter 1, and the

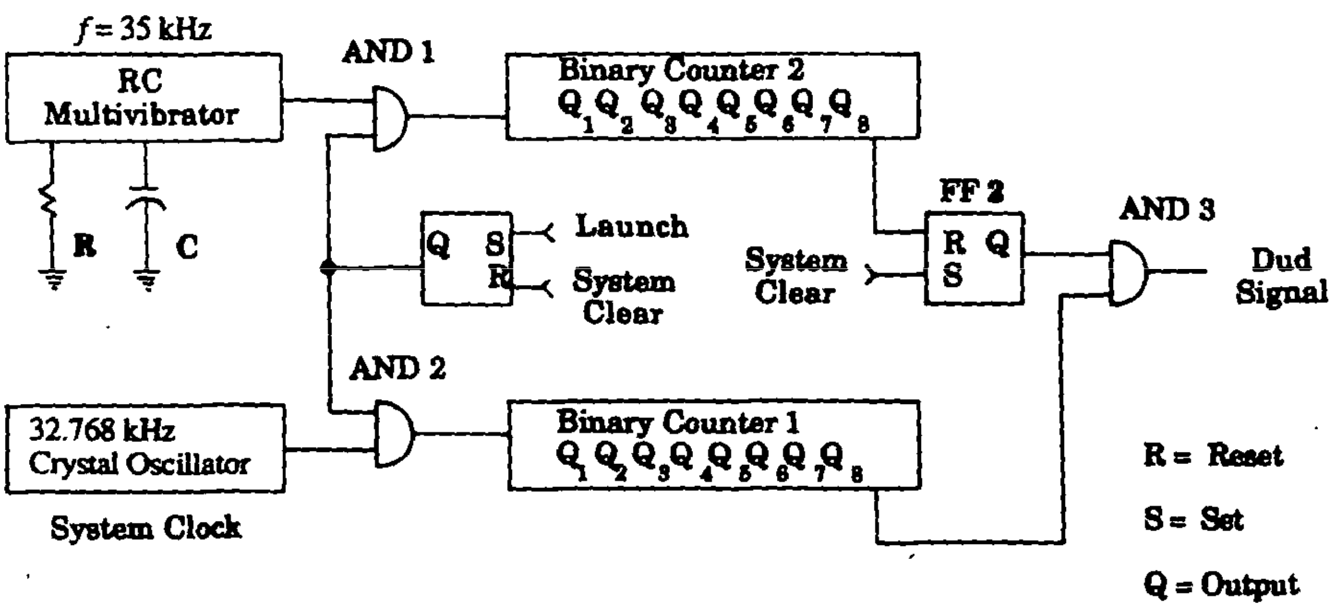


Figure 7-17. Fast-Clock Multivibrator Monitor Circuit

output of FF2 will be reset, will disable AND gate 3, and will prevent a dud signal from occurring. If the crystal clock is operating at a higher frequency than 35 kHz, however, then Q8 of counter 1 will go high before FF2 can be reset, and a dud signal will occur.

7-2.3.4 Sensor Interrogation

A wide variety of sensors can be used to initiate the detonation of a high-explosive warhead. Typical devices used to initiate detonation on target impact are trembler switches, inertial switches, ingestion switches, crush switches, capacitance switches, and piezoelectric crystals. Other, more sophisticated devices are used to provide some standoff from the target when the warhead is detonated. Some examples of standoff sensors are (1) mechanical probes, both extendable and fixed, which can provide standoffs of several centimeters to several meters, and (2) electronic sensors, i.e., radio frequency (RF), infrared (IR), capacitive, and optical, which can provide standoffs of a few centimeters, a few meters, or hundreds of meters.

Although a premature initiation of the warhead usually would not be harmful to the launching vehicle because of the SAD, overhead safety could be compromised and/or warhead effectiveness could be reduced to zero. Sensor interrogation is the use of an electronic timer and electronic gates and logic to determine the status of a target sensor prior to and after arming and to adjust fuze operation to compensate for a defective sensor. The logic diagram depicted in Fig. 7-18 contains two sensor interrogation schemes: one for a TDD (RF, optical, or probe) and one for an impact switch.

The STINGER fuze M934, described in par. 1-3.3.2 and Ref. 5, contains numerous safety and status sensor logic circuits to detect duration of launch acceleration, rocket motor staging, safety and arming (S&A) rotor status, impact switch, and hard-target switch interrogation.

The launch sensor is a simple spring-mass system similar to that illustrated in Fig. 7-1. This switch is monitored for the first 40 ms after launch, and if it remains closed for more than 20 ms, the S&A counter is activated. If the switch does not remain closed for the required 20 ms, no fuze timing function occurs.

Separation of the launch motor from the missile (staging) is sensed by a simple shorting clip. Upon staging the clip is broken; this action enables the flight motor ignition relay, the arming actuator, and the flight motor timer. Absence of proper staging results in the fuze not functioning.

During the first second of flight, the S&A rotor status is monitored by an electronic abort switch (photoelectric cell). If rotor motion occurs during this period, the abort switch senses it and provides an initiation signal to an explosive piston actuator, which fires and permanently blocks arming of the rotor.

At arming, which occurs one second after launch, a signal is generated by the main fuze timer, which enables the impact switch circuitry and interrogates the hard-target sensor circuit. Impact switch closure prior to this time is ignored. Interrogation of the hard-target-sensor circuits consists of determining the state of the sensor and generating corresponding enable or disable signals.

7-3 DIGITAL TIMERS

7-3.1 THEORY AND CURRENT TECHNOLOGY BASE

A digital timer system is generally comprised of a power supply, a time base (clock, oscillator), at least one frequency counter, various logic elements, a preset circuit (for programmable timers), and check circuitry (either self-check or external check). A digital timer can be constructed from various clocks and digital ICs (counters and logic) to provide the desired output times and control logic. If size is not a constraint, these various devices can be purchased in standard packages (dual in-line package (DIP) and single in-line package (SIP)) and assembled on a printed circuit board. If size is a constraint, packaging options are available to permit the designer to shrink the circuitry. Some examples of packaging options are

1. *Small Outline Integrated Circuits (SOIC)*. These devices occupy one-fourth to one-third of the circuit board area occupied by an equivalent conventional DIP.
2. *Small Outline Transistors (SOT)*. These devices occupy one-tenth to one-fourth of the board area of an equivalent conventional T018 or T05 transistor.
3. *Leadless Carriers*. An IC chip can be purchased from many manufacturers and assembled into a leadless chip carrier with a dramatic decrease in required space, e.g., a 16-pin device is 6.35 × 6.35 mm (0.25 × 0.25 in.) and replaces a 16-pin DIP, which is 7.6 × 20 mm (0.3 × 0.8 in.).
4. *Quasi-Custom Integrated Circuits (gate arrays, standard cells)*. A timer design requiring several DIP devices can very often be integrated into one or two quasi-custom integrated circuits at relatively low cost and can yield a truly dramatic reduction in the board area required.
5. *Fully Custom Integrated Circuits*. A fully custom IC yields the ultimate in space savings because each custom device is tailored to the designer's requirements. This technique permits integration of the timer functions in the smallest volume. It is more efficient than quasi-custom designs because there is no wasted space. Quasi-custom designs generally have a utility factor of 80 to 90%.
6. *Microprocessors*. Very often, the most economical implementation of a digital timer can be designed by using a microprocessor with on-board programmable read-only memory (ROM). The ROM can be mask programmed to meet individual user requirements, or it can be an electrically erasable programmable ROM (EEPROM), which permits the user to modify the program if system requirements change.

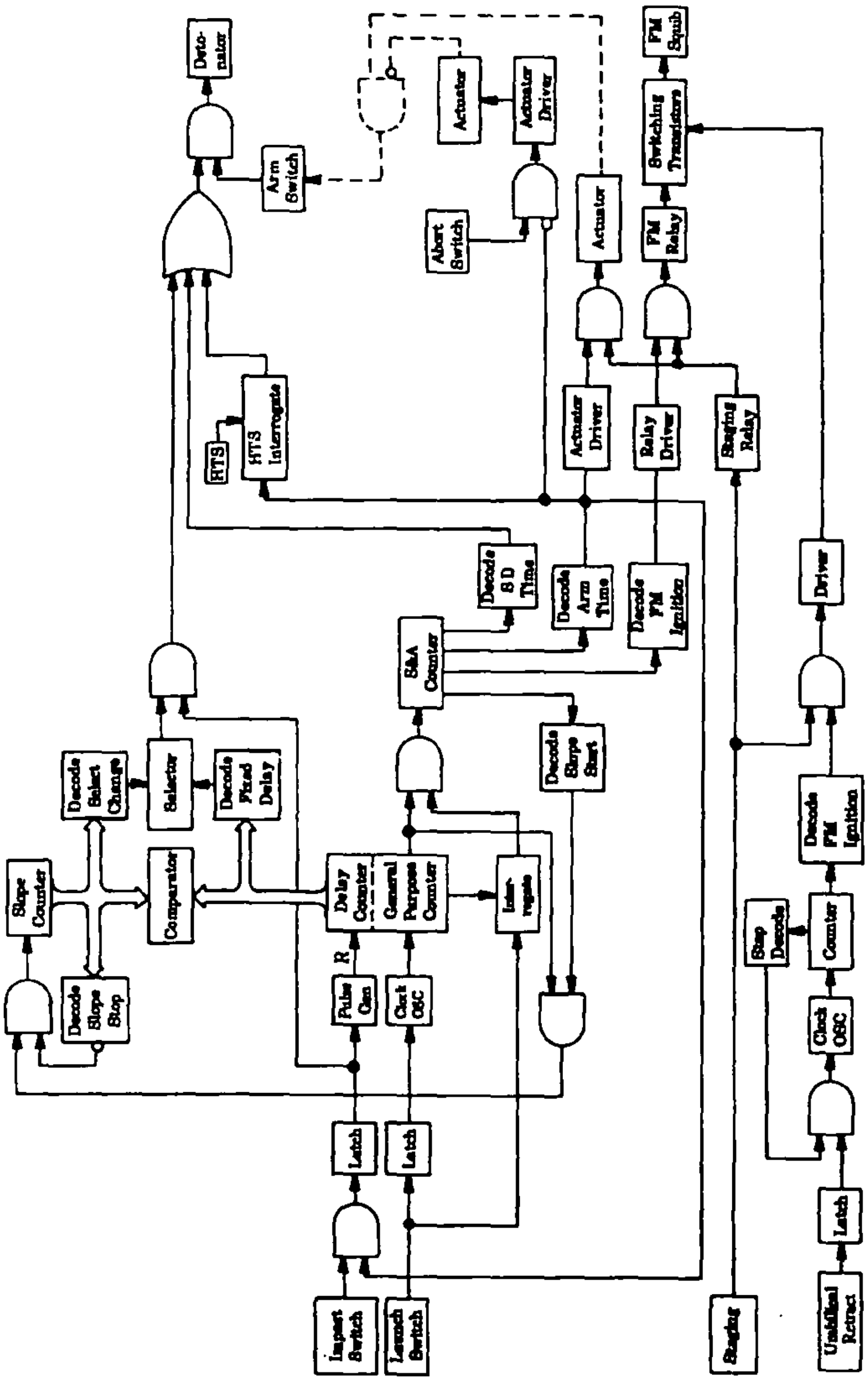


Figure 7-18. M934 STINGER Prototype C Fuze Functional Diagram (Ref. 5)

The design techniques using discrete ICs are very different from the techniques using a microprocessor. With the discrete ICs the designer creates his own architecture and must be familiar with various logic families to minimize the number of DIPs required. With the microprocessor, its internal architecture already exists, so the designer must write a program which most efficiently uses that internal architecture in order to achieve his system requirements. Microprocessor systems require a higher system clock frequency than discrete designs and more input power. Most microprocessors run at 5.0 Vdc, which may not be true for discrete timers.

Fig. 7-19 is a schematic of a typical digital 16-s precision timer with high-energy output.

7-3.2 POWER SUPPLIES

As mentioned earlier, most recent digital timers for fuze applications are constructed from some type of CMOS technology because CMOS is currently the most energy efficient IC technology, especially at lower frequencies (<1 MHz). The fact that space is usually at a premium in a fuze dictates minimum power supply volume. Examples of power sources for ordnance applications are discussed in detail in Chapter 3.

Very small power supplies generally contain enough energy and current capacity to power a CMOS timer for much more than 200 s. The designer must provide a battery output of 3 to 18 Vdc and must consider the activation time of the battery if timing accuracy is critical. Concern about activation time is important if the timer derives its start signal when the output voltage of the battery rises to the threshold of a voltage level sensor. This activation time of the battery then becomes an error term in defining the true accuracy of the timer. This error time can be eliminated if the battery is activated before launch or if a charged capacitor can power the timer during the first 25 to 50 ms of postlaunch operation while the battery is activating. In this case, the timer start signal could be provided by a setbac[illegible] spin switch that closes within a few milliseconds of launch. [illegible] assumes a power supply is available prior to or during launch to charge the capacitor.

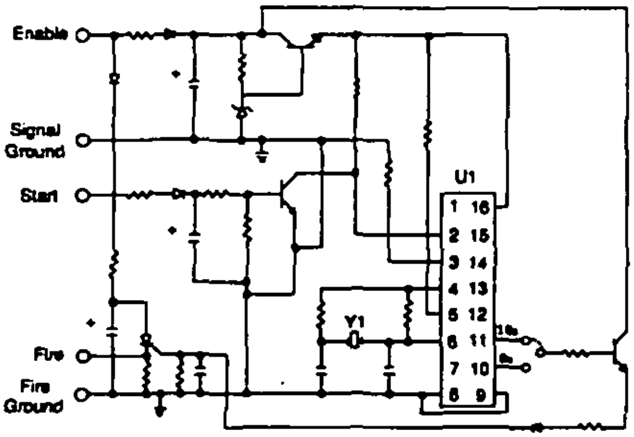


Figure 7-19. 16-Second Precision Ordnance Timer

Supercapacity capacitors are a relatively new technology. They have been advertised as "keep-alive" power sources for nonvolatile random access memory (RAM). These "supercaps" contain one farad or more of capacity and, if charged to 5 Vdc, can power a CMOS timer for an extremely long time.

7-3.3 TIME BASES (OSCILLATORS) FOR DIGITAL TIMERS

Oscillators are used as time bases for digital timers and, for most current digital timing applications, can be broken down into four types: relaxation oscillators, RC multivibrators, quartz crystal oscillators, and ceramic resonator oscillators. The capabilities and limitations of each type are discussed in the paragraphs that follow, and schematics are presented.

7-3.3.1 Relaxation Oscillator Using a Programmable Unijunction Transistor (PUT)

A schematic of a PUT oscillator is shown in Fig. 7-20. The period of oscillation T is given by

$$T = R_T C_T \ln \frac{V_{IN}}{V_{IN} - V_A}, \mu s \tag{7-2}$$

where

C_T = capacitance across transistor, µF

$$V_A = V_S + V_T, \text{ V} \tag{7-3}$$

V_S = set voltage determined by $R1/R2$ ratio (See Fig. 7-20.), V
R_1 = resistance 1 (See Fig. 7-20.), Ω
R_2 = resistance 2 (See Fig. 7-20.), Ω
V_T = offset voltage, typically 0.4 V
V_{IN} = input voltage, (See Fig. 7-20.), V
R_T = resistance T (See Fig. 7-20.), Ω.

Conditions for sustained oscillation are

$$1.\ \frac{V_{IN} - V_A}{R_T} (MAX) > I_p (MAX) \tag{7-4}$$

where

I_p = peak point current, µA
$I_p(MAX)$ = maximum value of I_p, µA

2. $$\frac{V_{IN} - V_V}{R_T}(MAX) < I_V \quad (7\text{-}5)$$

where

I_V = valley current, µA
V_V = valley voltage = 0.6 V

3. $$1 - \frac{R_2}{R_2 + R_1} >> \frac{V_T}{V_{IN}}. \quad (7\text{-}6)$$

Parameters (i.e., I_P, I_V, and V_T) are specified in the data sheet for a particular PUT device. One such device is the 2N6120 for which the specified values for I_P, I_V, and V_T are

I_P = 1.0 µA MAX, @ $R_G = 10\,K$, $V_s = 10$ V
I_V = 25 µA MIN, @ $R_G = 10\,K$, $V_s = 10$ V
V_T = 0.2 V MIN to 0.6 V MAX, @ $R_G = 10\,K$, V_s = 10 V

where

$$R_G = \frac{R_2 R_1}{R_2 + R_1}, \Omega.$$

The output frequency of oscillation f_{OUT} in Fig. 7-20 of a PUT oscillator is a series of pulses reflecting the capacitive discharge nature of the oscillator. Each pulse represents the discharge of C_T through R_L to ground.

7-3.3.2 RC Multivibrator Using Integrated Circuit Inverters

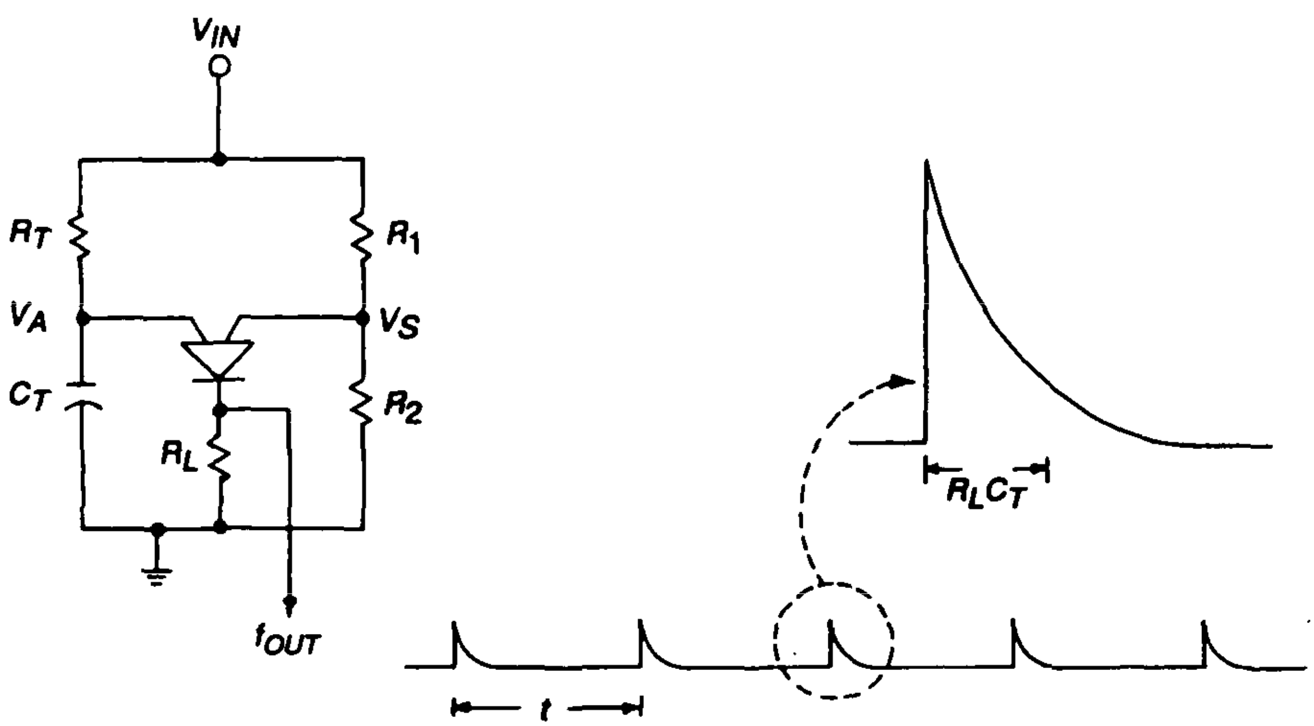
The RC multivibrator in its simplest form is any of the configurations shown in Fig. 7-21 less resistor R_S. The period T of the simplest RC multivibrator is given by

$$T = -RC\left[\ln\left(\frac{V_{DD} - V_{TR}}{V_{DD}}\right) + \ln\left(\frac{V_{TR}}{V_{DD}}\right)\right], \mu s \quad (7\text{-}7)$$

where

R = resistance, Ω
C = capacitance, µF
V_{TR} = transfer voltage at switching point of inverter, V
V_D = diode forward voltage drop, V.

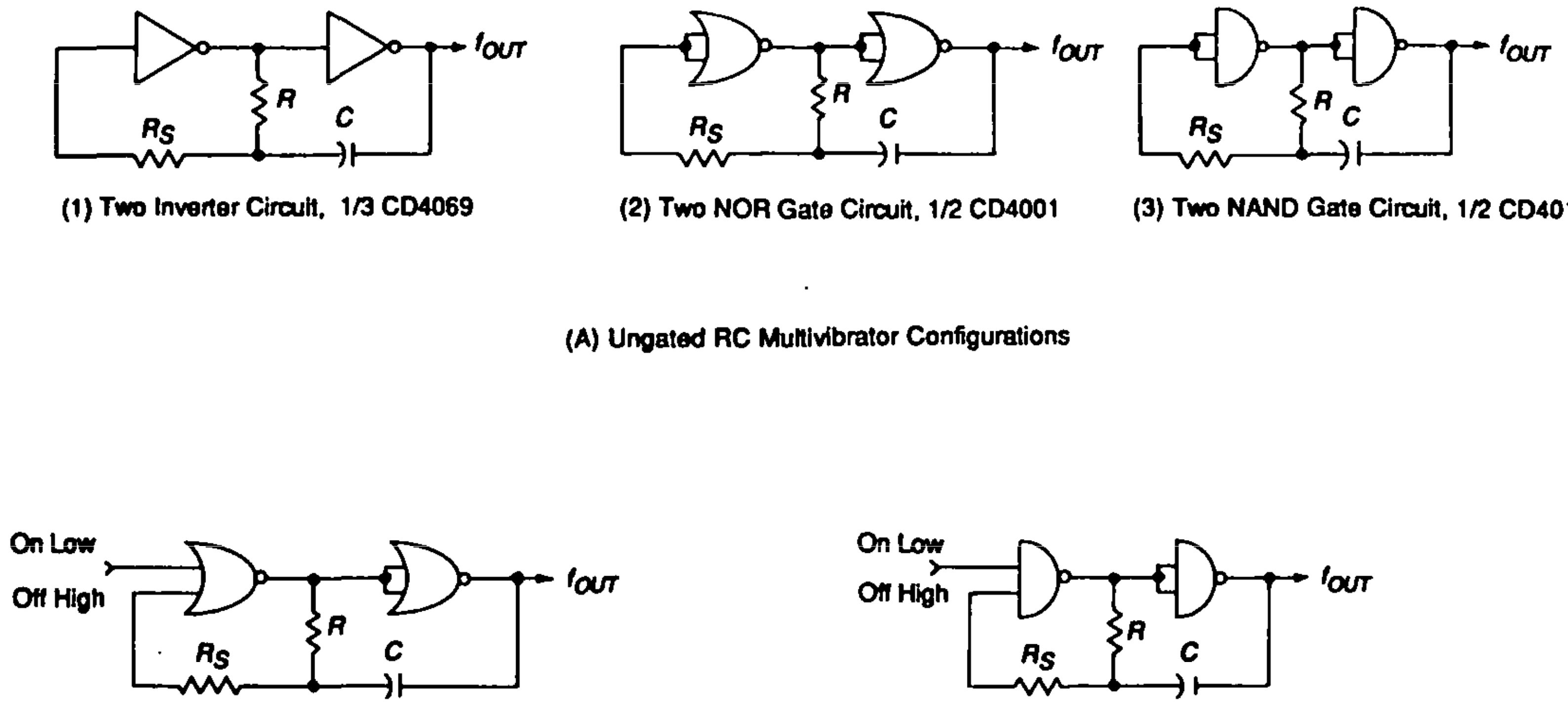
The period of this multivibrator is sensitive to variations in V_{DD} as well as to variations in V_{TR}. The addition of R_S to the simplest RC multivibrator form results in the forms shown in Fig. 7-21. The addition of R_S greatly reduces the



(A) Schematic of a PUT Oscillator

(B) Output Frequency of Oscillator

Figure 7-20. Programmable Unijunction Transistor (PUT) Oscillator



(1) Two Inverter Circuit, 1/3 CD4069

(2) Two NOR Gate Circuit, 1/2 CD4001

(3) Two NAND Gate Circuit, 1/2 CD4011

(A) Ungated RC Multivibrator Configurations

(4) Two NOR Gate Circuit

(5) Two NAND Gate Circuit

(B) Gated RC Multivibrator Configurations

Figure 7-21. RC Multivibrator Configurations Using Integrated Circuit Inverters sensitivity of the period to variations in V_{DD} and V_{TR}. The period of the modified RC multivibrator T_1 is given by

$$T_1 = -RC\left[\ln\left(\frac{V_{TR}}{V_{DD}+V_{TR}}\right) + \ln\left(\frac{V_{DD}-V_{TR}}{2V_{DD}-V_{TR}}\right)\right], \mu s \qquad (7\text{-}8)$$

provided $R_s \geq 10R$.

A good approximation of Eq. 7-8 is $T_1 = 2.2\ RC$, with $K = 10$. Either (2) or (3) of Fig. 7-21 can be converted into a gateable oscillator by using one input of the first inverter as a control input.

7-3.3.3 RC Multivibrator Using CD 4047 Integrated Circuit

An RC multivibrator using a CD 4047 integrated circuit is shown schematically in Fig. 7-22. The periods T_A at pin 13 and T_B at pins 10 and 11 of the oscillator are given by

$$T_A = \frac{1}{f_{OUT}} = 2.20\ RC, \text{ s} \qquad (7\text{-}9)$$

$$T_B = \frac{2}{f_{OUT}} = 4.40\ RC, \text{ s} \qquad (7\text{-}10)$$

where

T_A = period of oscillation of pin 13, s (See Fig. 7-22.)

T_B = period of oscillation at pins 10 and 11, s (See Fig. 7-22.)

f_{OUT} = output frequency of oscillation, MHz.

7-3.3.4 RC Multivibrator Using a 555-Type Integrated Circuit

An RC multivibrator using a 555 IC timer is shown schematically in Fig. 7-23. The output frequency of oscillation f_{OUT} of this oscillator is given by

$$f_{OUT} = \frac{1.46}{(R_A + 2R_B)\,C}, \text{ MHz} \qquad (7\text{-}11)$$

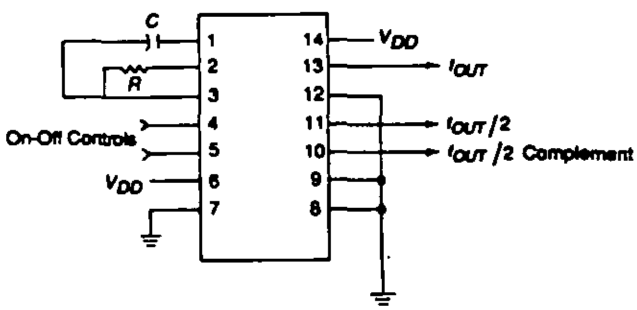


Figure 7-22. RC Multivibrator Using CD 4047

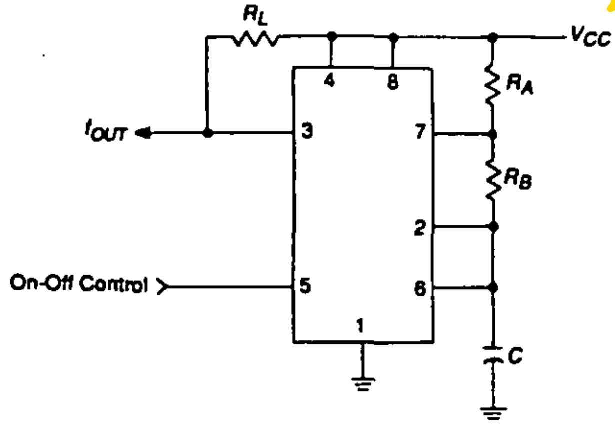


Figure 7-23. RC Multivibrator Using a 555 Timer Chip

where

R_A = resistance A, Ω

R_B = resistance B, Ω

and the duty cycle η, which is that portion of the period where the output is high, is given by

$$\eta = \frac{R_B}{(R_A + 2R_B)}, \text{ dimensionless.} \qquad (7\text{-}12)$$

7-3.3.5 Ceramic Resonator Oscillator

A ceramic resonator oscillator is shown schematically in Fig. 7-24. The frequency of oscillation is determined by the resonant characteristics of the ceramic resonator. Typically, ceramic resonators are available in the frequency range of 380 kHz to 12 MHz.

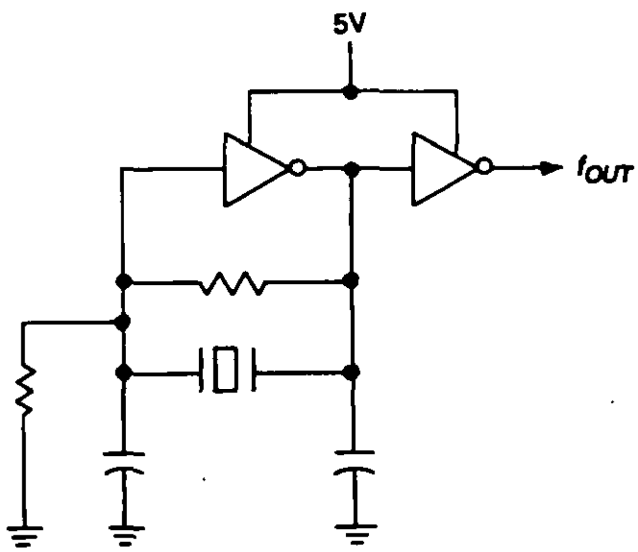


Figure 7-24. Ceramic Resonator Oscillator (380 kHz to 12 MHz)

7-3.3.6 Quartz Crystal Oscillators Using Discrete Crystals

Two examples of quartz crystal oscillators using discrete crystals are shown in Fig. 7-25. The frequency of oscillation is determined by the resonant characteristics of the crystal and the mode in which it is operated (fundamental or overtone). Typically, quartz crystals are available in the frequency range of 10 kHz to 100 MHz. Some crystals are cut in the shape of a tuning fork in order to obtain very low-frequency oscillations for watches and time fuzes.

7-3.3.7 Integrated Quartz Crystal Oscillators, Fixed Frequency and Programmable

Integrated quartz crystal oscillators are available in either fixed frequency or programmable forms and are able to interface directly with either CMOS or TTL logic families or microprocessors. The oscillators also may contain built-in frequency dividers. Oscillators with built-in frequency dividers span the frequency range of 0.005 Hz to 1 MHz. Fig. 7-26 shows a block diagram for one such device, which is available in a standard 16-pin DIP.

7-3.3.8 Time Base Accuracy

The PUT oscillator is among the simplest of oscillator configurations, but it provides the poorest performance of any of the types discussed because of the relatively large variation in V_T at ambient temperature and over the temperature range. Typically, V_T will change from 0.65 to 0.17 V over the temperature range of −40° to 75°C (−40° to 167°F).

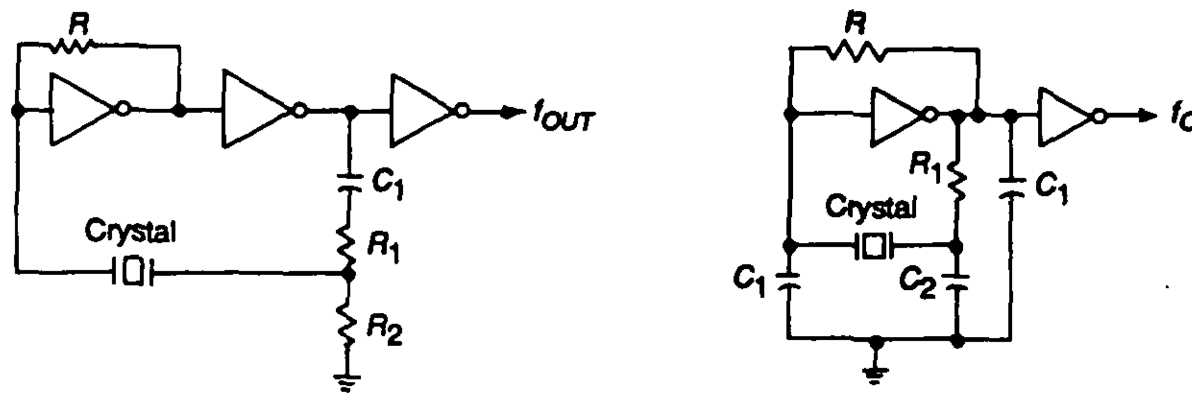
The various RC multivibrators have slightly better performance characteristics but are still not very accurate. Therefore, generally RC multivibrators should not be used in systems requiring an accuracy of 2% or better. By selecting an R and a C that are very stable and whose temperature characteristics are opposite, e.g., +100 ppm and −100 ppm, and by adjusting the value of one or the other at ambient temperature to achieve the exact frequency desired, however, it is possible to obtain oscillator performance of better than 1%. This performance level is best accomplished by using hybrid microelectronic techniques by which chip capacitors can be obtained with a desired temperature characteristic and the frequency-determining resistor can be dynamically trimmed by laser to achieve the exact frequency desired. Also the temperature coefficient of the resistor can be adjusted to compensate for the temperature coefficient of the capacitor.

The ceramic resonator oscillator provides better accuracy than RC types but should not be used in systems requiring an accuracy of 0.5% or better. Crystal oscillators are the most accurate of all oscillator types; accuracies range from 0.002 to 0.05%. Complete crystal oscillators are available in leadless carrier packages measuring 12.7 × 12.7 mm (0.50 × 0.50 in.) and, if desired, tested to the requirements of MIL-STD-883 (Ref. 7).

7-3.4 COUNTERS

There are many counter types, but some of the more common types are Binary, Decade, Programmable, Binary Coded Decimal (BCD), Up/Down, and Presettable.

A counter, such as the CD 4040, which is a 12-stage binary counter, divides the input clock frequency by two for each binary stage. The switching action takes place on the high-to-low transition of the clock waveform. The clock input rise and fall times are unlimited because the clock input of the counter has Schmitt trigger action. When the counter is used in the ripple mode, the first low-to-high transition takes place on the $2^{(n-1)}$ clock pulse, whereas on a repetitive basis, the low-to-high or high-to-low transitions take place on the 2^n clock pulse. For example, a seven-stage binary counter (CD 4024) has a 2^7 (128) division capability on a repetitive basis, but the first low-to-high transition for



(A) Series Oscillator, 1/2 CD 4069

(B) Pierce Oscillator, 1/3 CD 4069

Figure 7-25. Quartz Crystal Oscillators (10 kHz to 2.2 MHz)

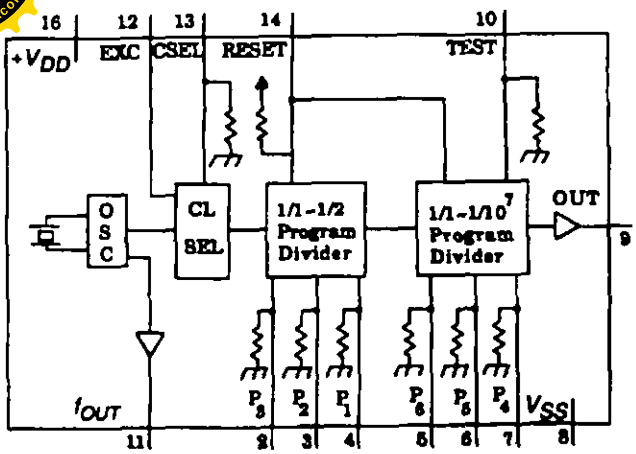


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Figure 7-26. Integrated Quartz Crystal Oscillator, Fixed Frequency and Programmable (Ref. 6)

the Q_7 output occurs after 2^6, or 64, clock pulses. By proper choice of clock frequency and by selecting an appropriate counter stage, a wide variety of system clock frequencies is achievable. For example, Fig. 7-27 shows a crystal clock of 40.96 kHz driving a CD 4040 counter. A decade counter—CD 4017, CD 40160, or CD 40162—divides the input clock frequency by a factor of 10.

A programmable counter—CD 4018, CD 4059, MC 14522, and MC 14526—can be programmed via certain control inputs to divide the input clock frequency by different amounts depending on the input code. The CD 4018 can be programmed to divide by 10, 8, 6, 4, or 2, and with the addition of a CD 4011, it can be programmed to divide by 9, 7, 5, or 3. The CD 4059 can be programmed to divide the input clock frequency by any number "n" from 3 to 15,999. The MC 14522 is a 4-bit BCD counter, which can be programmed to divide by 1 to 10. The MC 14526 is a 4-bit binary counter, which can be programmed to divide by 1 to 16.

A variety of other counters is available for performing digital timing functions. A partial list of digital counters includes

1. CD 4029—Presettable Up/Down Counter, Binary or BCD Decade
2. CD 4510—Presettable 4-Bit BCD Up/Down Counter
3. CD 4016—Presettable 4-Bit Binary Up/Down Counter
4. CD 40102—Presettable 2-Decade BCD Down Counter
5. CD 40103—Presettable 8-Bit Binary Down Counter
6. CD 40160—Decade Counter With Asynchronous Clear
7. CD 40161—Binary Counter With Asynchronous Clear
8. CD 40162—Decade Counter With Synchronous Clear
9. CD 40163—Binary Counter With Synchronous Clear
10. CD 4045—21-Stage Binary Counter With Oscillator Amplifier
11. CD 4536—24-Stage Programmable Timer With Oscillator Amplifier

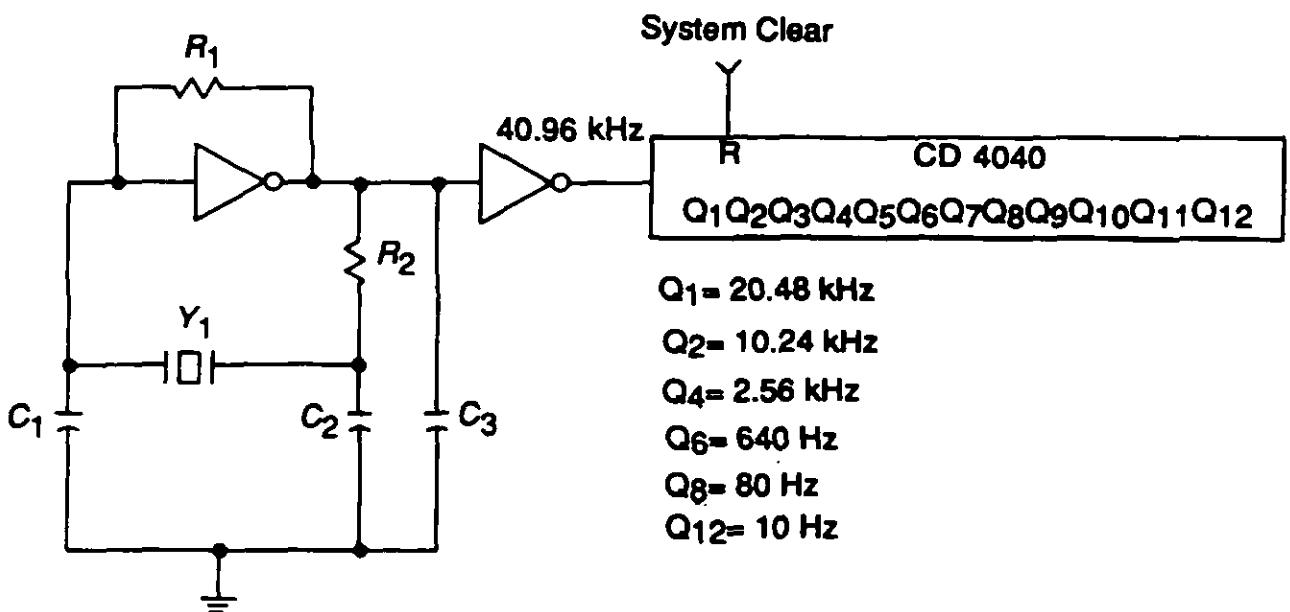


Figure 7-27. A Crystal Clock (40.96 kHz) Driving a CD 4040 Counter

12. MC 14521—24-Stage Frequency Divider With Oscillator Amplifier.

7-4 OUTPUT CIRCUITS

The output of a digital timer is usually a pulse, often one clock pulse period wide, which may be positive or negative going, i.e., ground to +V or +V to ground. In some applications the pulse may be adequate to meet system requirements, but in others the timer output may be latched to give a *continuous* voltage level after the timer output has occurred. The output from the timer may not have enough energy to perform the desired function; if it does not, the timer output must be buffered or isolated through use of a transistor amplifier. Some examples of timers are presented in Figs. 7-28 through 7-32.

In the example shown in Fig. 7-28 and Table 7-1, the CD 4536 is used as a programmable timer. The timer output pulse width can be programmed through components *R* and *C*.

In the example shown in Fig. 7-29 and Table 7-2, the CD 4536 output is used to set a flip-flop. The timer output is then latched and will stay high until a system clear pulse is applied to the latch.

The decode out selection table, or truth table, shown in Tables 7-1 and 7-2, shows the outputs available from the "decode out" terminal when various combinations of 1's and 0's are applied to the 8 bypass and to inputs A, B, C, and D. A logic 1 on the 8 bypass input enables a bypass of the first eight stages and makes stage 9 the first counter stage (labeled "1" under the column headed "8 Bypass = 1"). Selection of any of the 16 outputs is accomplished by the decoder and the inputs A, B, C, and D.

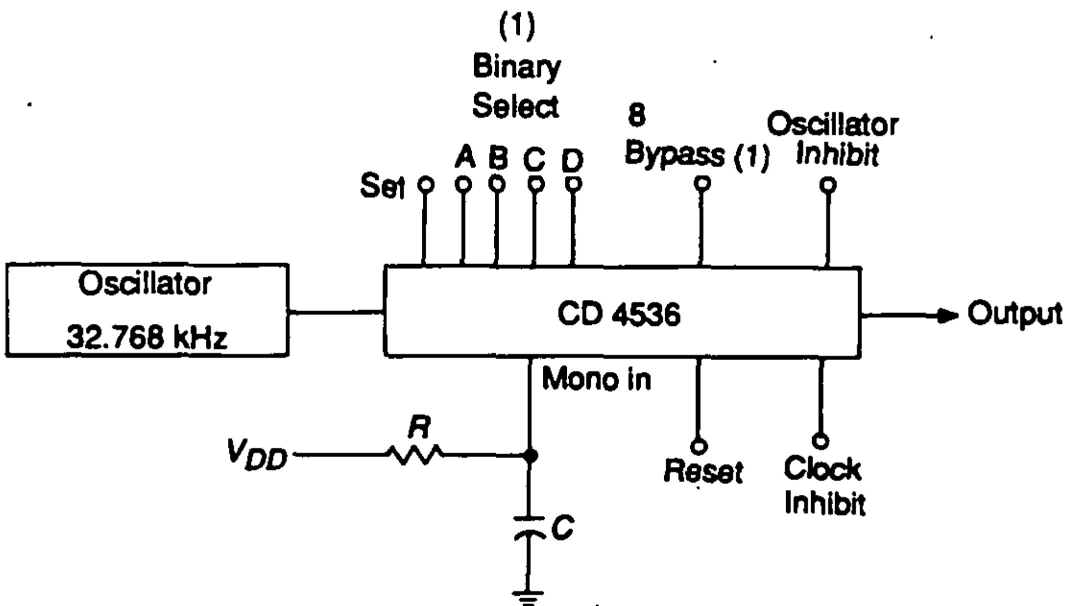
Example 1. Refer to Table 7-1 and set a logic 1 on the 8 bypass; then, by setting A and B = 1 and C and D = 0, an output pulse is obtained from the decoder output terminal. This output comes from the twelfth stage of the 24 ripple-binary counter stages and is the fourth in the list of 16 possible input combinations shown in the table.

Example 2. Refer to Table 7-2 and set A, B, C = 0 and D = 1, with 8 bypass = 0. The seventeenth stage will give a time-out delay of 2 s.

In the example shown in Fig. 7-30, the MC 14521 is used as the timer. The timer output at 4.0 s is latched with a flip-flop, and the latched output is buffered with a two-transistor level shifter to drive a 28-Vdc relay coil.

In the example shown in Fig. 7-31, a CD 4020 is used with a 32.768-kHz crystal oscillator to generate an output 0.25 s after the system clear signal goes low. The time delay output is buffered with an NPN transistor to drive a high-energy, capacitive discharge firing circuit. The CD 4020 cannot supply enough current to turn on the silicon-controlled rectifier (SCR) directly.

In the example shown in Fig. 7-32, the CD 4020 provides the same 0.25-s delay as the circuit shown in Fig. 7-31,



Note: See Table 7-1 for Explanation of the Use of the 8 Bypass and Binary Select Inputs

Figure 7-28. Programmable Timer With Pulse Output

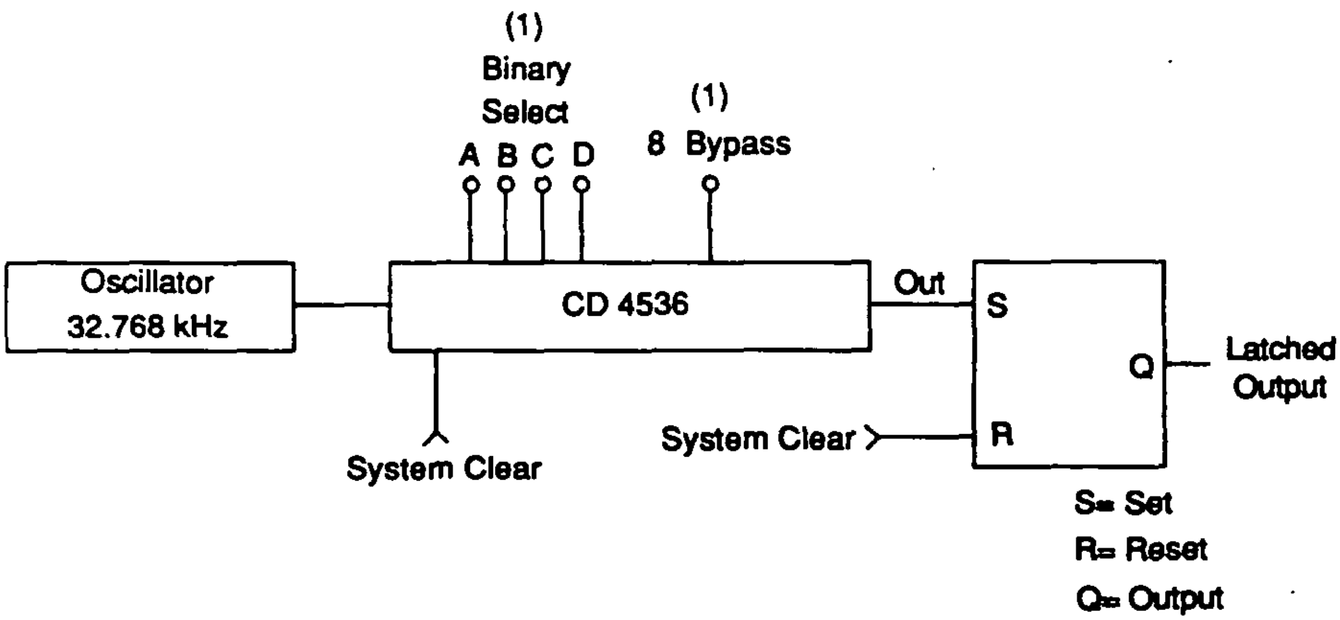
TABLE 7-1. PROGRAMMABLE TIMER WITH PULSE OUTPUT

D	C	B	A	NUMBER OF STAGES IN DIVIDER CHAIN	
				8 Bypass = 0	8 Bypass = 1
0	0	0	0	9	1
0	0	0	1	10	2
0	0	1	0	11	3
0	0	1	1	12	4
0	1	0	0	13	5
0	1	0	1	14	6
0	1	1	0	15	7
0	1	1	1	16	8
1	0	0	0	17	9
1	0	0	1	18	10
1	0	1	0	19	11
1	0	1	1	20	12
1	1	0	0	21	13
1	1	0	1	22	14
1	1	1	0	23	15
1	1	1	1	24	16

except that the output pulse occurs only once and is a sh pulse of 244-µs duration. The output pulse sets a flip-flop, which resets the timer. The output buffer uses a two-transistor level shifter that delivers energy to the load for 244 µs.

In the examples shown in Fig. 7-33, a high-energy and a low-energy capacitive discharge firing circuit are shown. The low-energy circuit contains 1.36×10^{-3} J of energy, and the high-energy circuit contains 0.321 J of energy. Neither circuit can deliver the full amount of energy to the electro-explosive devices (EED) because of circuit losses, particularly in the storage capacitor and SCR. Aluminum electrolytic capacitors are available, which outperform tantalum capacitors in energy transfer efficiency.

EEDs can vary in firing energy requirements. In some applications, a very insensitive EED is required. There is a class of EEDs, known as 1-AMP, 1-WATT, NO-FIRE devices. These devices can dissipate 1 W of power in the bridgewire and not fire. The firing energy required to guarantee EED firing is called the "all fire" and is usually specified as an ampere-second product. That is, a constant current applied for the proper amount of time is guaranteed to fire the EED. If this technique is used, a design margin should be allowed to account for component tolerances in the firing circuit. A more common method for firing EEDs, however, is to use the capacitive discharge method, which involves storing energy E on a firing capacitor according to the equation



Note: See Table 7-2 For Explanation of the Use of the 8 Bypass and Binary Select Inputs

Figure 7-29. Programmable Timer With Flip-Flop and Latched Output

TABLE 7-2. PROGRAMMABLE TIMER WITH LATCHED OUTPUT

SELECTION TABLE					
D	C	B	A	8 Bypass	Number of Stages
0	0	0	0	0	9
0	0	0	0	1	1
0	0	0	1	0	10
0	0	0	1	1	2
1	0	0	0	0	17
1	0	0	0	1	9
1	0	1	0	0	19
1	0	1	0	1	11
1	1	1	1	0	24
1	1	1	1	1	16

STAGE SELECTED	TIME OUT, s
15	0.5
16	1.0
17	2.0
18	4.0
19	8.0
20	16.0
21	32.0
22	64.0
23	128.0
24	256.0

$$E = 5CV^2, \text{erg} \tag{7-13}$$

where

C = capacitance, μF.

Statistical test methods exist to determine the all fire energy requirement for a particular EED using the capacitive discharge firing method. Firing energy data are available for current procurement EEDs in MIL-HDBK-777 (Ref. 4).

Firing circuits for a low-energy EED (5×10^{-4} J) and a high-energy EED (1 AMP, 1 WATT, NO-FIRE) are shown in Fig. 7-33. Normally, a firing margin of two or more should be allowed, especially if the circuit is expected to operate reliably over the temperature range of $-54°$ to 71°C ($-65°$ to 160°F). At -54°C (-65°F), the value of the firing capacitor may be reduced by 10 to 40% or more, and the internal impedances of the firing capacitor (effective series resistance (ESR)) and the SCR may be increased significantly and thereby reduce the amount of energy available to the EED.

Some designers prefer not to use SCRs in EED firing circuits for fear that system noise spikes might cause them to fire prematurely and latch on. For an out-of-line EED the SCR latch-up would not create a hazard, but the firing circuit would be rendered inoperative. This latch-up problem can be avoided by making R (470 Ω in Fig. 7-33(A) and 10 Ω in Fig. 7-33(B)) large enough to starve the SCR, i.e., lower the current through R to a value less than the minimum holding current value of the SCR. If the system cannot tolerate the RC charge time constant, some other scheme may have to be employed to fire the EED. The technique shown in Fig. 7-33 would be appropriate since the firing circuit in this example is activated only as long as the timer output pulse is present. If the timer output pulse width is too long, it can be shortened by using a one-shot multivibrator whose period can be programmed to be virtually any value and is independent of the timer output pulse width. The 470-Ω resistor and 0.01-F capacitor from the SCR gate-to-ground of each of the circuits of Fig. 7-33 help immunize the SCR from system noise. A resistor from the SCR cathode-to-ground could also be helpful if the SCR and EED are separated in the system by 76.2 mm (3.0 in.). This extra resistor is shown with a dashed connecting line in the two circuits in Fig. 7-33.

There are alternative output switching devices, which could be used in place of an SCR. Some examples include power metal oxide semiconductor field-effect transistor (MOSFET), Darlington transistors, and a combination of PNP and NPN transistors, such as is shown in Fig. 7-32. These alternatives have the advantage of not latching on; they also provide very high current gain (output signal amplification).

7-5 STERILIZATION CIRCUITS

It is a safety requirement in most ordnance devices that the firing capacitor have an energy bleed resistor placed across it. The system requirement usually dictates the minimum "safing" period. Fig. 7-34 shows a typical firing circuit. If the EED has a "No-Fire" energy of 500 ergs, then from Eq. 7-13

$$V_{NO-FIRE} = \sqrt{\frac{E}{5C}} = \sqrt{\frac{500}{50}} = 3.2 \text{ V.}$$

If the system requires a "safing" period of 1 h, then from the following relationship

$$R' = \frac{t}{C\ln\left(\frac{V_{IN}}{V_{CAP}}\right)} = \frac{3600}{10^{-5}\ln\frac{30}{3.2}} = 1.61 \times 10^{8}\ \Omega \tag{7-14}$$

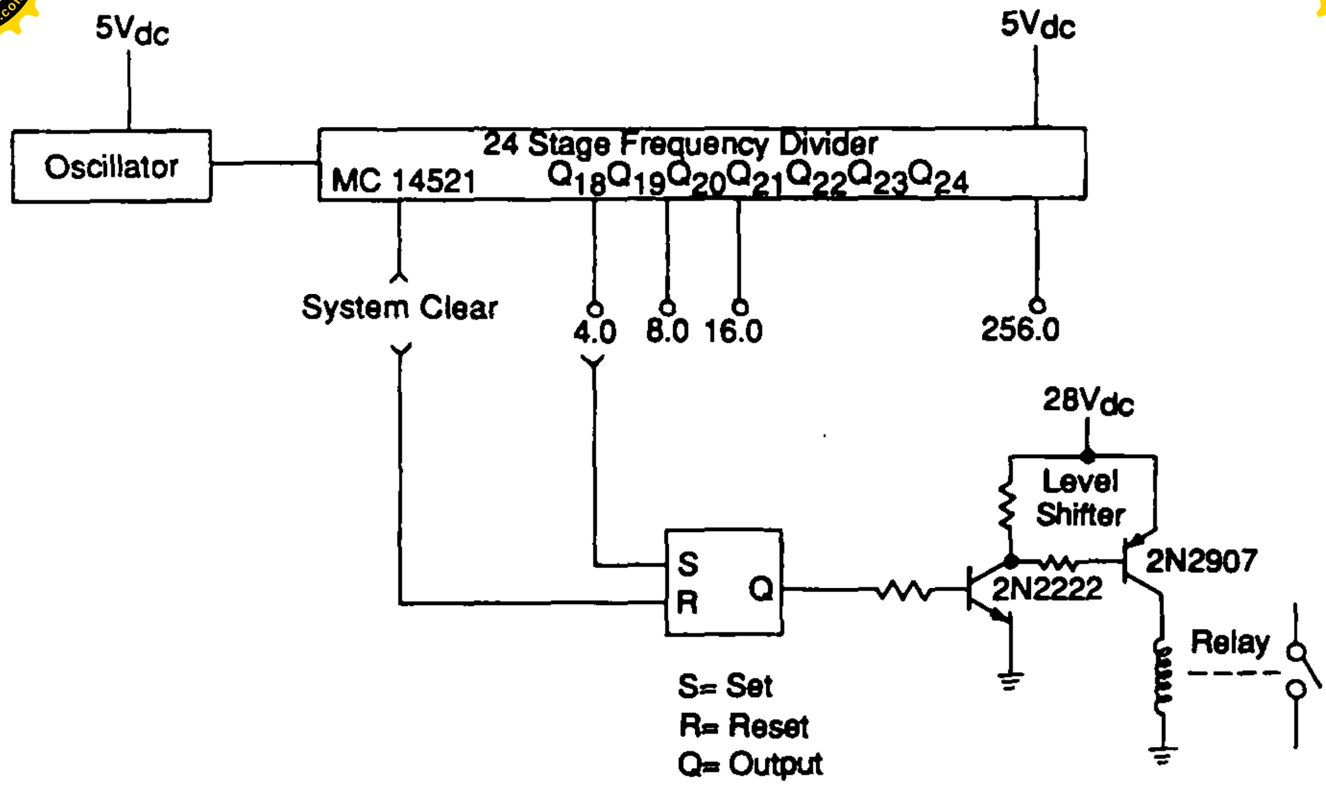
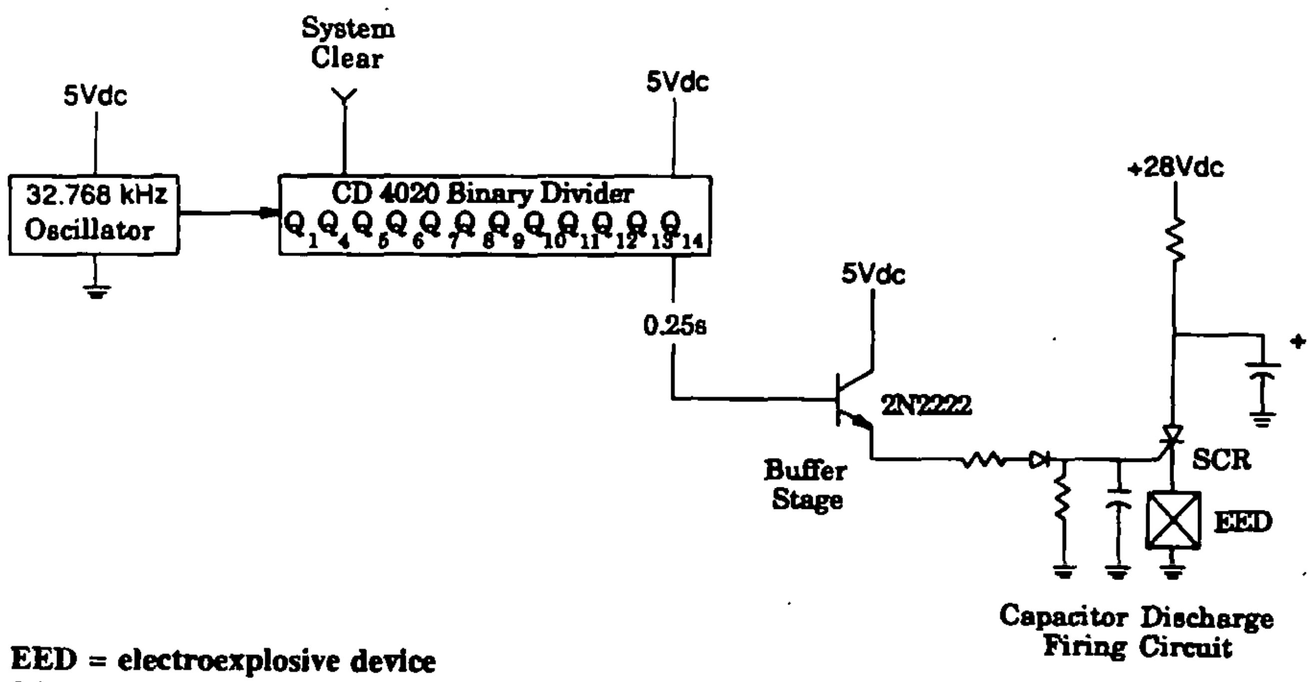


Figure 7-30. MC14521 Timer Output Latched With Flip-Flop and Transistor Buffer



EED = electroexplosive device
SCR = silicon-controlled rectifier

Figure 7-31. Firing Circuit With Transistored Buffered Capacitor Discharge Output

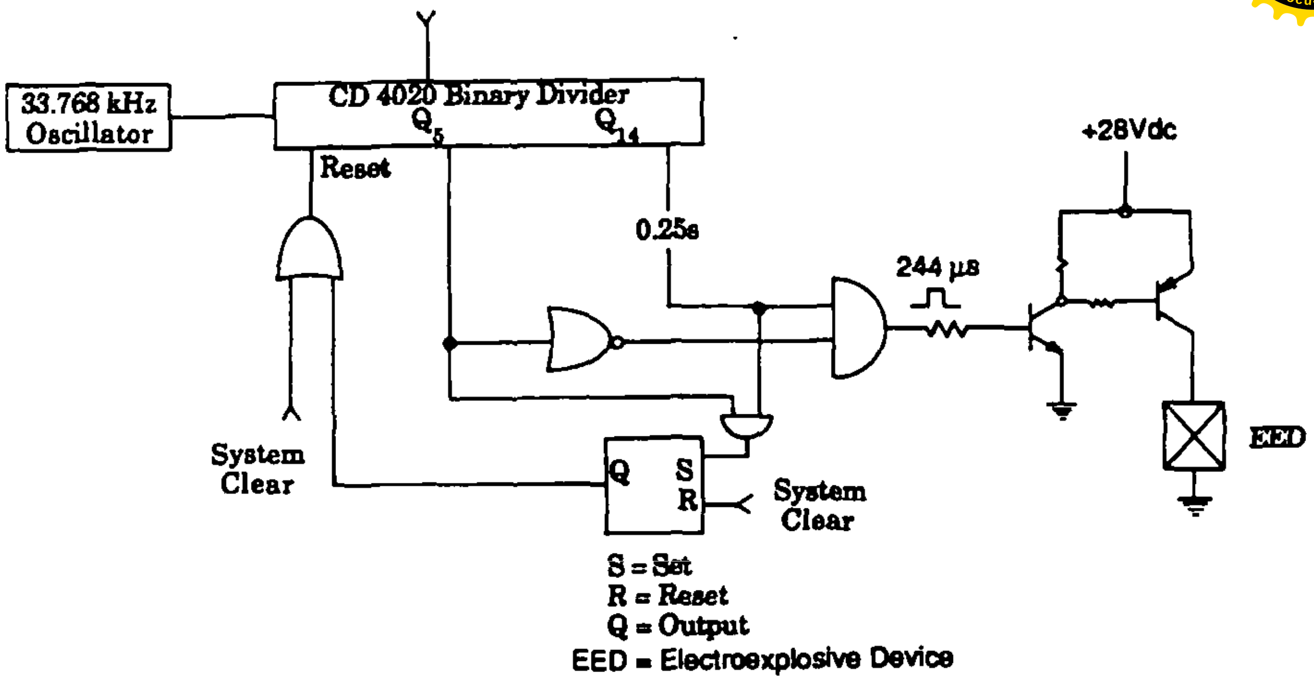


Figure 7-32. Firing Circuit With Short Duration Output

where

R' = required bleed resistor, Ω
C = capacitance, F
t = time, s
V_{CAP} = EED no-fire voltage, V.

The energy bleed requirement exists so that, in the event of a dud piece of ordnance, an explosive ordnance disposal (EOD) team can recover or remove the ordnance with the assurance that the electrical firing circuit is safe.

7-6 MICROPROCESSORS

Microprocessors are being used in a variety of fuzing applications to provide numerous programmed functions including timing, sensor monitoring, self-checking, sensor control, and signal processing. The advantages of using a microprocessor in fuzing applications are that hardware design is minimized and fairly complex fuzing algorithms can be implemented routinely. One disadvantage is that current microprocessors usually run at a maximum clock frequency of 10 to 20 MHz or less, and their actual signal processing speed is considerably less. This speed limitation could preclude using a microprocessor in a fuze for very high-speed target encounters.

Virtually all timing and logic functions required of an electronic fuze can be performed by any of the many microprocessors currently available. The choice of a particular microprocessor is determined by power, speed, size, and cost restrictions imposed by the system on the fuze. Single-chip microcomputers and microcontrollers are particularly well-suited to fuzing because they require the least number of peripheral circuits and their internal architecture is suited to timing and control applications.

Two eight-bit microprocessors that are widely used in fuzing applications are the MC 146805G2 and the 80C48, -49, -50, and -51 family. Both are fabricated from high-performance silicon gate CMOS technology.

The MC146805G2 will operate up to 4 MHz and has a set of 61 basic instructions. The 80C48 and 80C49 can operate in a single-step mode or up to 11 MHz and each has a set of 111 basic instructions.

One advantage to using the 80C48-51 family is that the microprocessors share a common instruction set. Thus a designer can start with an 80C48 (least RAM and ROM memory space) and expand upward in memory space as system requirements grow without having to perform a major rewrite of program software.

Functional block diagrams of the MC146805G2 and the MSM80C48 microprocessors are presented as Figs. 7-35 and 7-36, respectively.

7-7 ELECTRONIC SAFETY AND ARMING SYSTEMS

One emerging technology that is being pursued by all branches of military service is the use of electronic safety and arming devices in missiles and smart weapons. Basically, an electronic SAD can be defined as an S&A system that contains neither primary explosives in the explosive

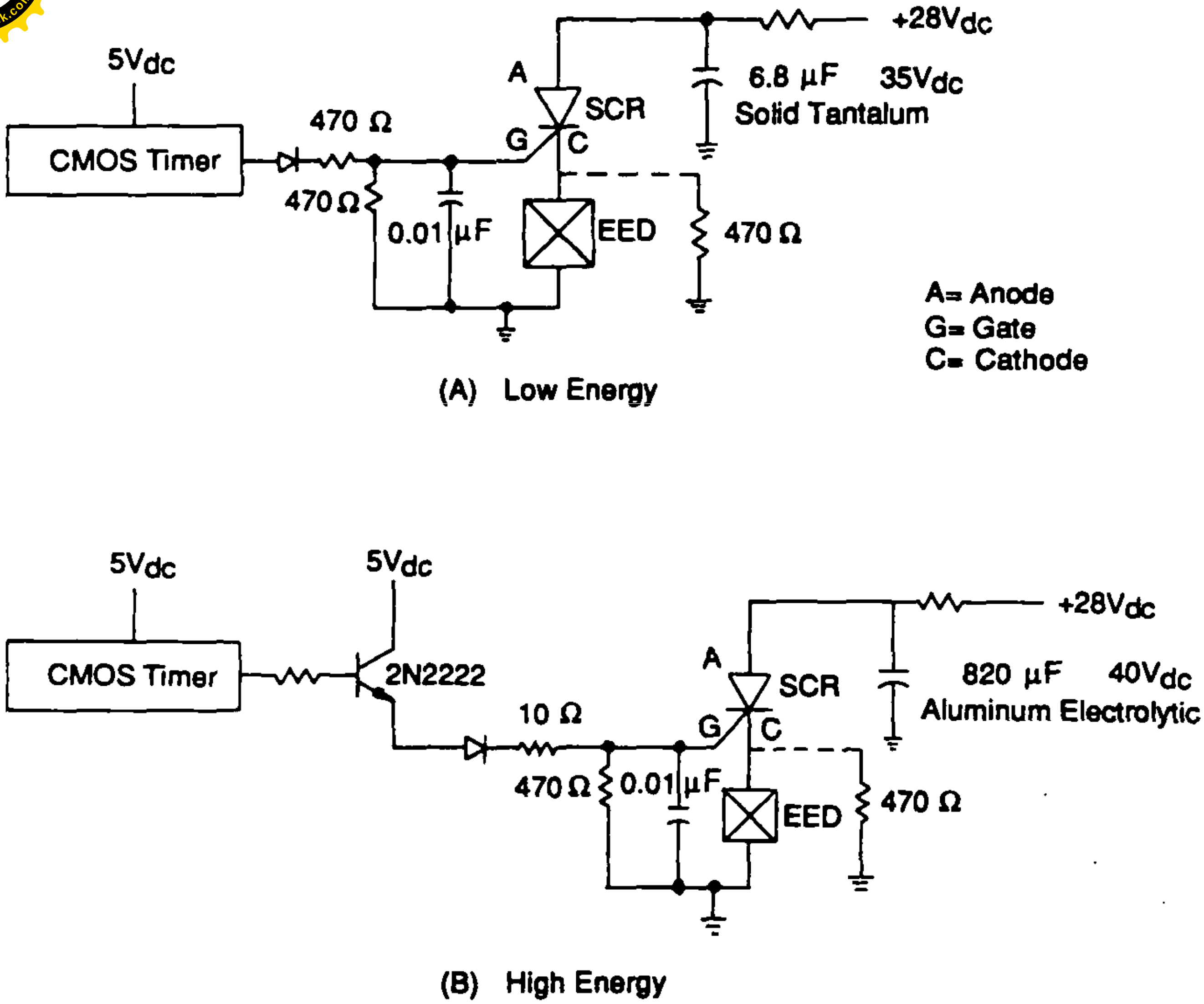


Figure 7-33. High- and Low-Energy Capacitive Discharge Firing Circuits

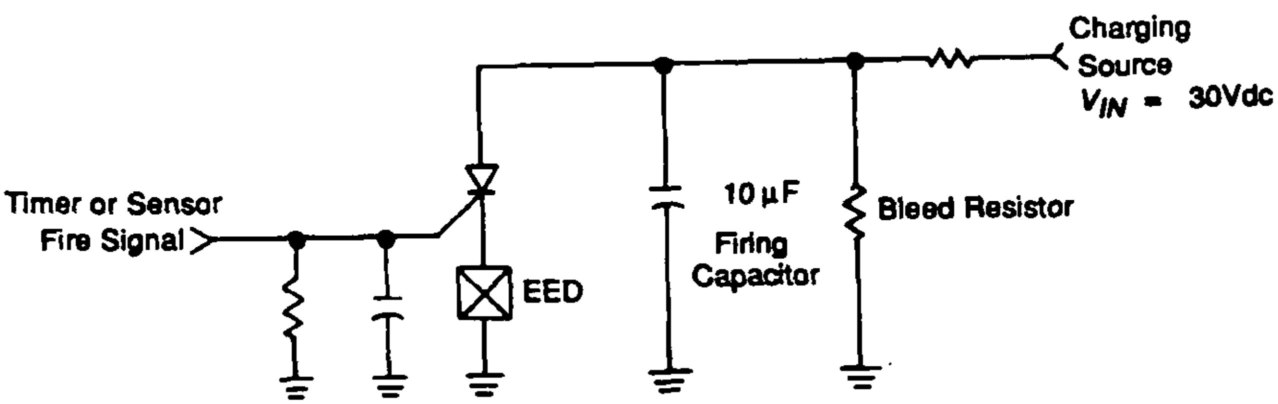
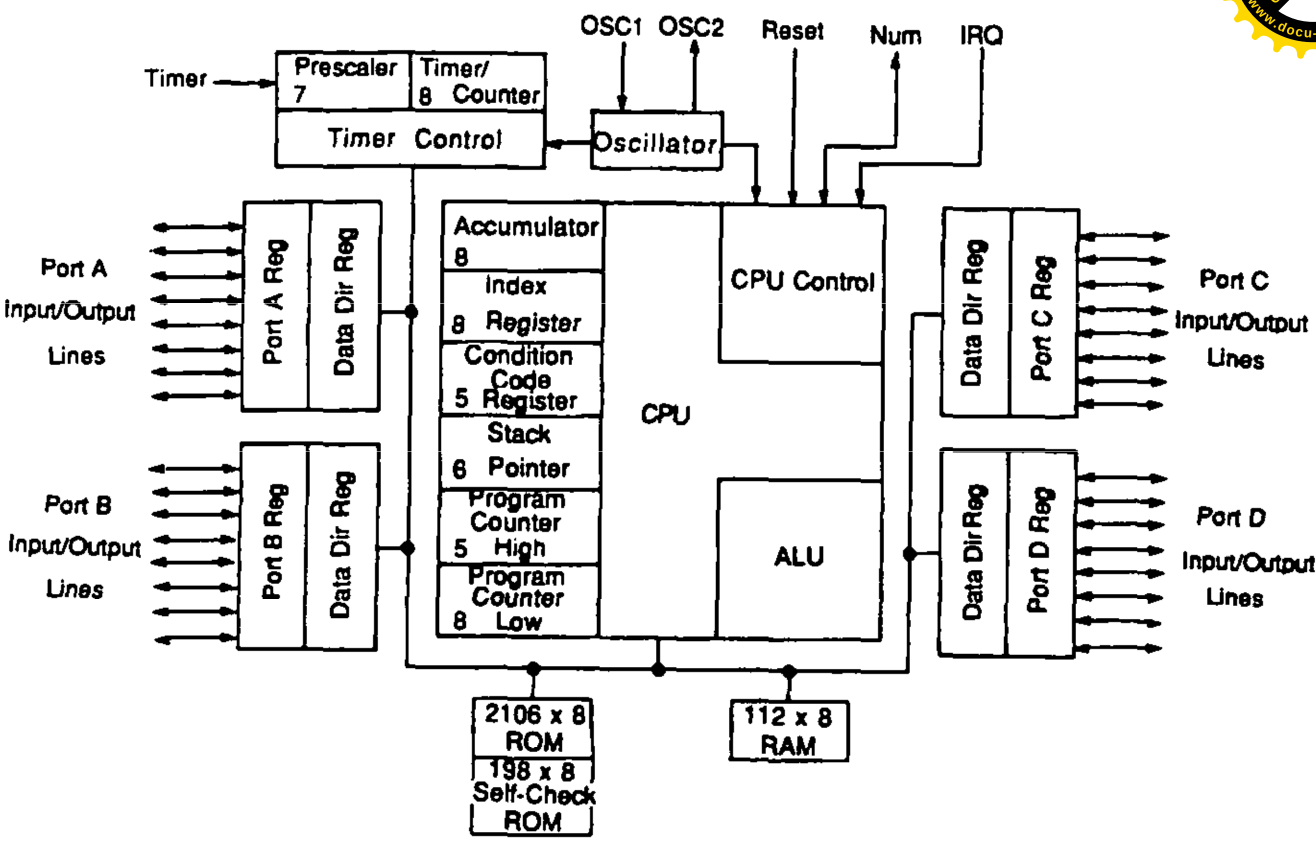


Figure 7-34. Energy Bleed Resistor Example



Courtesy of Motorola, Inc.

Figure 7-35. Functional Block Diagram MC14680G2 8-Bit Microcomputer (Ref. 8)

train, nor an interrupted explosive train, nor a mechanical energy interrupter, but does have access to an energy source sufficient for warhead detonation. It is a no-moving-parts, solid-state unit employing a slapper detonator explosive train. Therefore, it is expected to provide significant advantages in safety, reliability, size, cost, and other performance features compared to SADs based on existing technology.

A block diagram of a generic electronic SAD is shown in Fig. 7-37. It is basically a single-channel, single-point-initiation unit having two connectors: a multipin connector for inputs and monitors and an output connector for attachment to a slapper detonator. It does not contain any explosive and can be fully tested including the firing of disposable slapper detonators. This SAD has a microcontroller or similar large scale integration (LSI) element that will enable it to be factory programmable for a wide range of applications. Environmental sensors are part of the S&A system, but they are shown as external inputs because they are usually unique to each application. The SAD is capable of being used with a wide variety of sensors, such as launch signals, fin deployment signals, and command-arm signals. Some of the safety features illustrated by Fig. 7-37 are

1. The use of two separate IC elements, neither of which can arm the SAD independently

2. The use of two dc switches and one dynamic switch in the arming power path

3. The use of dc switches on both sides of the converter drive

4. The use of transformer coupling between the high- and low-voltage sections.

Two advantages of this arrangement are that application of power to any point in the circuit cannot result in arming and that shorting any or all of the arming switches does not result in arming.

The SAD firing capacitor can be designed for single- or multiple-point output to fire slapper detonator(s). The slapper detonator and HNS-4 explosive pellet are external to the SAD housing and are connected by cabling.

The technology to produce electronic S&A is maturing, and a fully developed system is being used by the US Army in the Fiber-Optic Guided Missile (FOGM). There are still problems to be solved, e.g., establishment of safety criteria for electronic S&A; development of service-accepted logic and environmental sensors; and reduced cost and size, but the potential is great for next generation SADs for missile and smart weapon application.

Additional information on electronic S&A systems is included in Ref. 10.

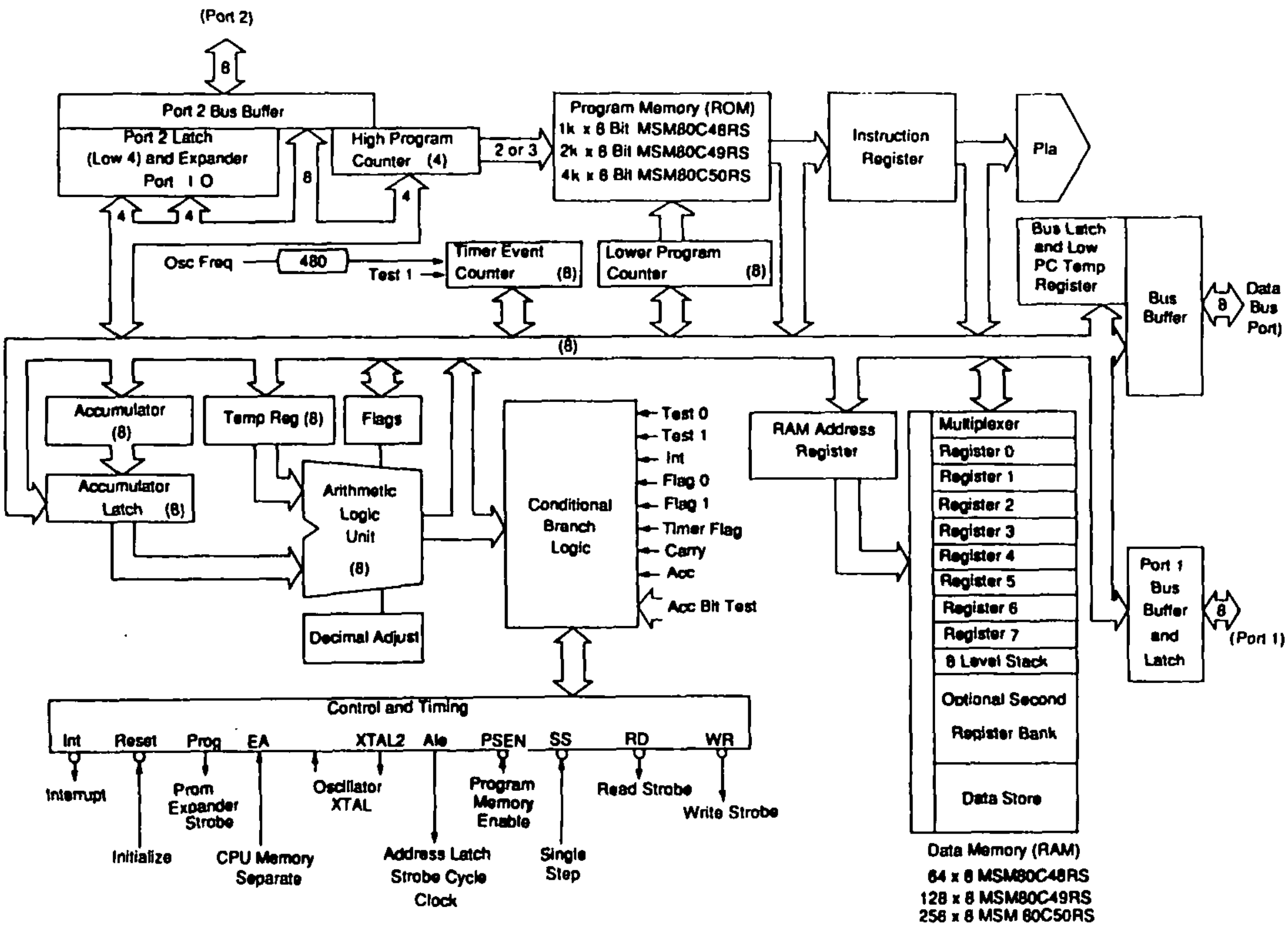


Figure 7-36. Functional Block Diagram MSM80C48 Family 8-Bit Microcomputer (Ref. 9)

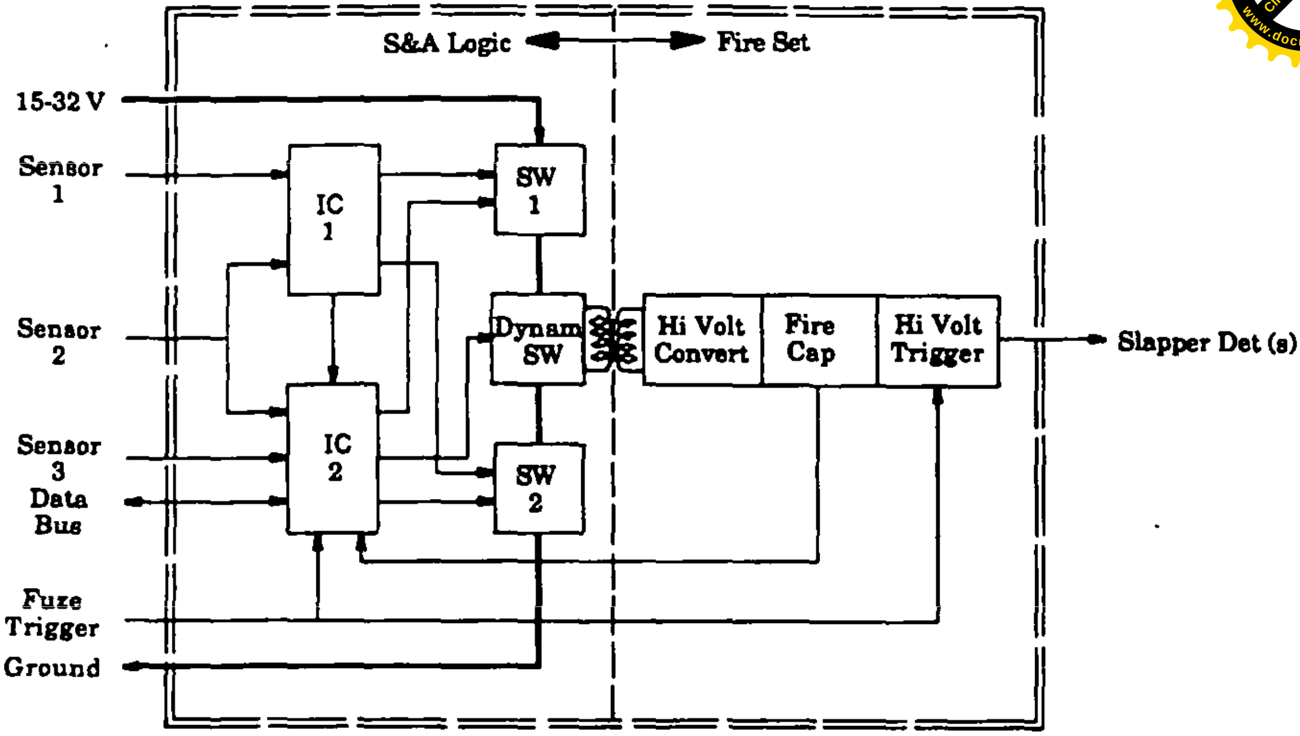


Figure 7-37. Generic Electronic Safety and Arming Device (Ref. 10)

7-8 MICROMECHANICAL DEVICES

Recent advances in the technology of microelectronic chips have led to the development of a new technology called micromachining, which allows silicon mechanical devices to be made almost as small as microelectronic devices (Ref. 11). Chemical etching techniques are added to micromachining to form three-dimensional shapes that can be used as switches and as sensors for environments such as force, pressure, and acceleration. The excellent physical properties of silicon, the small size of micromachined silicon devices, and its adaptability to high-volume CMOS manufacturing techniques make this technology cost-effective for fuzing applications.

Accelerometers with an on-board amplifier have been designed and fabricated on chips as small as 17.4 $mm^2 \times 0.5$ mm thick (0.027 $in.^2$ × 0.021 in. thick). A silicon oxide beam is formed over a shallow well and using a boron etch-stop technique, a metal layer is deposited on the top surface of the oxide cantilever. The metal layer and the flat silicon on the bottom of the well act as two plates of a variable air-gap capacitor. A lump of gold is formed on the free end of the beam by plating. If the silicon chip is moved suddenly, the inertia of the gold weight causes the beam to flex and change the air gap and hence the capacitance. The output of the sensor is a voltage that is proportional to acceleration. One accelerometer of this type had a sensitivity of 2 mV/g, where g is the acceleration due to gravity. The amplifier is an important part of the circuitry because signal conditioning of some kind must precede the voltage transmission in most small capacitive sensors. Fig. 7-38 illustrates an accelerometer design with capacitive temperature compensation and amplification integrated on the same chip. Refs. 12 through 15 provide additional material on this technology and on other types of micromechanical sensors.

7-9 ELECTROCHEMICAL TIMERS

Electrochemical timing devices are simple, small, low-cost items capable of providing delays that are from seconds to months long (Ref. 16). The operation of electrochemical timers is based on Faraday's first two laws of electrolysis. These two laws can be summarized to state that the mass of an element deposited or liberated during an electrochemical reaction is proportional to the electrochemical equivalent of the element, the current, and the time the current flows. When a solution is electrolyzed, the number of electrons received at the anode must equal the number delivered from the cathode. The ions arriving at the cathode are reduced, i.e., they obtain electrons, and those arriving at the anode are oxidized, i.e., they forfeit electrons. Electrochemical systems that use these principles are called coulombmeters.

7-9.1 ELECTROPLATING TIMER WITH ELECTRICAL OUTPUT

The Bissett and Berman E-Cell has been used in several military applications, including arming and self-destruct delays in the Antipersonnel Mine, BLU-54/B (Ref. 17).

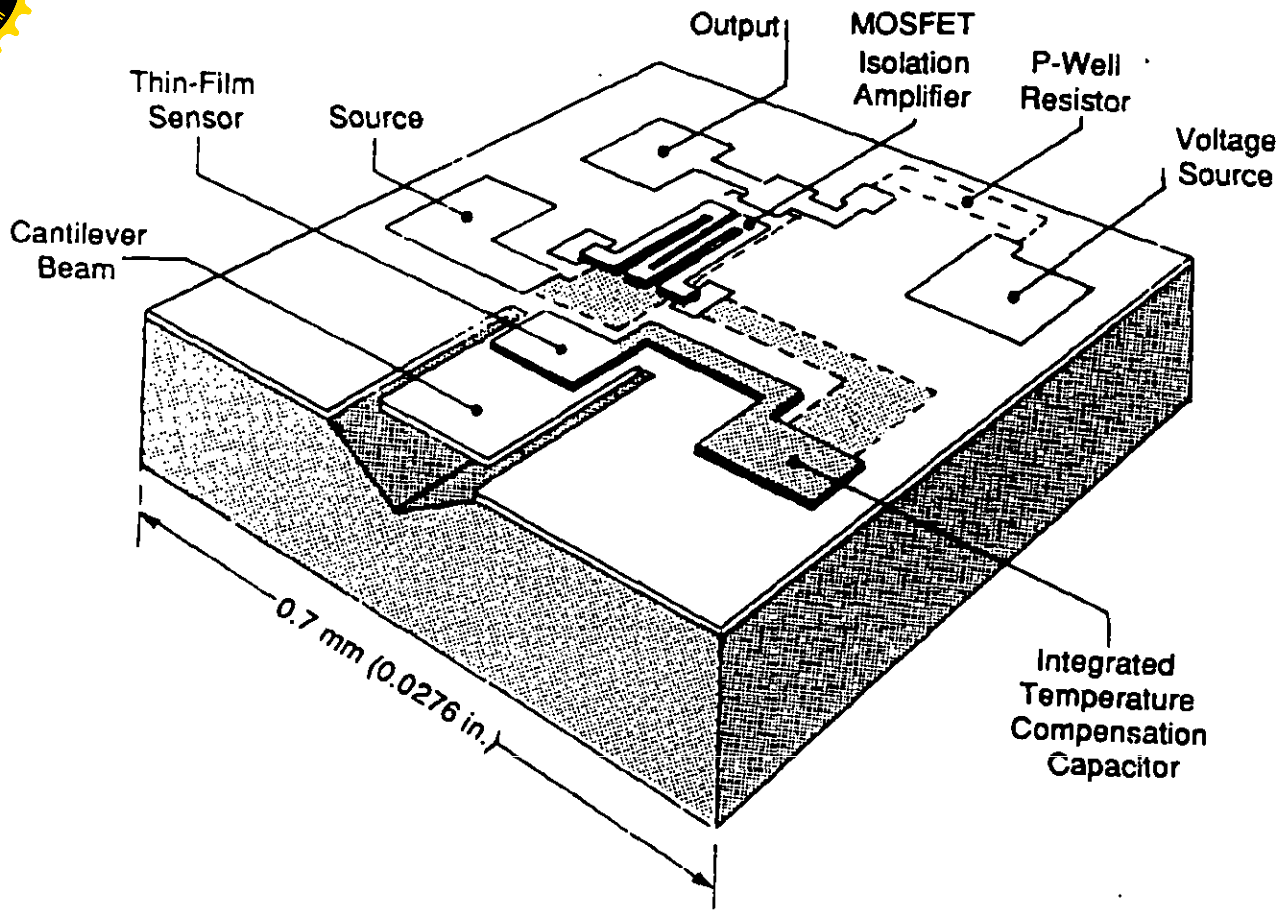


Figure 7-38. Accelerometer Using Micromechanical Technology With Integrated CMOS Circuitry (Ref. 12)

Cell construction is illustrated in Fig. 7-39. The cell consists of a silver case (the reservoir electrode), 6.35 mm (0.25 in.) in diameter and 15.88 mm (0.625 in.) long. The working electrode of gold over base metal is held in place by two plastic disks that function as both seals and electric insulators. The case is filled with electrolyte that contains a silver salt in a weak acid (Ref. 19). Electrical leads complete the cell. Cell mass is about 2.8 g (1.92×10^{-4} slug).

The cell illustrated is a single-anode cell, which permits a single time delay. If more than one delay is desired, several anodes of different sizes may be combined in the same unit (Ref. 20). A dual-anode cell is useful because of the common military requirement for two different time delays. For example, a mine may require an arming delay of a few minutes and a self-sterilization delay of several days.

The system consists of three parts: a source of dc voltage, an electroplating cell in which the constant current causes the metal anode (silver in this design) to be deplated at a known rate, and a detector circuit that senses the progress of the reaction.

During the timing period the voltage across the E-cell is low, as illustrated in Fig. 7-40. Upon completion of anode deplating the voltage rises rapidly and thus indicates the end of the timing interval. One way to detect this voltage rise is to use the simple detector circuit shown in Fig. 7-41. The performance of this circuit can be understood by considering its three phases of operation:

1. While the cell deplates, the run voltage V_R, shown in Fig. 7-40, is below the activation voltage of the transistor. Therefore, since the cell is drawing practically all the current, the equivalent circuit consists of just the cell plus its resistor.

2. During the rapid transition to the high-voltage state, the current level through the cell is reduced as the transistor base starts to take current.

3. While operating at the stop voltage V_s, the cell draws a very small residual current, which in most cases is negligible compared with that drawn by the transistor. Thus the equivalent circuit is essentially the original circuit without the coulombmeter.

Typical voltage-current characteristics at various operating temperatures are shown in Fig. 7-42. Fig. 7-42(A) shows the maximum running (deplating) voltage V_R and current I_R, whereas Fig. 7-42(B) shows the stop voltage V_s

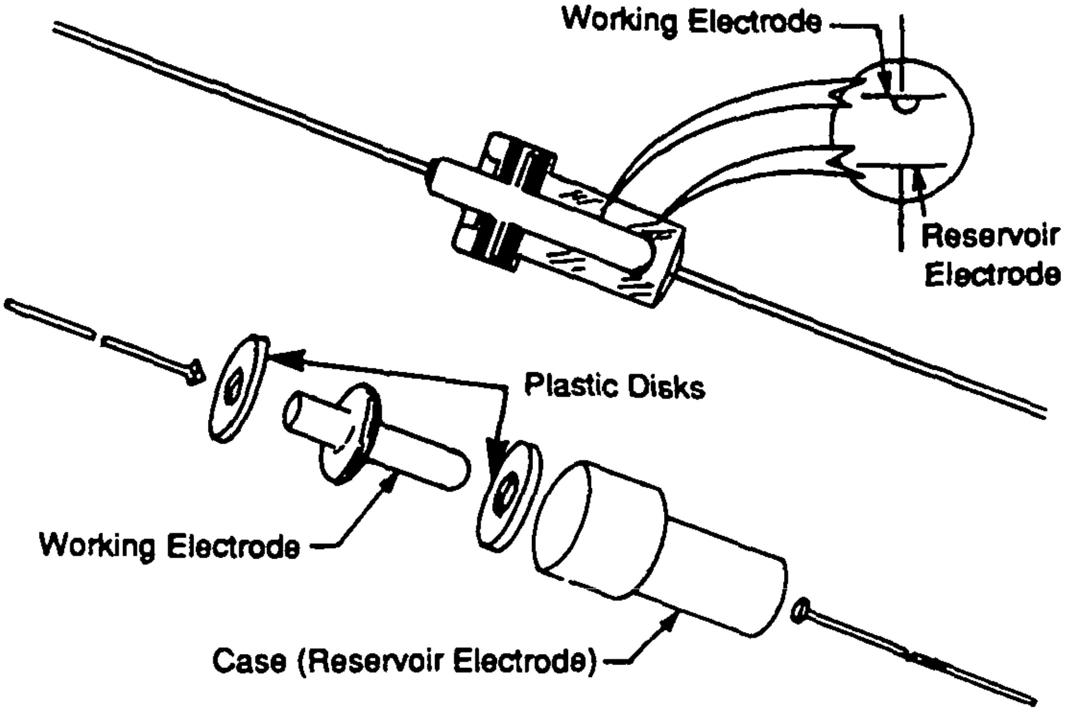
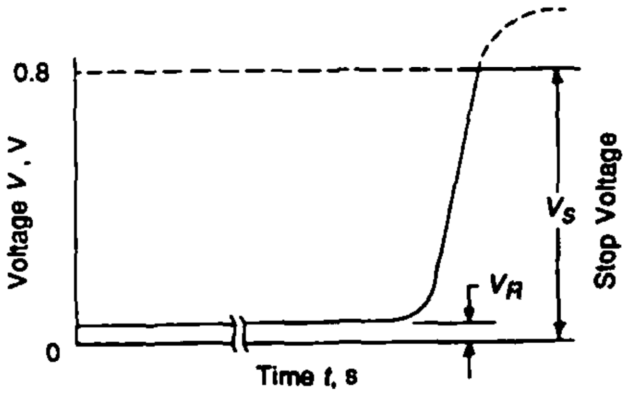
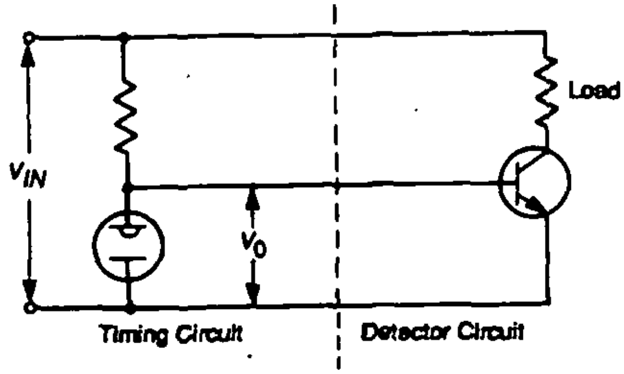


Figure 7-39. Bissett-Berman E-Cell (Ref. 18)



V_R = Run Voltage, V
V_S = Stop Voltage, V

Figure 7-40. Operating Curve of Coulombmeter at Constant Current (Ref. 18)



V_0 = Output Voltage
V_R = Running Voltage
V_R = V_0 While Running (Deplating)

Figure 7-41. Coulombmeter Detector Circuit (Ref. 18)

and its associated current. The stop voltage V_s is associated with the activation voltage threshold of the transistor, whereas the stop current I_s is the residual current passing through the cell.

The advantages of an E-cell electrical output coulombmeter are

1. Good accuracy (within ±4%)
2. Good miniaturization
3. Simplicity and inexpensiveness
4. Wide variety of timing intervals
5. Very low power requirements
6. Good shock and vibration resistance
7. Operation over the military temperature range
8. Repeated use (by deplating).

The disadvantages are

1. A power source and detector circuit are required.
2. There is decreased accuracy for short set times after long storage.

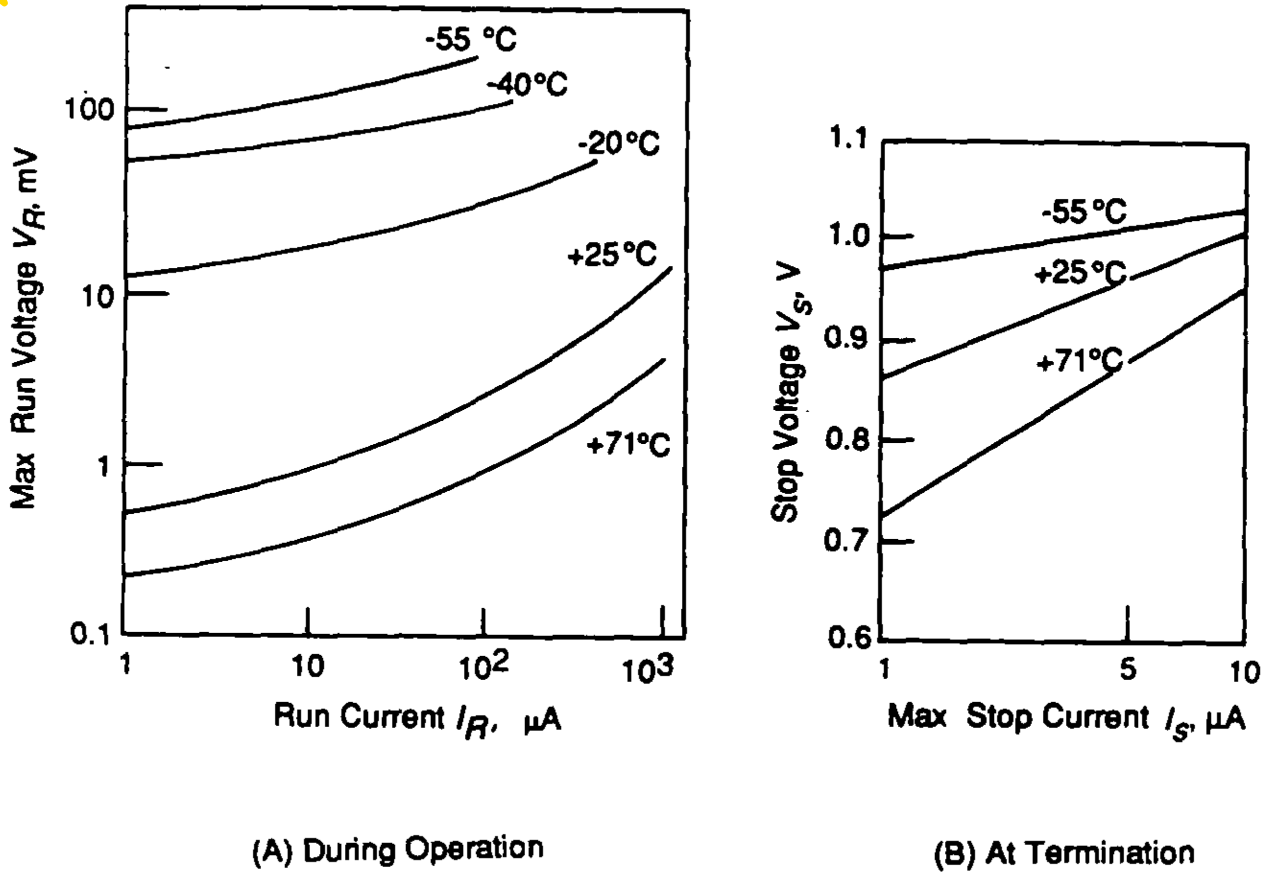


Figure 7-42. Typical E-Cell Coulombmeter Voltage-Current Characteristics (Ref. 18)

7-9.2 ELECTROPLATING TIMER WITH MECHANICAL OUTPUT

The mechanical output timer operates electrochemically in the same manner as the electrical readout E-cell design. At the end of deplating, however, the action is mechanical switching rather than electrical. Fig. 7-43 illustrates the Internal Timer MK 24 Mod 3, which operates on this principle. The timer cell (based on a patented idea (Ref. 21)) consists of a molded polychlorotrifluoroethylene (Kel-F) cup, which holds the anode assembly. After it is filled with an electrolyte of a silver fluoroborate solution, the cup is heat sealed with an end plug, which holds the silver cathode. The anode assembly consists of a silver plunger to which a contact disk is fastened, and the plunger is surrounded by a compression spring and sealed with an O-ring coated with fluorosilicone lubricant. All materials were selected for their chemical compatibility with the electrolyte.

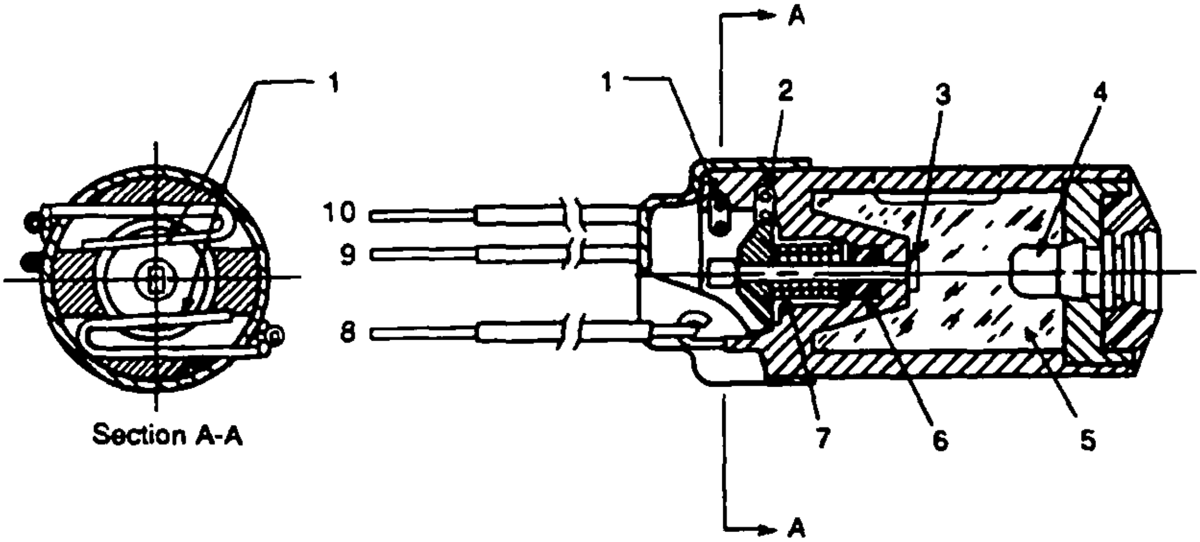
At the end of the timing interval, the anode plunger is pushed to the left. In its new position the contact disk closes a single-pole, single-throw (SPST) switch and opens the anode switch to terminate the deplating action. The contact force at switch closure is 3.6 N (0.800 lb), and contact resistance after switch closure is less than 0.3 Ω.

The timer is 15.88 mm (0.625 in.) in diameter, 41.3 mm (1.625 in.) long, and has a mass of 9 g (6.16×10^{-4} slug). Timer accuracy underwater (the designed-for condition) at −2.22° to 32.22°C (28° to 90°F) is ±5%. Over the entire military temperature range, the accuracy is ±10%. Models have withstood shocks as high as 12,000 g, low- and high-frequency vibrations, cold storage at −62.2°C (−80°F), and temperature-humidity cycling.

7-10 REDUNDANCY AND RELIABILITY TECHNIQUES

Par. 2-3 discussed ways in which reliability can be improved by parallel redundancy and listed a number of standards that address the subject of reliability. To achieve reliability in electronic fuzes, the designer has a number of techniques at his disposal (Ref. 22).

Because of the large number of variables involved, it is not feasible to assess precisely the relative merits of commercial parts versus parts that meet military specifications for any given situation. The designer must select these components based on which are the most technically sound and cost-effective for the design. To achieve this goal, the designer should



1	SPST* Switch Contacts	6	O-Ring Seal
2	Anode Switch	7	Compression Spring
3	Silver Anode	8	Lead From Anode and Second SPST Switch Terminal
4	Silver Cathode	9	Lead From First SPST Switch Terminal
5	Electrolyte	10	Lead From Cathode

* = Single-Pole, Single-Throw

Figure 7-43. Interval Timer MK 24 MOD 3 (Ref. 16)

1. Design for a minimum number of parts without degrading performance.
2. Apply derating techniques.
3. Perform design reliability analyses.
4. Reduce operating temperature by providing heat sinks and good packaging.
5. Eliminate vibration by good isolation and protect against shock, humidity, corrosion, etc.
6. Specify component reliability and burn-in requirements.
7. Specify production quality requirements and system performance tests.
8. Use components whose important properties are known and are reproducible.
9. Use techniques that interrogate fuze operation prior to launch whenever possible.

The quality of the parts used in a system is only one factor in the overall reliability equation, albeit a very significant influence (Ref. 23). The logical starting point in the creation of a reliable system is obviously high-quality parts. There are measures, however, that can compensate, at least partially, when circumstances militate against procurement of parts that fully conform to the most rigorous standards. Such measures include, but are not limited to, more exacting quality assurance provisions at assembly levels during fabrication, and properly designed assembly and end-item level screening and acceptance tests. If these techniques do not sufficiently reduce the component or system failure rate, redundancy, or standby, systems can be used.

The designer of electronic fuzes often must decide whether to use commercial parts or parts that meet military specifications in the electronic design. For example, in high-value weapon systems, the use of higher grade electronic components is mandatory, and the designer must comply or must justify the rationale for his noncompliance. In general, the cost of higher grade discrete components, e.g., resistors, capacitors, and transistors, is not significantly greater than that for commercial grade. The biggest cost differential is in the plastic versus ceramic IC components. For example, a ceramic IC that meets military specifications can cost as much as forty times that of an identical screened plastic IC. Ceramic ICs, however, have the following advantages:

1. The seal is hermetic, so it protects the chip from the deleterious effects of moisture.
2. They are capable of operating at very high temperatures, e.g., 125°C (257°F).
3. They have a lower mean-time-before-failure rate than plastic because of more extensive mechanical and electrical testing.

Disadvantages of military-grade, high-reliability ceramic ICs are