

Thus we obtain for the different approximation values N_2/N_1 :

$$\frac{A}{A'} = \frac{1}{1} = 1$$

$$\frac{B}{B'} = \frac{3}{4} = 0.75$$

$$\frac{C}{C'} = \frac{4}{5} = 0.80$$

$$\frac{D}{D'} = \frac{15}{19} = 0.7894736$$

$$\frac{E}{E'} = \frac{34}{43} = 0.7906976$$

$$\frac{F}{F'} = \frac{49}{62} = 0.7903225$$

$$\frac{G}{G'} = \frac{83}{105} = 0.7904762$$

$$\frac{H}{H'} = \frac{132}{167} = 0.7904191$$

$$\frac{I}{I'} = \frac{347}{439} = 0.7904328$$

16-3.6.2 Brocot's Approximation Method

Example as above: $i = \frac{347}{439} = 0.7904328$.

From the table we obtain the two approximation values

$$\frac{34}{43} = 0.7906976 \text{ and } \frac{49}{62} = 0.7903225$$

of which the one is greater and the other smaller than the exact value 0.7904328. It may be seen that these approximation values also can be obtained without the table. They

are contained in the procedure using continued fractions (row E/E' and F/F'). Actually, Brocot's method represents an expansion of teeth number determination by continued fractions.

We let

$$\frac{34}{43} = \frac{a}{b} \text{ and } \frac{49}{62} = \frac{c}{d}.$$

These two approximation values show a difference ϵ_i in comparison to the exact value of:

$$\frac{a}{b} - i = \epsilon_1 \text{ and } i - \frac{c}{d} = \epsilon_2$$

From values b , d , ϵ_1 , and ϵ_2 one forms the quotient

$$k = \frac{d \epsilon_2}{b \epsilon_1},$$

which at first yields a double fraction (numerator and denominator decimal fraction). This double fraction is expanded by 10, 100, etc. so that numerator and denominator become a low decimal number > 1 , which after division by each other would yield the value k_1 . By rounding off (or possibly by additional increase by one of both numerator or denominator) one finally obtains an ordinary fraction x , which is used to calculate the corrected value

$$i = \frac{ax + c}{bx + d}$$

which, upon suitable selection of x , approximates considerably closer the original i -value than the two original approximation values a/b or c/d .

As applied to our example

$$\begin{aligned} \epsilon_1 &= \frac{a}{b} - i = 0.7906976 - 0.7904328 \\ &= 0.0002648 \end{aligned}$$

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$$\epsilon_2 = i - \frac{c}{d} = 0.7904328 - 0.7903225 \\ = 0.0001103$$

$$k = \frac{62(0.0001103)}{43(0.0002648)} \approx \frac{6.8}{11.4}$$

For $x = 7/12$ we obtain

$$i = \frac{34(7) + 49(12)}{43(7) + 62(12)} = \frac{14(59)}{19(55)} = 0.7904305.$$

Since Brocot's table is calculated only for true fractions whose numerators and denominators go no higher than 99 (two-place numbers), one can carry the approximation even farther by selection of even higher-place fractions as provided by the continued fraction method (e.g., F/F' and G/G' or G/G' and H/H' as limits).

The difference in comparison to the true value $i = 0.7904328$ when using continued fractions is for

$$F/F' = \frac{49}{62} (0.0001103)$$

$$G/G' = \frac{83}{105} (0.0000434)$$

$$H/H' = \frac{132}{167} (0.0000237)$$

and according to Brocot's method is 0.0000022. In the last case two gear elements also are required.

16-3.7 GEAR TRAIN DESIGN

The design of gear train for a timer depends on the time interval to be measured. The following equation can be used to determine the gear train ratio

$$\chi = \frac{f_n t 360}{\theta N_w} \quad (16-10)$$

where

f_n = natural frequency of pallet operation, Hz

t = functioning delay, sec

θ = required angle for last pinion, deg

N_w = number of teeth on the escapement wheel

χ = gear train ratio, reciprocal of gear velocity ratio i

N_w should be designed to place a maximum number of teeth on the escape wheel within the predetermined limits of the moment of inertia of the escape wheel. The natural frequency of the escapement system f_n should be as high as possible for increased resolution; and t is determined by the specifications placed on the timer.

After the gear train ratio is determined, the train can be designed so as to fit into the available space using a minimum of gears to reduce friction losses and inertia of the system.

16-4 ESCAPEMENTS

The escapement is the part of a mechanical clockwork which regulates the transmission of energy. The rate of energy release can be controlled by either a two-center untuned escapement or by a tuned escapement of two or three centers.

16-4.1 UNTUNED TWO-CENTER ESCAPEMENT

Known variously as a runaway escapement, verge escapement, or inertial governor, the untuned two-center escapement (Fig. 16-22¹³) is an inertial system that lacks the resonance characteristics of the spring-mass type of timing escapement. In order to rotate,

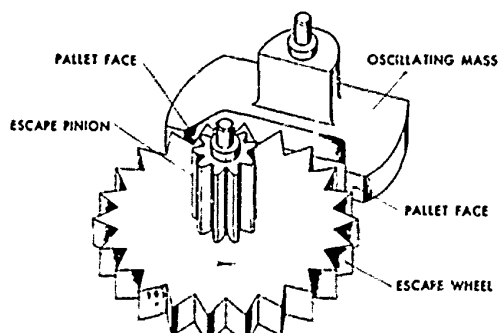


Figure 16-22. Runaway Escapement, Flat Pallet Faces

the escape wheel (sometimes referred to as the starwheel) must drive an inertial mass alternatively clockwise and counterclockwise. The direction of rotation of the inertial mass changes each time a tooth of the escape wheel passes by one of the two contact surfaces on the oscillating mass. These contact surfaces, called the "pallets" or "pallet faces", are contacted alternately by the escape wheel teeth, thereby producing the oscillatory motion of the mass. The mass itself often is referred to as the pallet. This continuous reversal of the rotational direction of the mass results in a drag that resists the input torque (energy is lost primarily by collision), and the average rotational velocity of the escape wheel becomes a function of the torque. The escapement, therefore, provides a useful timing function if the driving torque has acceptably small variations in its magnitude. The period T for one rotation of the escape wheel is approximately

$$T = \frac{k}{\sqrt{G}}, \text{ sec} \quad (16-11)$$

where

G = input torque, lb-in.

k = system constant, (in.-lb)^{1/2}-sec

This escapement commonly is used in two

forms. One has an escape wheel and oscillating mass combination of the type shown in Fig. 16-22 where the teeth of the escape wheel engage the flat pallet faces formed by a special configuration of the mass. The other form, shown in Fig. 16-23^{1,3}, has a pin pallet. The escape wheel engages pallet faces formed by two pins that project from the oscillating mass perpendicular to its plane of oscillation. This second type is preferred by some designers who believe that the pin location is controlled more easily in production, providing better control of the geometrical position of the pallets. However, it is less reliable because a pin may be missing or bent.

16.4.1.1 Factors Affecting Escapement Operation

The following variables affect the running rate of a runaway escapement:

- (1) Net driving torque (input torque less output load)
- (2) Change in the geometrical relationship of the pallet and escape wheel (due to wear or manufacturing variations)
- (3) Gear train and escapement tolerances
- (4) Friction

All effects considered, typical lot-to-lot error for movements regulated with this type of escapement is usually within $\pm 15\%$ when operating over the military temperature range, -70° to 125°F .

The timing error can be reduced to $\pm 5\%$ with tight tolerances, good quality control, individual adjustment of the output angle of rotation to match a particular escapement rate, individual adjustment of balance inertia, and constant output load.

The frequency f_n of pallet oscillation may be calculated from the net driving torque (Eq.

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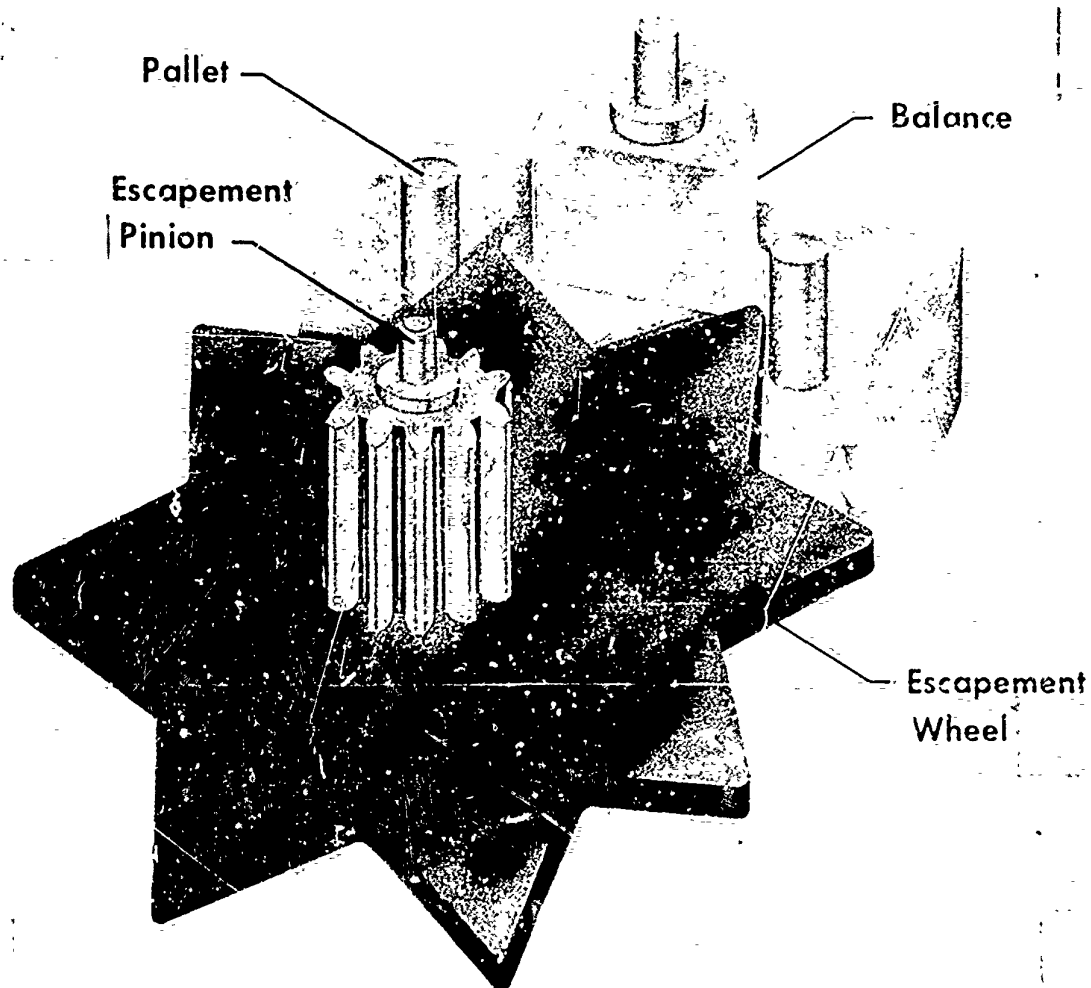


Figure 16-23. Runaway Escapement, Pin Pallet Type

16-12) on the escape wheel if the following assumptions are made¹:

(1) Half cycles of the pallet are equal in time.

(2) Driving torque is constant.

(3) Impact is inelastic.

(4) Friction is negligible.

$$f_n = \frac{1}{2\pi} \sqrt{\frac{Gr_p/r_w}{2I_m \theta}}, \text{ Hz} \quad (16-12)$$

where

G = net driving torque, lb-ft

r_p = radius of pallet pin, in.

r_w = radius of escape wheel, in.

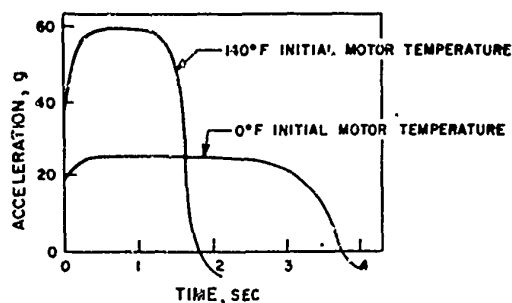


Figure 16-24. Typical Rocket Accelerations

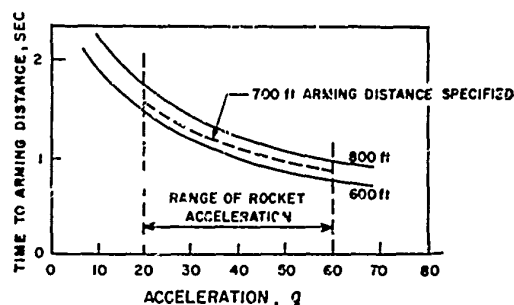


Figure 16-25. Variation in Rocket Arming Time

θ = angle between extreme positions of pallet, rad

I_m = moment of inertia of oscillating mass of pallet, slug-ft²

Thus the frequency varies as the square root of the escape wheel torque, or damping force is proportional to the square of the escape wheel angular velocity. When designing a gear train, the designer must remember that G is the actual torque delivered rather than the theoretical torque. (Use 30% of the theoretical torque as a first approximation.)

16-4.1.2 Runaway Escapement Applied to Rocket Fuze

As an example, let us investigate the problem of arming a rocket fuze at 700 ± 100 ft from the launcher. For safety, the fuze must not become armed until the rocket has traveled a certain minimum distance.

Inasmuch as measuring this distance directly is a difficult if not impossible task, a timing interval is measured in a manner that is related directly to distance. If the speed of the rocket were constant, a timing device would suffice. The timing devices for arming artillery projectiles can be applied with reasonable confidence, but the behavior of rockets is too variable to measure arming distances with timing devices even if all rockets performed normally.

This variability in behavior of rockets can be illustrated by the influence of rocket motor temperature (at time of firing) upon the acceleration (see Fig. 16-24¹). Other factors such as air density can have pronounced effects on the acceleration-time diagram.

Fig. 16-25¹ shows that the arming time must vary with the acceleration of the rocket if the arming distance is to be held within the specified tolerance.

A solution to this problem can be to use a runaway escapement. Using the acceleration of the rocket as a source of power to drive the escapement, the escapement can be designed to effect arming in the same distance even though the acceleration varies. Fig. 16-26¹ shows a device in which the torque applied to the escapement will be proportional to the setback acceleration.

The time to arm t can be expressed as

$$t = \frac{1}{k'f_n}, \text{ sec} \quad (16-13)$$

because it depends upon the number of oscillations of the pallet and thence upon its frequency f_n . The distances that the rocket will travel during the arming time is

$$s = \frac{1}{2} at^2 \quad (16-14)$$

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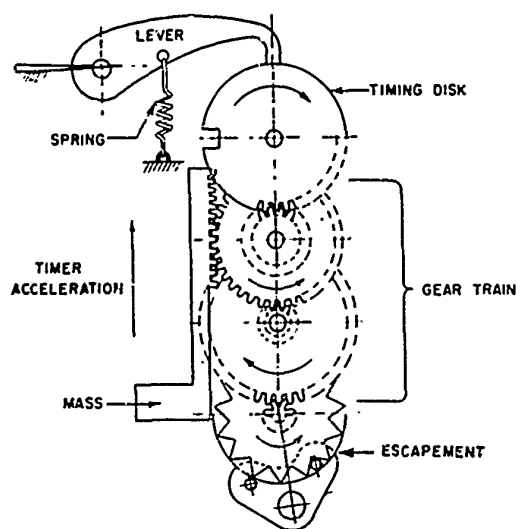


Figure 16-26. Runaway Escapement

The torque G is given by

$$G = m a r_w k'_1 \quad (16-15)$$

where

m = mass of the driving rack (Fig. 16-26), slug

a = acceleration of the rocket, ft/sec²

r_w = radius of the escape wheel, ft

k'_1 = ratio of number of teeth of driving gear and escape wheel

Combining Eqs. 16-12 to 16-15 results in

$$s = \frac{4\pi^2 I_m \theta}{k'^2 m k'_1 r_p} = k'_2, \quad (16-16)$$

in which all terms of definition are independent of the rocket ballistics.

The runaway can be employed to establish a constant arming distance in this circumstance. However, the analyses assumed that for any one rocket the acceleration during

flight would be constant which is not necessarily true. Some rocket motors exhibit characteristics that make the rocket accelerations vary with time. Fortunately, the arming distance is only moderately affected as shown in Eq. 16-17.

$$s = k'_2 + \frac{1}{k'_3 a^3}, \text{ ft} \quad (16-17)$$

Since both k'_3 and a are large compared with k'_2 , the second term becomes insignificant.

Eq. 16-12 describes an idealized device and cannot account for effects of friction or materials. For a particular one-second timer, the empirical equation for the average angular velocity ω of the escape wheel is given by¹

$$\omega = \frac{0.231 I_w^{0.112} G^{0.5}}{I_m^{0.012}}, \text{ rad/sec} \quad (16-18)$$

where

I_w = moment of inertia of escape wheel, slug-ft²

I_m = moment of inertia of oscillating pallet, slug-ft²

G = torque, lb-ft

This is the same form as Eq. 16-12 because

$$f_n = N_w \omega / (2\pi), \text{ Hz} \quad (16-19)$$

where N_w is the number of teeth on the escape wheel. The constant coefficient (0.231) was found to depend upon various factors: center-to-center distance between escape wheel, friction in the gear train, and number of times that the mechanism had been "run down".

16.4.1.3 Dynamics of Runaway Escapement

There has been considerable analytical

work done in the dynamics of this type of escapement¹⁴. Three conditions of pallet wheel motion were studied. These include (1) cycle of no free motion, (2) cycle of no contact motion (all free motion), and (3) cycle of half free motion half contact motion.

The effect of geometrical factors upon the behavior and nonuniformity of running rates of this system was investigated¹⁵. Some of the results of this study were:

- (1) Variations in apparently identical pallets may cause variations in period of as much as 0.13 sec.
- (2) Variation in period introduced by different starwheels and drive springs is negligible.
- (3) The factors in the pallet that caused radical changes of period are the shape and location of the leading pallet face.
- (4) A change of 0.002 in. in the center-to-center distance of pallet and wheel results in a change of period of 8%.
- (5) Friction is most important in the drive springs, and oiling the pallet surfaces strongly decreases the period.
- (6) Physical smoothness of shafts, pallet faces, shoulders, or bearing holes is of negligible importance in affecting the period.
- (7) Torque delivered at the escape wheel may vary greatly because of frictional effects from mechanism to mechanism.
- (8) If a mechanism has been dormant for some hours or days, its period is large when first rerun and then decreases to the constant period.
- (9) The nominal delay time may vary as much as 5% depending upon the operating positions.

16-4.2 TUNED TWO-CENTER ESCAPEMENTS

The tuned escapement is the part of a timing device that (1) counts the number of oscillations executed by the oscillating mass (pallet) and (2) feeds energy to its pallet. The pallet controls the rotation of the escape wheel while it receives energy that maintains its oscillations. Since the pallet teeth trap and release escape wheel teeth, the rotation of the escape wheel depends upon the frequency of oscillation of the pallet.

These escapements consist of a combination of a pivoted balance and a mass-restoring spring pulsed twice per cycle by an escape wheel. The axis of the escape wheel and balance mass pivot are usually parallel. The basic idea behind these, and all tuned escapements, is that the balance mass-restoring spring system has a natural frequency to which energy must be delivered so as to maintain the oscillation and alter the natural frequency as little as possible. These escapements might be classed in two groups, dead-beat and recoil. In dead-beat escapements, the escape wheel rests motionless against the locking face of the pallet. During the "free swing" phases of the cycle there is firm contact between escape wheel tooth and pallet except during the impulse, and catch-up phases. In recoil escapements almost all tooth action consists of impulse except for short angular displacements immediately after impacts where there may be a slight recoil of the escape wheel. Further discussion on the escapements follows:

(1) *Dead Beat Escapement.*

The original escapement of the dead beat type is the Graham dead-beat escapement used in pendulum clocks. To make this escapement suitable for military use, the number of teeth enclosed by the pallet was reduced to three and the impulse face was relocated to the escape wheel tooth. The resulting Junghans escapement is discussed in par. 16-4.2.1.

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Another form of dead beat escapement is the cylinder escapement where the pallet is formed by removing a small section of a full cylinder and only one tooth is enclosed. Cylinder escapements are discussed in par. 16-4.2.4.

(2) *Recoil Escapement.* Recoil escapements in their classical form are not used in military mechanisms. There are some almost dead beat escapements that exhibit small amounts of recoil. The escape wheels—in another class of escapements that might be classed in this category—always drive, supplying too much torque to permit any recoil. They really are tuned runaways and are not very accurate, but are highly reliable and are suitable for some safing and arming mechanisms. A good example of this is the normal Junghans escapement operated backwards.

16-4.2.1 Junghans Escapement

The principal tuned two-center escapements used in mechanical time fuzes in this country are forms of an escapement originally designed by Dr. Ing. Junghans of Germany during World War I. The advantages of this escapement are its relatively simple construction, ability to withstand extreme environments (ruggedness), and its inherent high frequency of oscillation.

Basically, the Junghans system consists of an escapement lever (the oscillating mass) with a beam escapement spring and an escape wheel (see Fig. 16-27¹⁶). The lever is made of spring steel and formed as shown. The pallet is an integral part of the lever and is ground accurately to shape. Small weights sometimes are fastened to the lever arms in order to obtain the desired inertia for the spring-mass system. The arbor, to which the lever is staked, provides its pivots and also secures the escapement spring. While the escapement spring is fixed to the arbor near or at its midpoint, both of its ends are supported simply by guides. The position of the guides is

made adjustable so that the timing mechanism can be regulated to the design frequency thereby compensating for small material and manufacturing variations from unit to unit. The escape wheel is made of thin brass or beryllium copper and usually has 20 teeth on its periphery, three of which are enclosed by the lever pallets during operation. The wheel teeth are so shaped that, as the escapement wheel is rotated, the lever is caused to oscillate which in turn imparts intermittent rotation to the wheel. The normal mode of operation of the Junghans original escapement was dead beat, i.e., the escapement wheel stops and does not reverse its motion.

Fig. 16-28(A) shows tooth A falling on pallet tooth A'. In Fig. 16-28(B) the lever is passing through the equilibrium point in its oscillation where tooth A is about to be released by the pallet. In Fig. 16-28(C) the escape wheel tooth C is the opposite part of the cycle. If the line of action of the impulse passes through the pivot of the lever, its motion will not be altered. As pallet tooth B' slides beneath tooth C, the escape wheel stops. In Fig. 16-28(D) the lever has returned to its equilibrium position and is being driven by the escape wheel as shown in Fig. 16-28(B). If the energy is added as the pallet passes through its equilibrium position, the frequency of the oscillating mass (regulator) is least affected.

Neglecting for the moment the interaction of the escapement wheel and pallets, the effects of variable driving torque, etc., the natural frequency f_n —from elementary theory for a spring-mass vibrating system—neglecting friction, is

$$f_n = \frac{1}{2\pi} \sqrt{\frac{12k}{I_m}} = \frac{1}{\pi} \sqrt{\frac{3k}{I_m}}, \text{ Hz} \quad (16-20)$$

where

k = torsional spring constant, lb-in./rad

I_m = moment of inertia of the oscillating system, slug-in.²

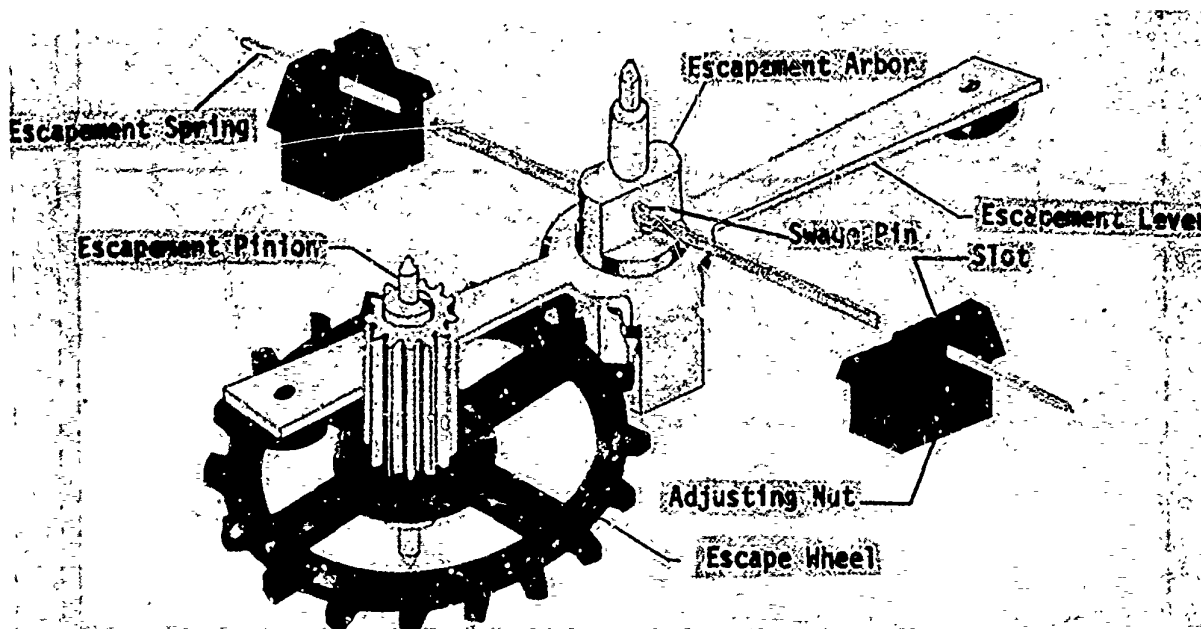


Figure 16-27. Standard Junghans Type Escapement

For the beam hairspring of a Junghans system with equal setting of guides (for small spring deflections)

$$k = \frac{12EI_A}{\ell}, \text{ lb-in./rad} \quad (16-21)$$

where

E = Young's modulus of the spring, lb/in.²

I_A = moment of inertia of the cross-sectional area of the spring, in.⁴

ℓ = total length of spring (twice length between arbor and guide), in.

thus

$$\begin{aligned} f_n &= \frac{1}{2\pi} \sqrt{\frac{12EI_A \times 12}{\ell I_m}} \\ &= \frac{6}{\pi} \sqrt{\frac{EI_A}{\ell I_m}}, \text{ Hz} \end{aligned} \quad (16-22)$$

For large deflections, the value of k is a function of escapement lever amplitude. A numerical solution for the nonlinearities is available¹⁷.

If the beam spring is replaced with a torsion bar

$$f_n = \frac{d^2}{8} \sqrt{\frac{12G}{2\pi \ell I_m}} = \frac{d^2}{8} \sqrt{\frac{6G}{\pi \ell I_m}} \quad (16-23)$$

where

G = shear modulus of elasticity, lb/in.²

d = diameter of the torsion bar, in.

ℓ = free length of the torsion bar, in.

I_m = moment of inertia of the cross-sectional area of the torsion bar, slug-in.²

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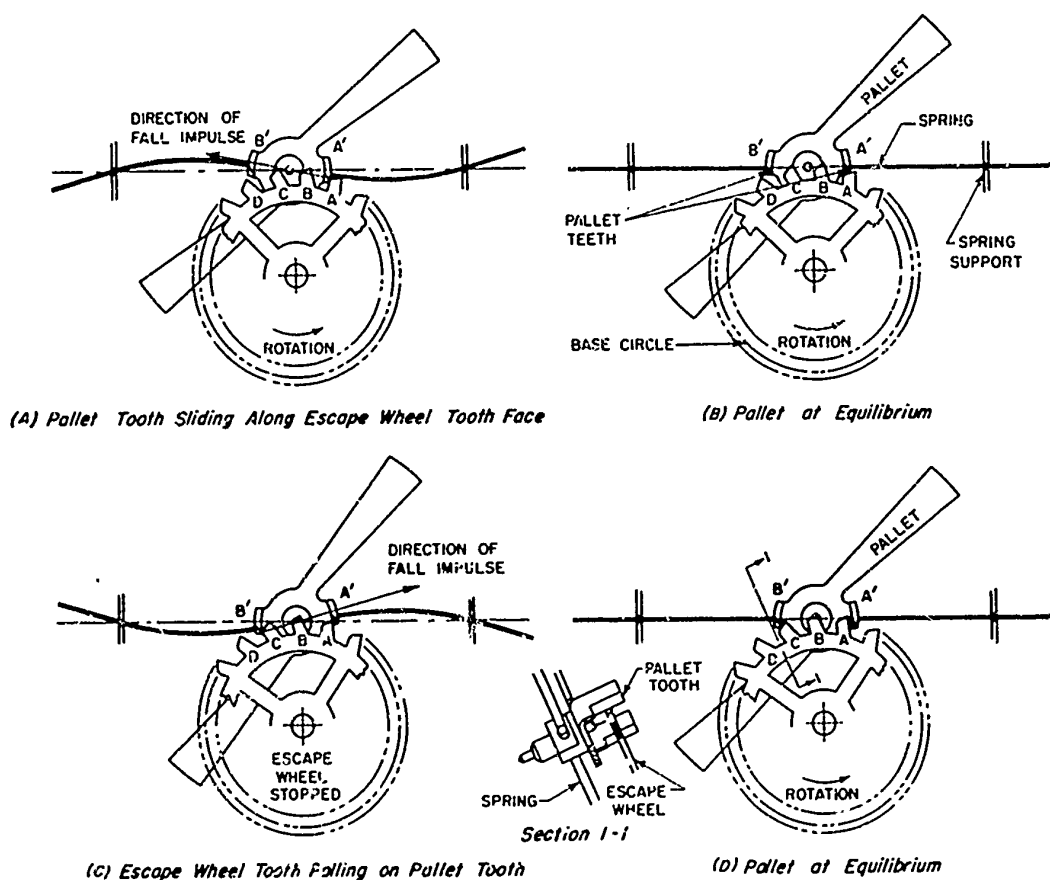


Figure 16-28. Action of Junghans Escapement

A typical experimentally determined frequency vs torque curve for a fuze movement containing a Junghans escapement is shown in Fig. 16-29¹⁸. Although this curve varies from movement to movement within a given lot of fuzes, the general shape of the curve is the same for all Junghans escapements.

Some preliminary analytical work indicates that the torque dependence on frequency can be expressed in the following form¹⁸

$$\frac{\Delta f}{f} = a \left[c^2 - \frac{(bG + c)^3}{(1 + b)G} \right] \quad (16-24)$$

where

a = constant dependent on escapement geometry

b = constant dependent on the friction coefficient between the tooth and pallet and on escapement geometry

c = constant dependent on pivot friction of the escapement lever

By examining Eq. 16-24 one can readily see the reasons for variations of frequency shift from movement to movement. Small changes

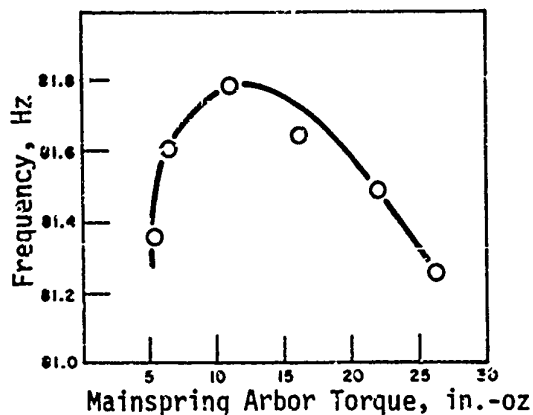


Figure 16-29. Junghans Escapement, Frequency-torque Curve

in c and b alter the value of $\Delta f/f$ appreciably. The relationship is especially sensitive to changes of c at low torque and to changes of b at high torques—i.e., at low torques, changes in pivot friction are critical; at high torques, changes in tooth friction are important. Since a larger random variation is expected of c rather than of b , the escapement is less stable at low torques.

The fundamental equation for the motion of the balance wheel neglecting the effect of friction is

$$\frac{I_m}{12} \left(\frac{d^2 \phi}{dt^2} \right) + k\phi = 0 \quad (16-25)$$

where

I_m = moment of inertia of balance wheel, slug-in.²

k = torsional spring constant, lb-in./rad

ϕ = angular displacement of balance wheel, rad, or

$\phi = A \cos(\omega T + \theta)$

A = amplitude, rad

ω = circular frequency, rad/sec

θ = phase angle, rad

T = period, sec

(A and θ are constants determined by the initial conditions)

$$\omega = \sqrt{\frac{12k}{I_m}} = 2\sqrt{\frac{3k}{I_m}} \quad (16-26)$$

$$T = \frac{2\pi}{\omega} = \pi \sqrt{\frac{I_m}{3k}}, \text{ sec} \quad (16-27)$$

The Junghans escapement has undergone many changes of an evolutionary nature since its introduction approximately forty years ago into the United States for use in artillery fuzes. Materials have been improved and more efficient processes have been used. Further a mainspring has replaced centrifugal weights, gear train values have been increased, and safety features have been added. Two such improvements are the Popovitch modification and the Dock modification which are described in the paragraphs that follow. Two additional modifications, proposed specifically to reduce spin sensitivity (E-K and PA systems), are discussed in par. 16-4.4.

16-4.2.2 Popovitch Escapement Modification

The Popovitch modification of the Junghans escapement is shown in Fig. 16-30¹. It uses two outboard springs instead of a spring fastened to the arbor. The modification reduces the spin sensitivity of the mechanism.

A mathematical analysis has been made concerning the feasibility of the Popovitch modification in the design of escapements for artillery fuzes¹⁹. This report shows the behavior of the spring, in its horizontal and vertical positions, under the influence of

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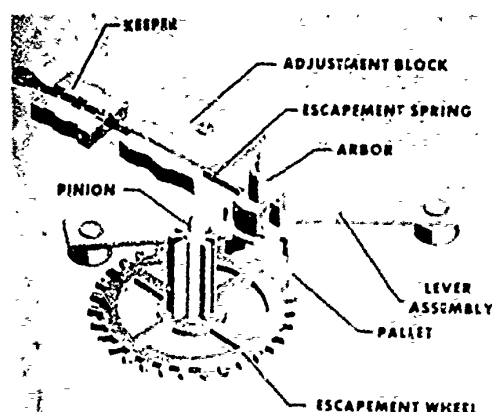


Figure 16-30. Popovitch Modification of Junghans Escapement

centrifugal and axial accelerations. Thermal expansion and gyroscopic effects also were considered in the analysis.

16.4.2.3 Dock Escapement Modification

The Dock modification is not directly concerned with the kinematical geometry of the escapement. It attacks the following problem: the natural frequency of the Junghans escapement changes in a spin environment because the spring must flex in a radial force field. The frequency change is proportional to the square of the spin speed. This is an appreciable effect. In addition to causing shifts in mean functioning time when the fuze experiences other than its regulation design spin, it also causes dispersion in functioning times. A large part of the timing variation of the Junghans escapement arises from this spin sensitivity (see par. 16-4.4).

In the Dock modification of the Junghans escapement the rectangular cross section spring is replaced by one of circular cross section (Fig. 16-31¹⁶). A reduction in spin sensitivity stems from this change alone. A

secondary benefit arises from the unique manner in which the round-wire escapement spring is fastened into the arbor. Fig. 16-32¹⁶ shows in detail how the springs in the Junghans (standard) and Dock (new) versions are held in the arbor, and also indicates the attendant changes to the adjusting nuts. In the standard design, the escapement spring is distorted badly in the neighborhood of the arbor, necessitating a manual straightening operation after the spring is pressed into place.

16.4.2.4 Cylinder Escapements

Cylinder escapements are relatively simple and inexpensive. They are not used in applications requiring extreme timekeeping accuracy. The timekeeping errors are, in general, one order of magnitude higher than the errors in a detached lever escapement. These errors are due mostly to the torque sensitivity of cylinder escapements, i.e., the beat rate is somewhat dependent on the value of the torque that drives the escapement.

Fig. 16-33²⁰ shows the essential components of a typical cylinder escapement. The escape lever is a cylindrical tube with part of the wall area cut away. It spans one tooth. The inertia of this lever and the coupled hairspring constitutes an oscillatory system that meters the speed of rotation of the escape wheel. This is done by allowing the escape wheel to advance one tooth for each complete cycle of oscillation of the escape lever. Fig. 16-34²⁰ shows the action sequence for this escapement.

The motion of the various parts of the cylinder escapement were analyzed using Newtonian mechanics and, since the coupled equations of the impulse are nonlinear, solutions were obtained by computer methods²¹. Figs. 16-35 to 16-41²⁰ give the results of the variation of several escapement parameters. The definition of the symbols appearing on the graphs are:

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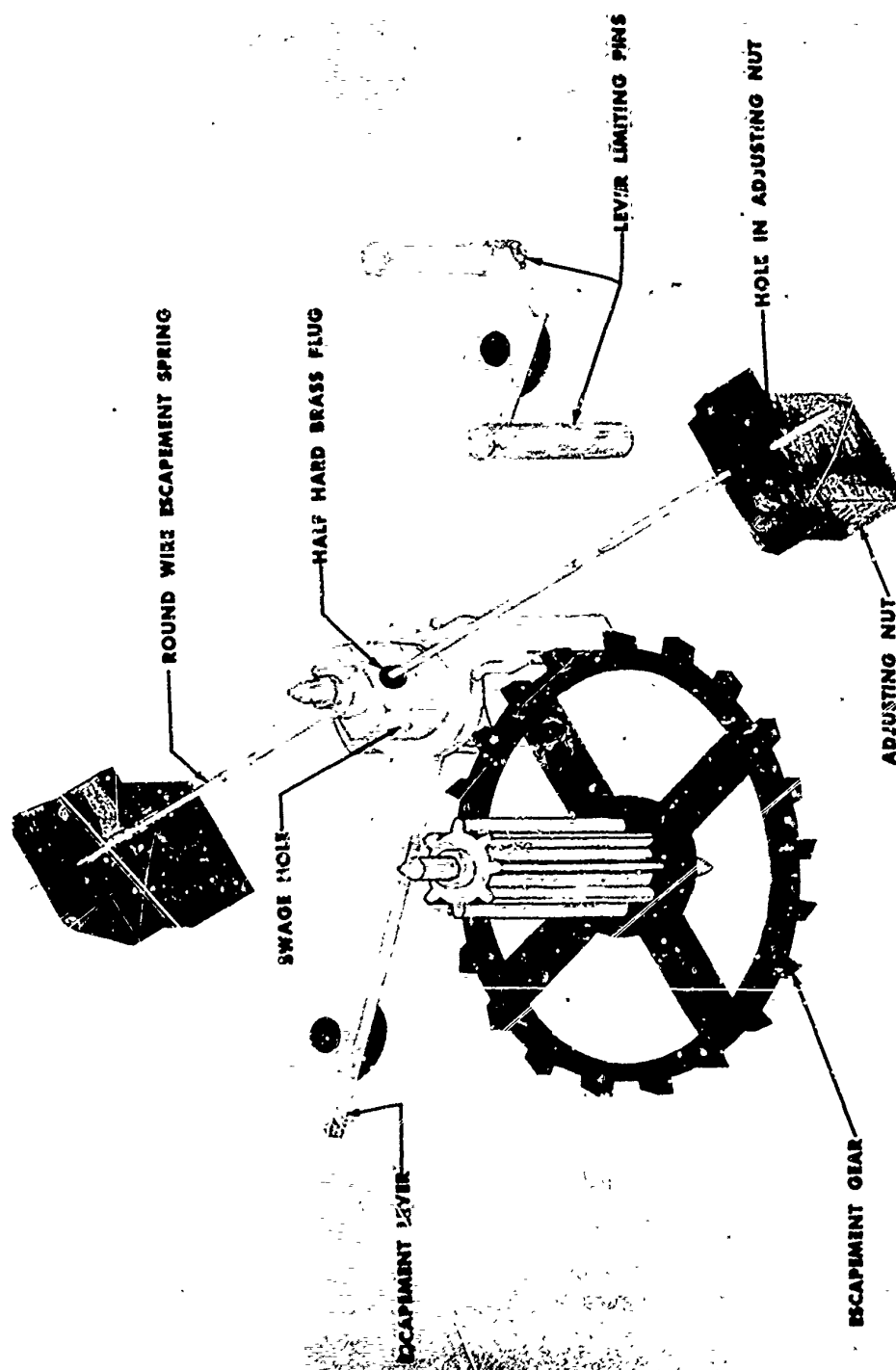
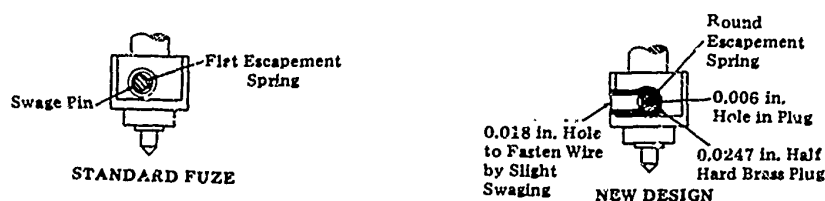


Figure 16-31. Dock Modification of Junghans Escapement

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(A) Escapement Arbor Showing New Configuration



(B) Adjusting Nut Showing New Configuration

Figure 16-32. Escapement Arbor and Adjusting Nut—Modified Configuration

μ_c = coefficient of friction at the pallet pivots

μ_p = coefficient of friction between escape wheel and pallet surface

BR = beat rate

BR_n = natural beat rate

J = ratio of escape wheel inertia to pallet inertia

G_s = drawing torque applied to escape wheel

k = torsional spring constant of pallet return spring

E = rebound coefficient, i.e., rebound velocity of pallet to the approach velocity

friction. The magnitude of this drag is determined by the coefficient of friction at the pivots, by the pivot diameter, and by the weight of the pallet. Study of the figures shows little change in performance as a result of changing the coefficient of friction.

Fig. 16-36 shows the variation introduced by differences in E . There is little or no

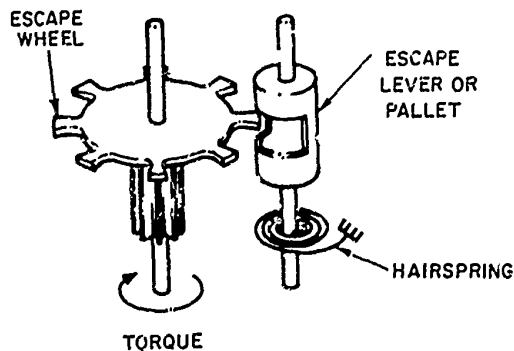


Figure 16-33. Cylinder Escapement Assembly

Fig. 16-35 shows the effect of variation of torsional drag on the pallet due to pivot

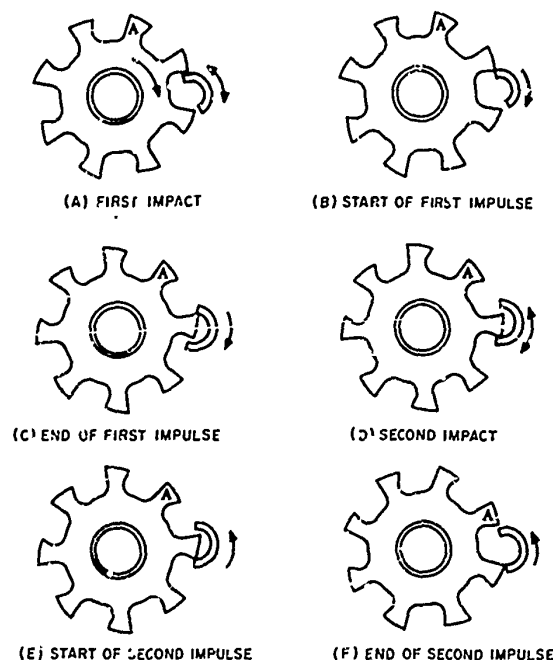


Figure 16-34. Action Sequence of Cylinder Escapement

sensitivity, for a change in E , in either timekeeping or amplitude properties.

Fig. 16-37 shows the results of varying the coefficient of friction μ_p . Both timekeeping and amplitude are highly sensitive to this friction. The magnitude of the friction is sensitive to influences such as temperature and loading pressure. The drooping tendency of the timekeeping curves is probably too severe because most lubricants show a smaller coefficient of friction as the loading pressure is increased.

From these results, the choice of an ideal lubricant for the pallet surface should be one which is temperature insensitive, load insensitive, and has as small a friction coefficient as possible (say about 0.1). In addition, the lubricant should have wear resistance, chemical stability, and be immobile. The temperature sensitivity problem may be solved by selecting a lubricant whose coefficient is not sensitive over the required operating range.

Fig. 16-38 shows the effect of varying the ratio J . It is evident that a minimum of escape wheel inertia should lead to good timekeeping and at the expense of good timekeeping, increased pallet inertia could be used to control pallet amplitude.

A real problem in production is the variation of center distance. Fig. 16-39 shows the performance changes that occur as a result of center variations. Even though little sensitivity is indicated in the figure, experience says otherwise. A possible cause of the observed sensitivity may be rapid change of direction of the common normal to the contacting surface of escape wheel and pallet.

If the escape wheel tooth lift is increased, there tends to be a slight flattening of the timekeeping curves as well as some increase in amplitude as lift is increased (see Fig. 16-40).

The degree to which the escapement is "cut of beat" is defined as the alignment error and is the parameter that is varied in

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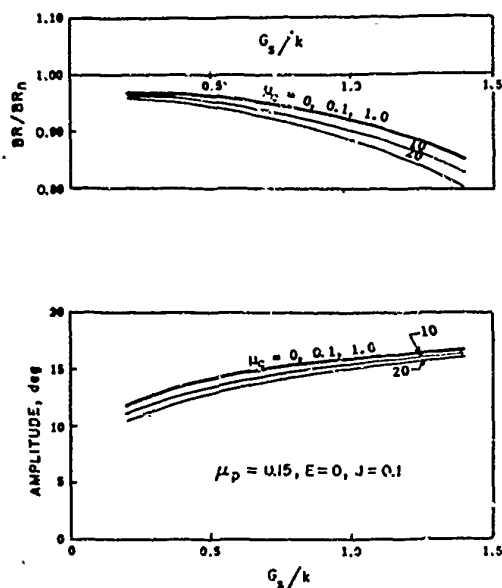


Figure 16-35. Pivot Friction Variation

Fig. 16-41. The figure shows that alignment errors—if they are small (2 or 3 deg)—have little effect but greater errors cause timekeeping degradation, increased torque sensitivity, and a lessening of the total range of torque over which the escapement will operate.

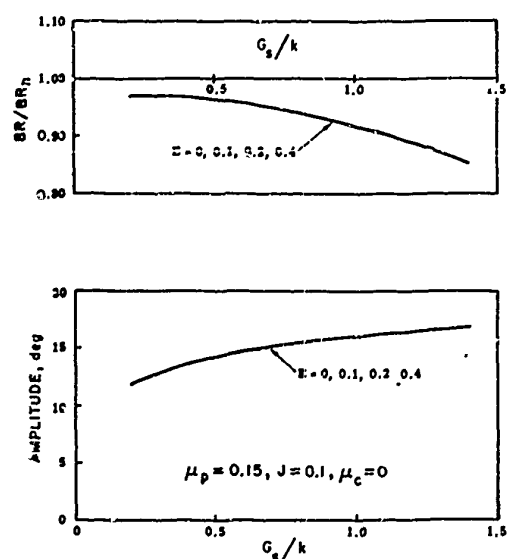


Figure 16-36. Rebound Coefficient Variation

Further work on the cylinder escapement indicates that the major contributor to torque sensitivity is the frictional drag between the pallet and escape wheel during the sliding phase of motion²⁰. Possible improvement could be made by designing a recoil pallet that causes the escape wheel to back up slightly as the pallet moves into engagement. The energy that was extracted from the pallet due to recoil during engagement is restored to the mainspring and, during disengagement, it is returned to the pallet. This causes a negative drag that acts to cancel part of the positive drag. If these two effects could be proportioned properly, better timekeeping would result.

16-4.2.5 Escapement Self-starting Capability

This capability refers to the ability of the escapement to start the oscillator moving, without an external force, from any rest position and to sustain the oscillations as long as energy is supplied. Self-starting capability is

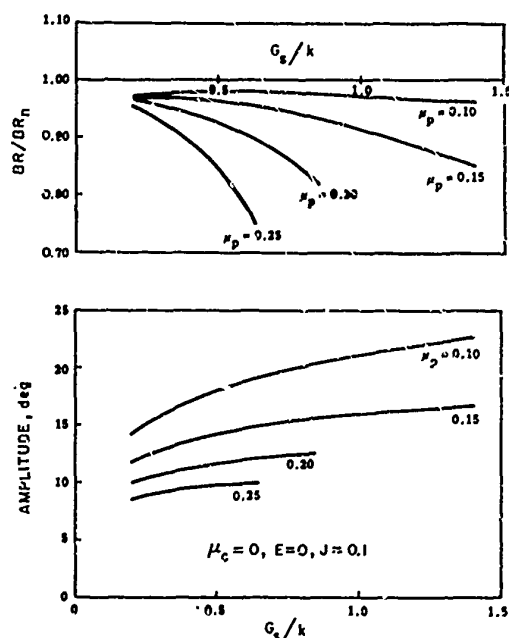


Figure 16-37. Pallet Friction Variation

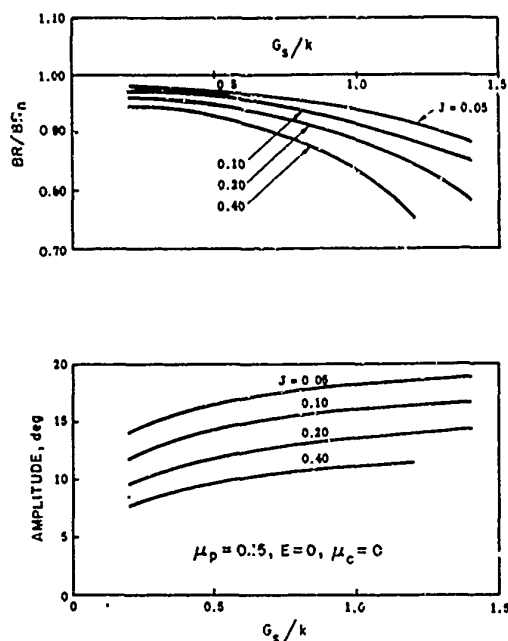


Figure 16-38. Inertia Variation

of great importance in many military applications.

Some escapements have dead spots or rest positions in which they will remain at rest, even when energy is being supplied, if they are allowed to stop in these positions. Restarting then requires an external distur-

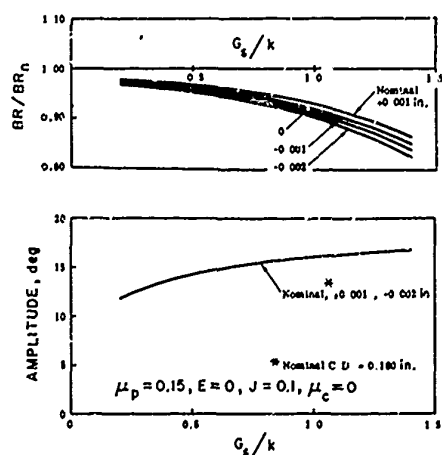


Figure 16-39. Center Distance Variation

bance. This is not a factor with the untuned two-center escapements that have no dead spots and are, therefore, inherently self-starting.

Some nonself-starting escapements can be made self-starting by putting them out of beat, i.e., making the relaxed position of the oscillator one other than that which is desirable for the best timekeeping accuracy. Another approach is to modify the tooth profile (see par. 16-3). However, care must be taken not to cause frictional drag. Gear trains can become self-locking due to friction (see par. 16-3.4).

An experimental and theoretical study was made of a variation of the Junghans system with a view to improve the self-starting capability²². The nonlinear equations of motion for the impulse phase are derived on the basis of energy considerations and are used to determine the relationships between escapement frequency and input drive torque. Experimental studies of frequency vs torque are described, and the test data are found to correlate reasonably the results of the theoretical investigation.

16-4.3 TUNED THREE-CENTER ESCAPEMENTS

Tuned three-center escapements, which exist in several forms, have the following principal common characteristics that distinguish them from two-center escapements:

- (1) There are three in lieu of two pivot centers.
- (2) The oscillating balance is free (detached) of the escapement through as much as 85% of its swing, whereas in two-center escapements the balance is essentially never free from the escapement.
- (3) Their timekeeping properties are improved significantly over two-center escapements.

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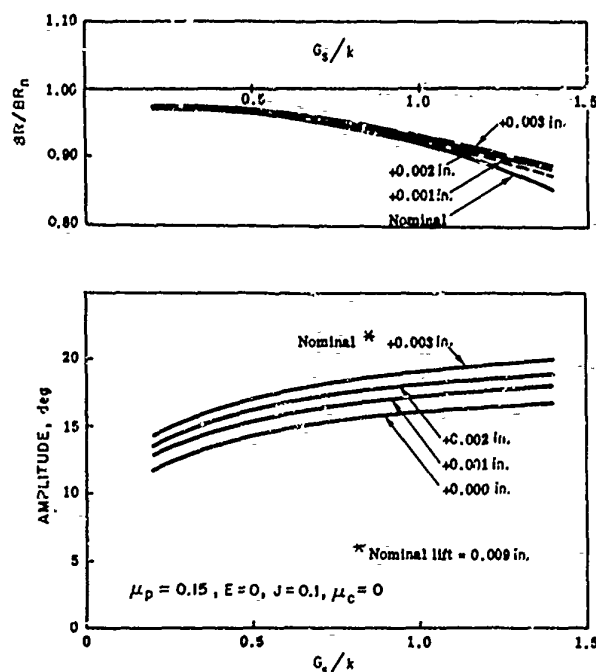


Figure 16-40. Variation of Lift

(4) The power requirements are minimal due to high operational efficiency.

(5) They are suited ideally to long runs because of their low natural frequency of oscillation.

The idea behind three-center or detached lever escapements is that an intermediate link between the escape wheel and the oscillating mass (balance) permits delivery of the impulses in a more precise manner, and also minimizes the drag torque imposed on the balance by the escape wheel.

The detached lever is capable of much greater accuracy and can be used for longer time delays than any other frictional movement. The poorest escapements are capable of accuracies of ± 0.1 to 0.2% while the best are capable of attaining accuracies of about $\pm 0.005\%$. The fundamental equations for the motion of the balance are the same as those

for the tuned two-center escapements (see Eqs. 16-25 to 16-27).

The detached lever escapement operates as follows: one end of a pivoted lever acts by means of two pallets in conjunction with the escape wheel; the other end acts on the balance. There are many slightly different versions of this escapement. The differences are in tooth shape and number, pallet design, lever ratio, fork geometry, etc. The escape wheel teeth are sometimes given a negative draw to improve reliability and give a self-starting feature but this destroys the detached lever characteristics because there is then a friction drag on the balance. For military applications, the amplitude may be reduced to permit higher frequencies. Both of these modifications tend to reduce the accuracy of the escapement.

Figs. 16-42¹³ and 16-43¹³ show the two main forms of the detached lever escapement,

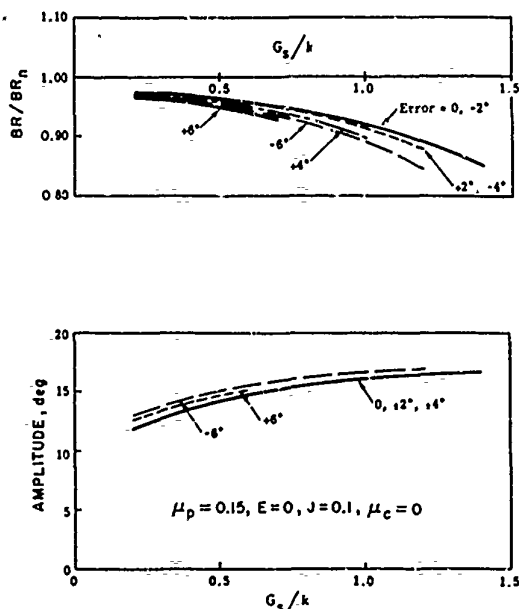


Figure 16-41. Alignment Error Variation

namely, the club-tooth type and the pin-pallet type. The pin-pallet escapement uses pins as pallets, and the impulse is entirely on the escape wheel tooth. This type is least expensive, rugged, and easiest to manufacture.

Detached lever escapements require a small

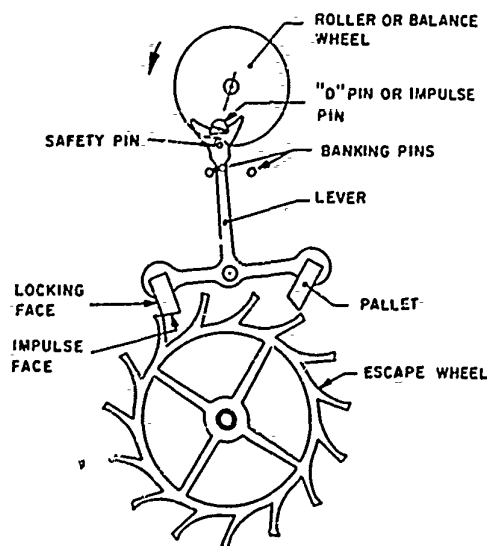


Figure 16-12. Detached Lever Escapement, Club Tooth Type

safety lever and roller on the balance staff (Fig. 16-43), and a pin on the lever to prevent unlocking the lever in the event the escapement receives a shock during the free motion of the balance wheel. In pin-pallet escapements, banking pins often are omitted and the pins are allowed to bank on the root diameter of the escape wheel.

The action of these escapements is as follows:

(1) The balance wheel travels in the direction indicated by the arrow (Fig. 16-42) with sufficient energy to cause the impulse pin to move the lever and pallet far enough to release the escape wheel tooth from the locking face, and allow it to enter on the impulse face of the pallet.

(2) The escape wheel, driven by the mainspring, moves in the direction of the arrow and pushes the pallet out of its path. After the wheel tooth has reached the end of the impulse face of the left pallet, its motion is arrested by the right pallet, the locking face of which has been brought into position to receive another tooth of the wheel.

(3) When the pallet is pushed aside by the wheel tooth, the lever imparts sufficient energy to the balance through the impulse pin to sustain oscillation of the balance wheel. The balance wheel proceeds on its excursion, deflecting the balance spring until it comes to rest. Then its motion is reversed by the uncoiling of the balance spring; the impulse pin again enters the notch of the lever but from the opposite direction, and the operation previously described is repeated.

16-4.3.1 Method of Increasing Torque Regulating Range of Detached Lever Escapements

An escapement has the twofold function of regulating the speed of the shaft and of dissipating the energy that is supplied through the shaft. While for watch making applications the speed regulation function is

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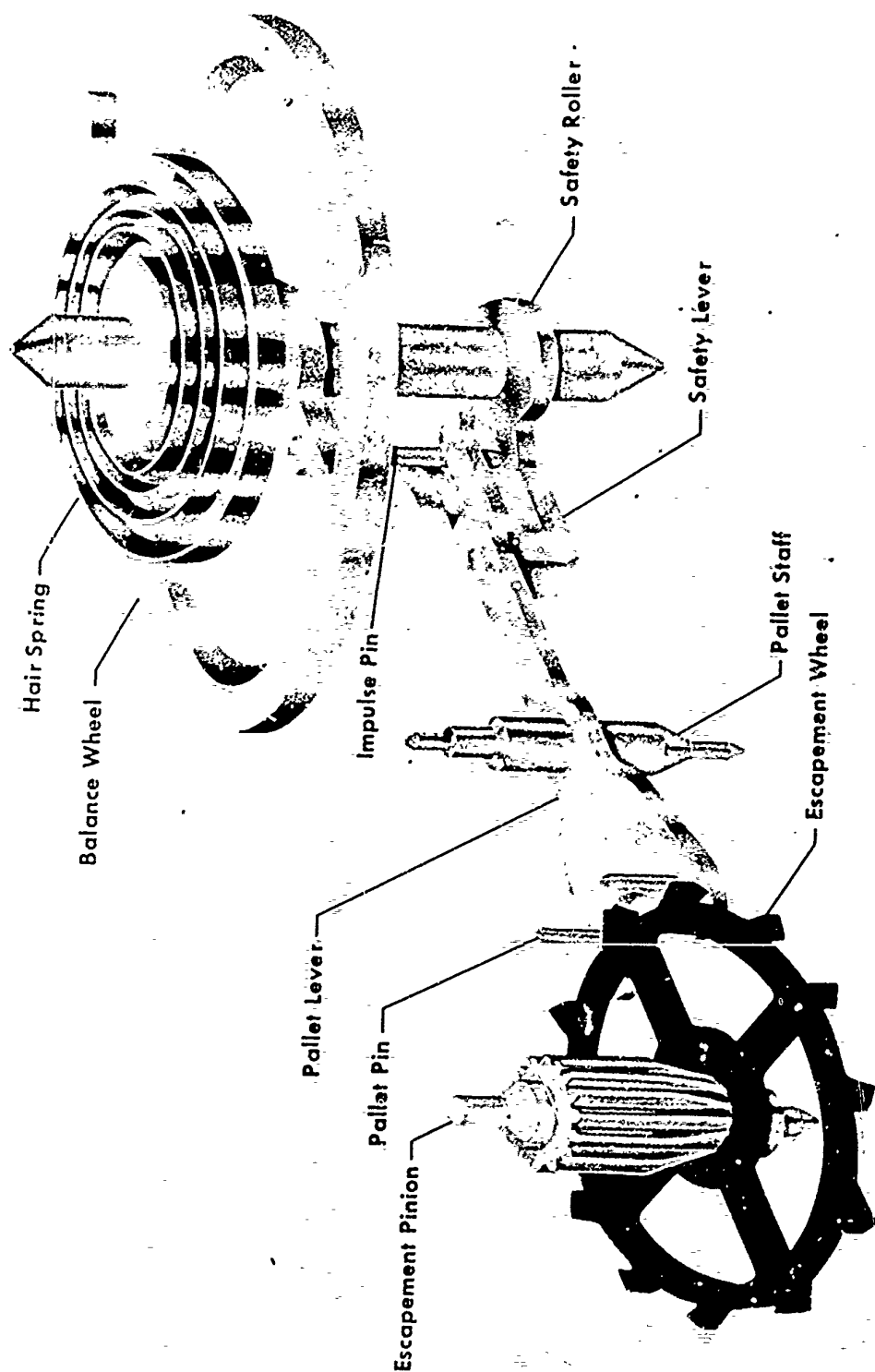


Figure 16-43. Detached Lever Escapement, Pin Pallet Type

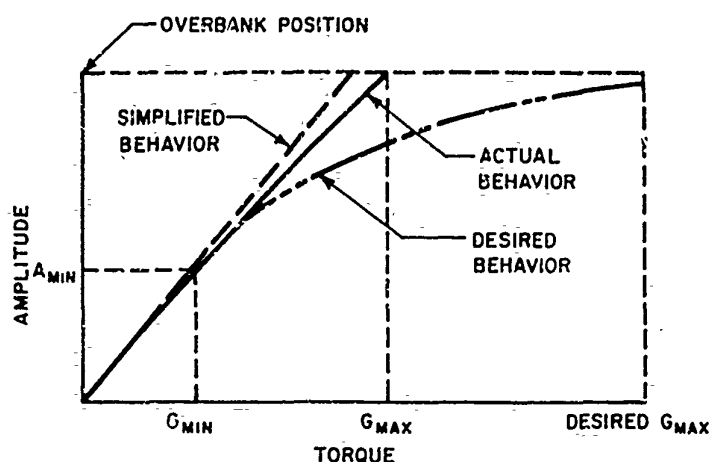


Figure 16-44. Amplitude vs Torque Behavior

paramount, in certain military applications the energy (or torque) regulation capacity is of primary concern.

The practically constant fraction of the energy that must be absorbed by the escapement is imparted to the balance during the impulse period; the remainder is dissipated as heat when the escape wheel impacts on the pallet. That energy that is imparted to the balance is dissipated primarily in coulomb friction at the balance pivots. It follows from an elementary energy balance that the amplitude of oscillation of the balance should increase in direct proportion to the applied torque. This is shown in Fig. 16-44²³ by the curve labeled "simplified behavior". At higher amplitudes, experimental curves deviate from linearity as is shown in the figure by the curve labeled "actual behavior" and indicate energy losses not directly proportional to input torque.

The permissible amplitude limits determine the range over which an escapement can operate. The maximum permissible amplitude is limited by the overbank position, i.e., the angular position of the balance wheel at which the pin strikes the outside of the lever fork. The minimum permissible amplitude is that amplitude for which the energy stored in the balance is just sufficient to provide

reliable unlocking action, accurate speed regulation, or both. These limiting amplitudes correspond to limiting torque values beyond which the escapement is said to be operating improperly.

The two methods available for increasing the torque regulation are either reducing the minimum permissible amplitude or introducing a nonlinearity into the amplitude-torque relationship so that higher torques can be accommodated without overbanking. This latter method is indicated in Fig. 16-44 by the curve labeled "desired behavior". Several methods for accomplishing nonlinearity are changes in windage drag, hairspring, escape wheel inertia, beat rate, and braking fork.

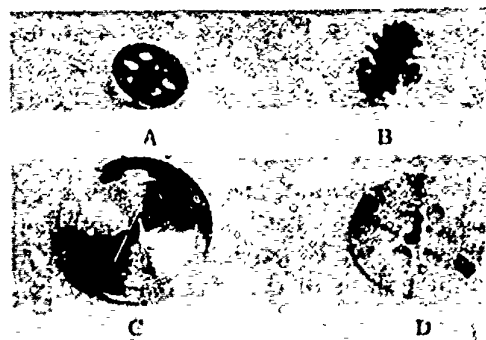


Figure 16-45. Balance Wheels

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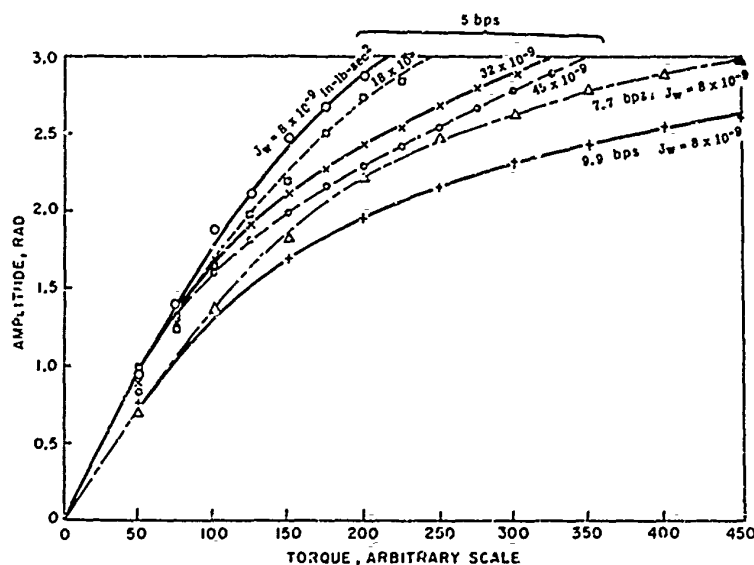


Figure 16-46. Effect of Varying Escape Wheel Inertia and Frequency

The windage drag, which is a function of velocity, can be amplified by altering balance geometry so that parameters bearing on windage can be made more prominent. Fig. 16-45²³ shows various arrangements of balances illustrating this principle. Although increases in windage effects are attainable, it was found that windage has little or no effect on nonlinearity.

Data and theory indicate that the hair-spring generates a radial thrust comparable in magnitude to the weight of the balance wheel. Since this thrust increases with amplitude, nonlinearity like that shown in Fig. 16-44 can be demonstrated. The increased pivot loading at high balance amplitudes causes a rate of increase in energy dissipation which is greater than the rate of increase of amplitude and hence the nonlinearity in the amplitude torque curve.

If the escape wheel inertia and frequency are changed, it has been shown that nonlinearity can be attained. Fig. 16-46²³ shows the effects of changing the inertia of the escape wheel and the natural frequency of the balance-wheel/hair-spring system. Fig. 16-47²³ shows the effect on frequency by

changing the inertia of the escape wheel, as a function of amplitude.

Another way of accomplishing the desired amplitude behavior is by applying a drag torque to the balance which is proportional to the applied torque. Energy dissipation at the balance would then be dependent on the product of amplitude and applied torque. This can be accomplished by using a braking fork mechanism as shown in Fig. 16-48²³. The effects of braking action which can be attained by this method are shown in Fig. 16-49²³. Possible disadvantages are degradation of timekeeping and difficulties of manufacture. Fig. 16-50²³ shows the effect of several braking surface combinations.

16-4.3.2 Dynamic Analysis of Detached Lever Escapement

The dynamics of the detached lever escapement has been the subject of two analytical works^{24,25}. The first is a Ph.D. dissertation on the dynamics of a detailed lever mechanism. The basic equation of an oscillating spring-mass system is augmented by adding terms that represent viscous damping, sliding friction, and a forcing function.

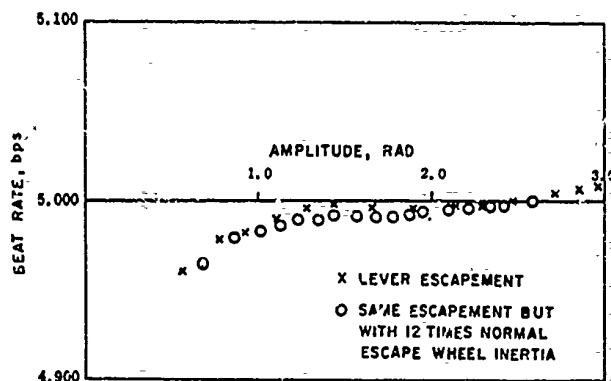


Figure 16-47. Beat Rate for a Detached Lever Escapement

The equation for the escapement is as follows

$$\ddot{\theta} + \omega_o^2 \theta + C\dot{\theta} + R \frac{\dot{\theta}}{|\dot{\theta}|} + X_o = 0 \quad (16-28)$$

where

θ = angular displacement

$\omega_o^2 = k/I$

k = torsional spring constant

I = moment of inertia of balance

C = (viscous damping coefficient)/ I

R = (sliding friction coefficient)/ I

X_o = forcing function

The equation of motion with certain values of C , R , X , was solved using computer programming and the results were plotted and compared with data taken from an actual operating unit in order to obtain the parameters C , R , X . Finally, tests were conducted on five experimental escapements. The experimental data gave excellent correlation to the theoretical data in both expected predictions and shape of the curves. A method of torque control is suggested to reduce the torque sensitivity of the detached escapement (see Fig. 16-51²⁴). In this method a low-power escapement controls the

time rate of output of a high torque source while tapping a small fraction of the torque for its operation. With this arrangement, it is claimed that the torque is relatively constant and this provides better regulation.

The second report²⁵ points out that the high accuracy traditionally realized in watches and clocks using the detached lever escapement could not be maintained when the detached lever escapement is adapted for

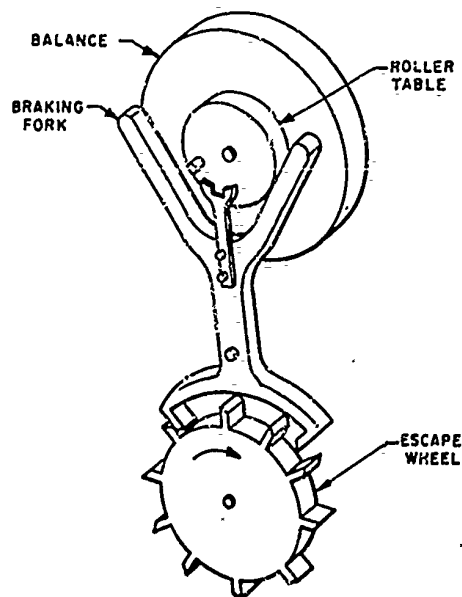


Figure 16-48. Braking Fork

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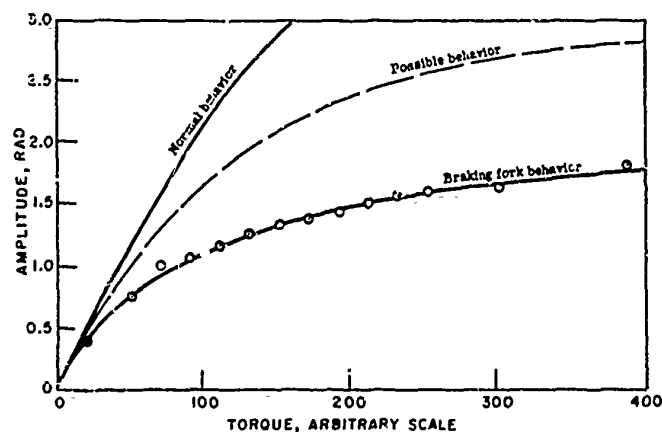


Figure 16-49. Effects of Braking Action

use in military timing mechanisms. Some of the causes believed responsible for the degradation in accuracy are:

- (1) Elimination of costly jewelled bearings
- (2) Strengthening of fragile, small diameter pivots
- (3) Loosening of tolerances to decrease costs

(4) Increased variations in input torques and output loads resulting from military applications

(5) Increased escapement frequency necessary for high resolution in short timing intervals

(6) Operation over wide temperature extremes and after prolonged exposure to shock and vibration.

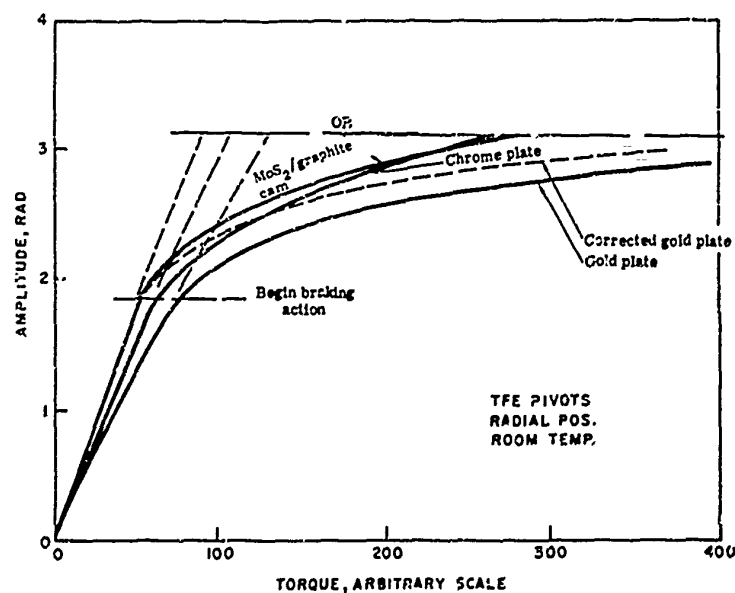


Figure 16-50. The Effects of Several Braking Surface Combinations

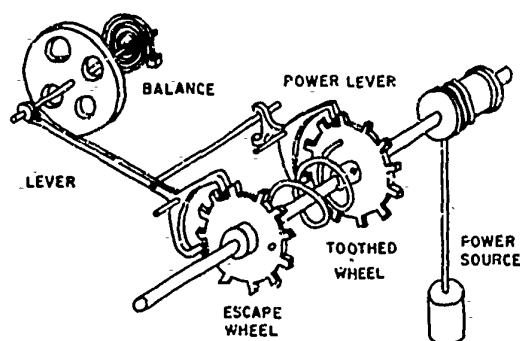


Figure 16-51. Modified Escapement

The gross effect of all these factors is to produce greater variations in the effective impulse delivered to the oscillating balance assembly.

Since an escapement that shows a large variation in timekeeping properties as the input torque is varied is said to be torque sensitive, the quality of a given escapement design can be assessed by determining its degree of torque sensitivity.

The main objective of the report²⁵ was to develop a mathematical model of the escapement which allows a more efficient investigation of parameter variations and the resulting performance changes not previously accomplished²⁶. The differential equations governing the motion of the escapement system are derived, and the solution to these equations are obtained by computer methods.

The equations include most of the essential geometric and dynamic design parameters such as shapes, center distances, and inertias of parts. Energy loss mechanisms that are influenced by the input torque, collision processes, and escape wheel lag are also considered. One of the effects found to play a major role was that of hairspring radial sidethrust.

As a result of the investigation, several

recommendations are made for an improved model:

- (1) Provision for unlocking to end before zero balance displacement
- (2) Addition of a draw angle in the escapement wheel tooth
- (3) Addition of a variable geometry for the lever fork
- (4) Provision for frictional losses during impulse
- (5) Provision for elastic collisions during unlocking and impulse.

16-4.4 SPIN SENSITIVITY OF TUNED ESCAPEMENTS

It has been observed that the frequency of oscillation of the escapement lever (balance mass) changes when the escapement is spun in an artillery fuze. As previously indicated, this change arises from the fact that the escapement spring is now flexing in a radial force field that is proportional to the square of the spin speed. This frequency change can be either positive or negative depending on the conditions of fixity of the spring.

In addition to the frequency change caused by the force field, a change is also due to changes in output of the escapement wheel. In a typical movement, when the torque input to the arbor varies from 5 oz-in. (the minimum operating torque) to 30 oz-in. a frequency change of 1% is possible causing either random or periodic fluctuations. Random fluctuations are due, at least in part, to slippage between coils of the mainspring as it unwinds. Periodic fluctuations are due to eccentricities of the gears and to the variation of efficiency of gear tooth mesh on the different portions of the tooth profile. In addition, there is a gradual diminishing of the output torque of the mainspring as it

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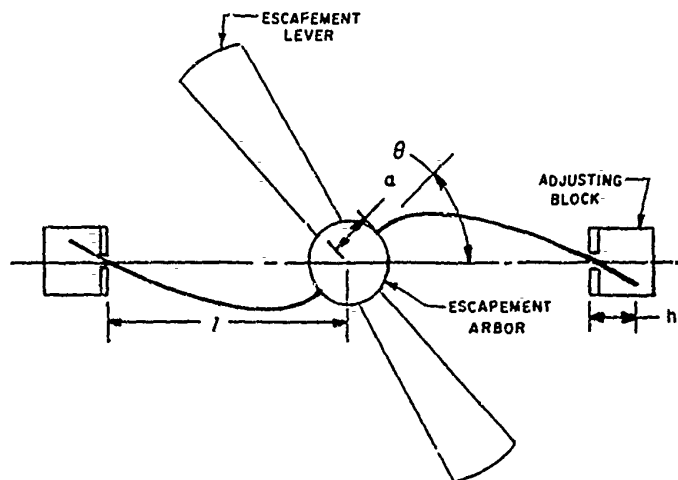


Figure 16-52. Escapement Spring Motion of Junghans Escapement

unwinds. Loss in torque due to this unwinding is on the order of 25%. (An exception to the decrease in output torque is the negator spring, see par. 16-2.1.)

Under spin conditions, the friction losses in the pivot of the off-center gears increase due to centrifugal force. If it is assumed that the spin has no effect on the mainspring, it can be shown that the torque output of the escape wheel can be expressed as a function of spin speed as follows¹⁸:

$$G = \eta G_a \left(1 - \frac{\omega^2}{\omega_o^2} \right) \quad (16-29)$$

where

G = escape wheel torque under spin conditions, lb-in.

G_a = arbor torque under nonspin conditions, lb-in.

ω = spin speed, rad/sec

ω_o = spin speed at which escape wheel gives no output torque, rad/sec

η = gear train nonspin efficiency times train value (ratio of teeth, driver/driven)

Since ω_o is not measured easily, the minimum arbor torque G_{min} and the spin speed ω_s at which the escapement stops running is found instead. Then

$$\eta G_{min} = \eta G_a \left(1 - \frac{\omega_s^2}{\omega_o^2} \right) \quad (16-30)$$

$$\left(\frac{\omega_s^2}{\omega_o^2} \right) = 1 - \frac{G_{min}}{G_a} \quad (16-31)$$

but from Eq. 16-29

$$G = \eta G_a \left[1 - \frac{\omega^2}{\omega_s^2} \left(\frac{\omega_s^2}{\omega_o^2} \right) \right] \quad (16-32)$$

Substituting

$$G = \eta G_a \left[1 - \frac{\omega^2}{\omega_s^2} \left(1 - \frac{G_{min}}{G_a} \right) \right] \quad (16-33)$$

The reduction in torque due to spin is appreciable. A typical timer operating at 80% of its stopping speed with $G_{min}/G_a = 1/4$ will be receiving only slightly more than half of its nonspin torque.

The spin sensitivity of the escapement spring in a standard Junghans escapement (Fig. 16-52¹⁸) is given by

$$\frac{\Delta f}{f_n} = \frac{A \rho \ell^4 \omega^2}{12 \times 112 EI} \left[1 + \frac{7h^2}{\ell^2} \right] \times (1 + 3\lambda - 12\lambda^2)^* \quad (16-34)$$

where

f_n = natural frequency of escapement lever, Hz

A = cross-sectional area of the spring, in.²

ρ = mass density of the spring, slug/in.³

ℓ = distance from pivot center to the adjusting nut slot, in.

E = modulus of elasticity of spring material, lb/in.²

I = moment of inertia of spring cross section, in.⁴

h = overhang of spring beyond adjusting nut slot, in.

λ = ratio of 1/2 arbor width to ℓ

Changes in certain parameters might reduce spin sensitivity, but care must be exercised. For instance, a change in λ can introduce nonlinearities in the system.

The equation for spin sensitivity for the Dock escapement modification is similar to Eq. 16-34 with terms involving overhang ratio and λ omitted as being too small to be of importance. Rewriting Eq. 16-34 we have

$$\frac{\Delta f}{f_n} = \frac{1}{12 \times 112} \left(\frac{\rho}{E} \right) \left(\frac{A}{I} \right) \ell^4 \omega^2 \quad (16-35)$$

or

$$\frac{\Delta f}{f_n} = c_s \omega^2 \quad (16-36)$$

*With restriction $\lambda \ll 1$. This expression is probably still good for λ as high as 0.25 or 0.3.

where

$$c_s = \frac{1}{12 \times 112} \left(\frac{\rho}{E} \right) \left(\frac{A}{I} \right) \ell^4$$

To investigate what the change from a flat spring to the Dock round wire spring would do, form the ratio $c_s(\text{Round})/c_s(\text{Flat}) = A/I(\text{Round})/A/I(\text{Flat})$ because the other parameters are unaffected. Substituting the approximate values of A and I for each type of spring, the ratio becomes

$$\frac{c_s(\text{Round})}{c_s(\text{Flat})} = \sqrt{\frac{\pi d}{3b}} \quad (16-37)$$

By use of values for the movement of Fuze, XM565, spring diameter $d = 0.0033$ in. and spring width $b = 0.013$ in. (nominal) the ratio becomes

$$\frac{c_s(\text{Round})}{c_s(\text{Flat})} = 0.516 \quad (16-38)$$

Therefore this change alone reduces spin sensitivity, and mean time shifts by one-half.

Two additional methods for reducing the spin sensitivity of the Junghans escapement are the E-K system and the PA system.

The E-K system (see Figure 16-53¹⁸) uses two springs with different end conditions and an off-center arbor. For this system, neglecting arbor width and overhang

$$\frac{\Delta f}{f_n} = \frac{A \rho \ell_1^4 \omega^2}{12 \times 112 EI} \left[\frac{1 - k \left(\frac{\ell_2}{\ell_1} \right)^3}{1 + \frac{\ell_1}{\ell_2}} \right] \quad (16-39)$$

where k is a constant calculated to be 13/15. The advantage of this system is that one half, the left side, has positive spring spin sensitivity, while the other half, the right side, has negative sensitivity. This permits either positive, negative, or null spring sensitivity depending on the ratio of the spring length ℓ_1

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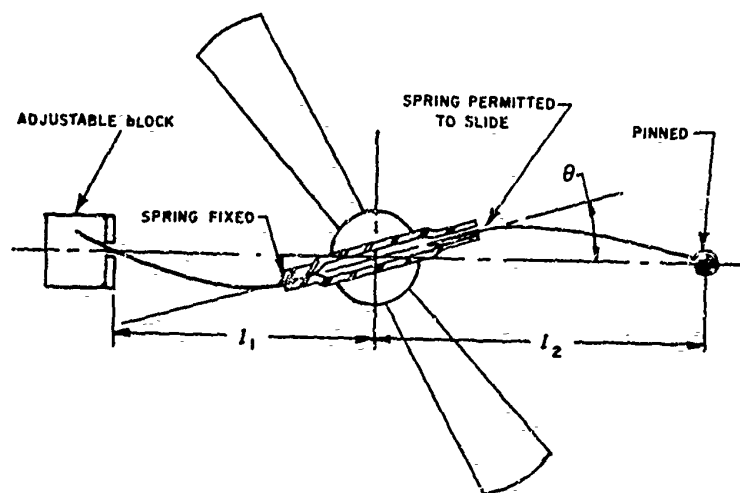


Figure 16-53. Escapement Spring Motion of E-K System

and l_2 . Besides the apparent disadvantage of increased cost to manufacture, the main drawback might be the necessity of simultaneously juggling two adjustments to arrive at both the correct frequency and net null sensitivity.

The PA system is shown in Fig. 16-54¹⁸. The spring sensitivity of this system is given by

$$\frac{\Delta f}{f_n} = - \left(\frac{6}{7} + \frac{r}{l} \right) \frac{A \rho l^4 \omega^2}{12 \times 16 EI} \quad (16-40)$$

where r = radius of arbor that intercepts the spring.

Spring sensitivity is always negative. Much smaller l 's are required in this system than in the standard Junghans system for equal frequencies.

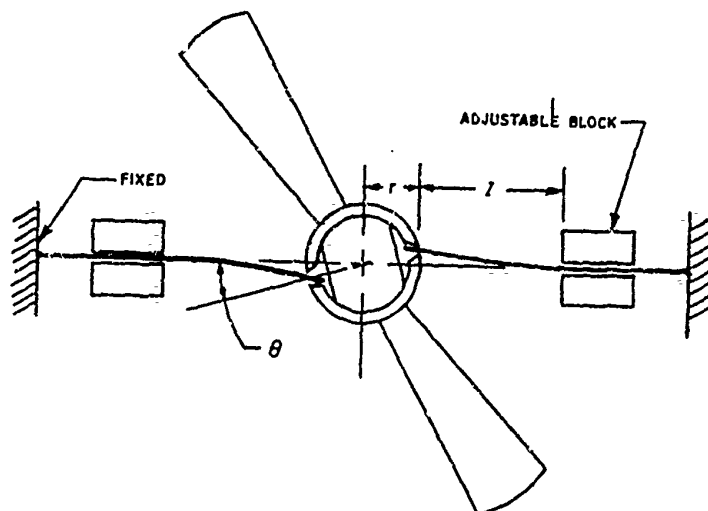


Figure 16-54. Escapement Spring Motion of PA System

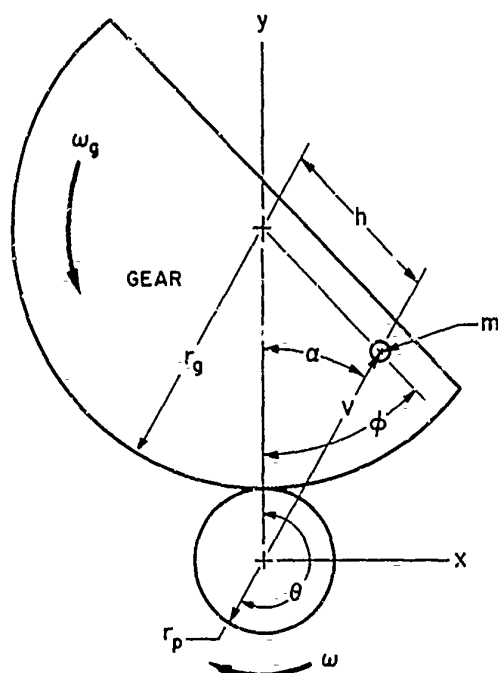


Figure 16-55. Segmental Gear Compensator

The problem of spin induced and run-down torque losses has been studied in order to determine the possibility of synthesizing an inertial (spin energized) compensator that will provide enough torque to balance out these effects²⁷. Two methods were considered: (1) segmental gear compensator, and (2) connected mass compensator. The first type of compensator consists of two weighted segmental gears engaging a pinion. Such an arrangement (with both gears represented by a single gear) is shown schematically in Fig. 16-55²⁷, and the second type is shown schematically in Fig. 16-56²⁷. The following symbols are used in the figures:

F = force, lb

h = distance from center of arbor or gear to center of mass, in.

l = length of flexible connection, in.

m = mass of gear, slug

r_a = radius of arbor, in.

r_g = radius of gear, in.

r_p = radius of pinion, in.

τ = tension in flexible connection, lb

ω = angular velocity, rad/sec

ω_g = angular velocity of gear, rad/sec

Analysis indicates that inertially generated torques can be used to compensate for friction, run-down, and spin decay energy losses in timing mechanisms. However, the analysis does not take into account two elements of the timing mechanism. These are torque gain due to spring spin, and torque loss

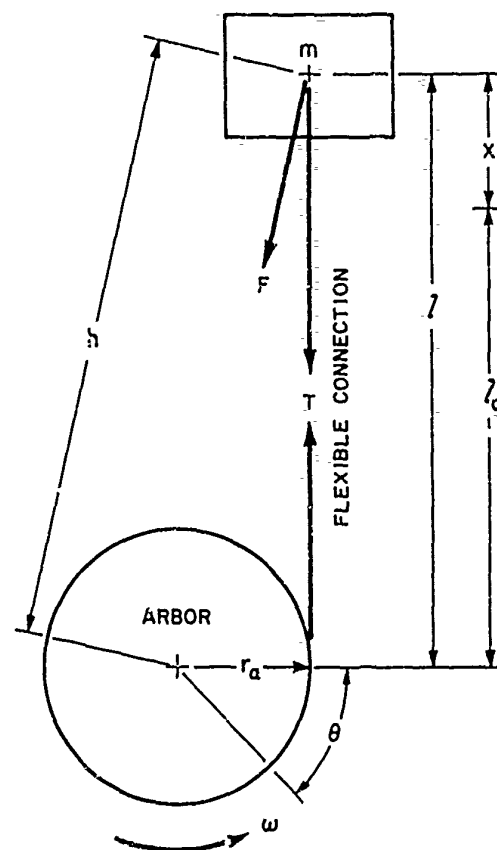


Figure 16-56. Connected Mass Compensator

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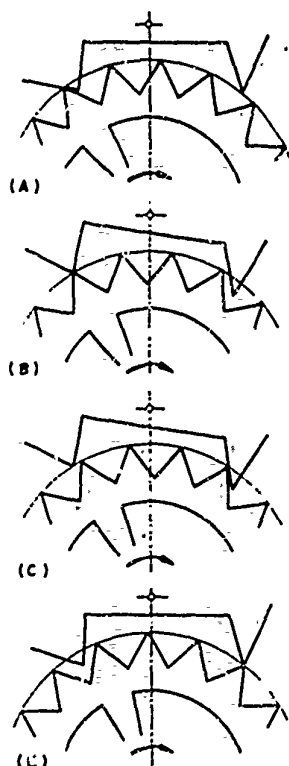


Figure 16-57. Operation of Runaway Escapement⁷

due to friction between spring leaves.

16-4.5 DESIGN FUNDAMENTALS

16-4.5.1 Untuned Two-center Escapements

In the runaway escapement the pallet is shifted by the teeth of the escape wheel, which act on the so-called lifting faces. There are two kinds of faces, the entering lifting face and the exit lifting face. The lifting face that is struck first by the teeth lying outside the span of the pallet as the escape wheel rotates is called the entering face. (In Fig. 16-57(A)⁷ this would be, considering the direction of rotation of the wheel, the left-hand face.)

Assume that a tooth touching an entering face begins the movement (Fig. 16-57(A)).

The pallet reaches its maximum excursion when the tooth of the escape wheel reaches the tip of the pallet as in Fig. 16-57(B). Simultaneously, during rotation of the pallet, the exit face is moved far enough into the pitch circle of the approaching tooth tip that the pallet intercepts the increasing motion of the escape wheel. This brief free rotation of the escape wheel, sometimes called the drop, is necessary. To insure reliable movement, the rise of the pallet on the exit side cannot be initiated at the moment when the tooth tip on the entering side reaches the edge of the pallet. Manufacturing defects, such as out-of-round motion, could lead to jamming. Lifting begins on the exit side after the drop (Fig. 16-57(C)). The rotation of the pallet here also continues until the tip of the tooth reaches the extremity of the pallet on the exit side (Fig. 16-57(D)).

The movement described is a basic characteristic of all runaway escapements even though different escapements differ in design details.

For satisfactory functioning of every escapement, a number of quantities must be related in a very definite way. Only a limited range of choice is possible, namely:

(1) All points on a lifting face (shown in Fig. 16-58⁷ in projection as a straight line) describe arcs during their motion which are referred to the center of motion of the pallet yoke (D) as their center. These circles are called the outer (r_o) and inner (r_i) pallet circles. The totality of these circles is limited by:

(a) The circle which runs through the intersection of the addendum circle with the lifting face on the entering side at the beginning of the lift (point R) and with the lifting face on the exit side at the end of the lift (point S'), see Fig. 16-58(A). (In this discussion, the escape wheel is assumed to rotate clockwise. The left-hand pallet, therefore, is the entering pallet.) and

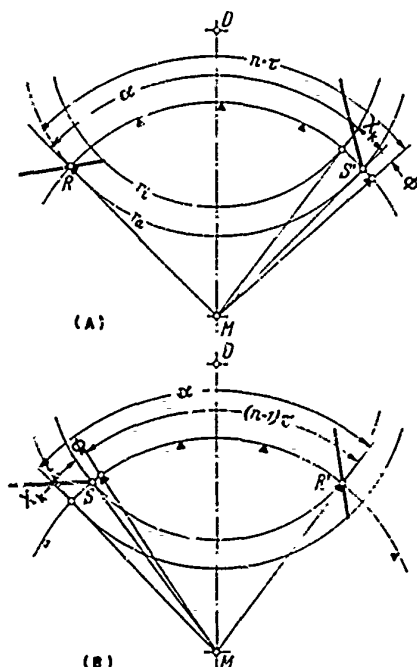


Figure 16-58. Quantity Relationships for Pallet of Runaway Escapement¹

(b) A second circle running through the intersection of the addendum circle with the lifting face on the entering side at the end of the lift (point S) and the exit lifting face at the beginning of the lift (point R') (Fig. 16-58(B)).

(2) As shown later, the circle passing through S' need not join up with the circle through R. The same holds for the circles through R' and S. It is only necessary that the difference $r_a - r_i$ be constant.

(3) The two points R and R' (beginning of lift) form the escapement angle α with the center of motion of the escape wheel M, while points R and S, and R' and S', form the pallet lead χ_k .

(4) The pallet lead and the drop cannot be chosen arbitrarily. Their magnitude is related to the escapement angle.

Let

α = escapement angle

χ_k = pallet lead

χ_z = tooth lead (also called the tooth tip width or tooth tip thickness)

ϕ = drop of the escape wheel

n = span of pallet

τ = pitch

then we can formulate the following relationship from the one position in which the tooth at the entering pallet initiates the lifting process (Fig. 16-58(A)), in the first instance ignoring the lift on the tooth,

$$\alpha + \chi_k + \phi = n \tau \quad (16-41)$$

Also on the exit side at the beginning of the lift

$$\chi_k + \phi + (n-1) \tau = \alpha \quad (16-42)$$

Therefore

$$\chi_k = \frac{\tau}{2} - \phi \quad (16-43)$$

If there is a run on the tooth, i.e., if the tooth has significant width at its tip, the pallet lead χ_k is reduced, if the drop interval of the wheel is to be preserved, to

$$\chi_k = \frac{\tau}{2} - \phi - \chi_z \quad (16-44)$$

From Eqs. 16-41 and 16-43 we obtain for the escapement angle

$$\alpha = n \tau - \frac{\tau}{2} = \tau \left(n - \frac{1}{2} \right) \quad (16-45)$$

The quantity n which defines the span of the pallet takes on these values:

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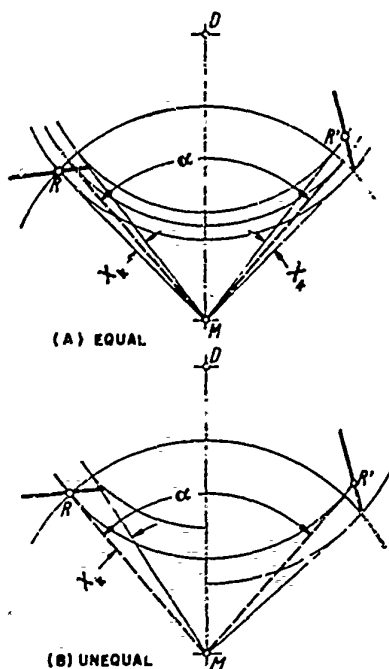


Figure 16-59. Runaway Escapement With Equal and Unequal Arms¹

For $n = 3$ the pallet spans 2.5 pitch intervals

For $n = 4$ the pallet spans 3.5 pitch intervals

For $n = 5$ the pallet spans 4.5 pitch intervals, etc.

A discussion of pallet vs escapement arm lengths follows:

(1) Pallet With Equal Arms. According to Fig. 16-59(A)², which shows the same situation as Fig. 16-58(A), the effective sections of the two lifting faces lie on concentric circles around the center of motion of the pallet. Hence the points are spaced unequal distances from the center of motion of the pallet at the beginning of the lift (R and R'). The two centers of the lifting faces are seen to be the only corresponding

points on the two faces spaced equal distances from the center of rotation of the escapement yoke. These center points, of course, also are spaced apart by the amount of the escapement angle. This design is called the *equal-arm escapement yoke*.

(2) Pallet With Unequal Arms. Certain detached lever escapements, for kinematic reasons, make it desirable to rotate the escapement angle in such a way that the two points R and R' become equidistant from the center of rotation of the escapement yoke (Fig. 16-59(B)). In this way the outer pallet circle of the entering pallet becomes the inner pallet circle of the exit pallet. Escapements of this type are called pallet escapements with *unequal arms*.

(3) Pallet With Semi-unequal Arms. The so-called semi-unequal-armed escapements constitute an intermediate solution. These are supposed to combine the advantages of the escapements with equal and unequal arms and avoid their disadvantages. They have not been very widely used.

The pallet requires a certain time to complete its swing. Since every pallet has a definite inertia, we can consider it as a physical pendulum in stable equilibrium. If the impulse of the escape wheel tooth acting on the entering and exit lifting faces is greater than the directional moment of the pallet, the pallet will execute forced oscillations. The time in this case is a function of the mass of the pallet, i.e., the moment of inertia of the pallet and the moment of rotation acting on the pallet.

The principles of construction of this escapement, which is designed as an equal-armed pallet, already have been shown in Fig. 16-58. Escapement angle and pallet lead can be calculated using Eqs. 16-43 and 16-45. The position of the center of rotation is arbitrary but it is not without influence on the shape of the pallet, especially the width of the lifting faces.

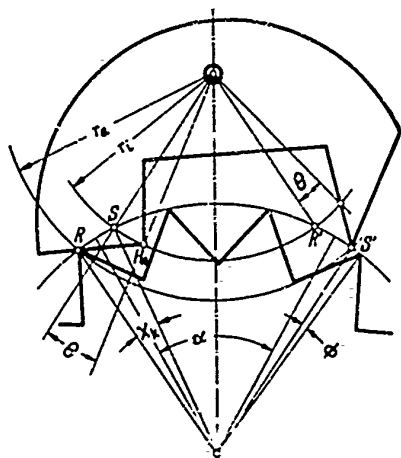


Figure 16-60. Untuned Two-center Escape-ment With Equal-arm Pallet⁷

Fig. 16-60⁷ shows the complete design of an escapement with:

- (1) An escape wheel of 15 teeth
- (2) A pallet rotation or lift angle θ of 11 deg
- (3) A drop ϕ of 2 deg
- (4) A span n of 3.

The position was chosen at a point when an escape wheel tooth had just left the edge of the lifting face (point S') on the exit side, and the tooth had just fallen on the lifting face (point R) on the entering side. If a pallet rotates through the lift angle θ on both the entering and exit sides, this angle is to extend inward from point S on the interior pallet circle and outward from point R'.

If the center of motion of the pallet is shifted toward the center of the escape wheel, the length of the lifting faces (distance R H₂) is shortened. Shorter lifting surfaces mean less space required for penetration of the pallet into the escape wheel.

In designing these escapements we find that several variables must be considered in

choosing the dimensions, the effect of which in operation cannot be calculated. The choice of dimensions, therefore, is based entirely on experiment.

Especially important factors are:

- (1) Size of the lift angle (depth of penetration)
- (2) Coefficient of friction of lifting face and escape-wheel tooth
- (3) Moment of inertia of the pallet
- (4) Driving impulse.

The rapid swing of the escape wheel (untuned two-center escapements are used mainly in fast-running mechanisms) and the resulting strong impact of each tooth tip on the lifting faces of the pallet require that pallet and escape wheel be made of hard materials so that surface wear is not significant during service life.

Escapements can be adjusted to a limited extent by changing the lift angle through adjustment of the penetration depth. Experiment has demonstrated that the greater the depth of penetration, the greater the moment of inertia of the pallet and the smaller the lift angle. It follows conversely that errors due to

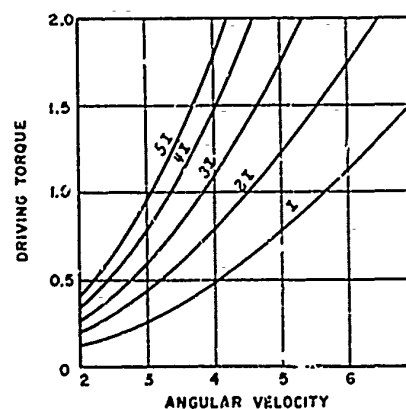


Figure 16-61. Escapement Curves for Different Moments of Inertia⁷

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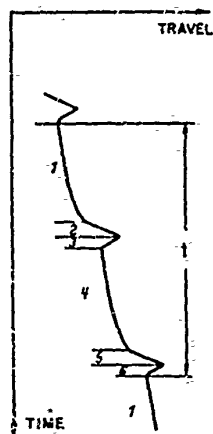


Figure 16-62. Rotating Drum Record of Escapement Motion⁷

radial tolerances are smallest with small moment of inertia and large lift angle.

It is possible, for instance, to modify the running speed by changing the moment of inertia of the pallet by using adjustable weights. Fig. 16-61⁷ shows the results of measurement on an escapement in which the moment of inertia of the pallet was changed in this fashion. It is apparent from the diagram that the regulation is simpler with increasing moment of inertia and that also, to maintain the desired rotational speed, the driving moment increases with increasing moment of inertia of the pallet.

Precise information about the individual phases of motion is obtained by recording the motion on a rotating drum. For this purpose both the motion of the escape wheel and that of the pallet can be used. To study the motion of the escape wheel, two or more small holes are bored near the teeth in the escape wheel spaced apart the distance of the pitch angle. These holes are illuminated with a condenser-equipped light source and projected by an optical system on the drum. The movement produces a curve like that shown in Fig. 16-62⁷.

During one period (vibration time t) the escape wheel makes the following movements:

(1) Entering pallet face of the pallet touches the escape wheel:

(a) The escape wheel rotates forward and drives the pallet. Lift on the entering side (first interval)

(b) The escape wheel moves farther out of contact with the pallet. Drop on the entering side (second interval).

(2) The exit pallet face touches the escape wheel:

(a) The escape wheel is moved backward by the pallet. A recoil is present which is evident only with relatively high pallet mass (third interval).

(b) The escape wheel rotates forward and drives the pallet. Lift on the exit side (fourth interval).

(3) The entering pallet face touches the escape wheel. The escape wheel is rotated backward by the pallet. Exit recoil (sixth interval).

Additional design information is contained in Ref. 28.

16-4.5.2 Tuned Two-center Escapements

The simple untuned two-center escapement has a disadvantage—the oscillation period depends strongly on the driving impulse. This disadvantage can be eliminated by use of an oscillating mass. The inertia of the mass must be large enough so that the pallet is not subject initially to reversal of direction at the moment when the escape wheel teeth fall on the lifting faces of the pallet. The pallet, in addition to the intermittent locking action, returns to the

oscillating mass the energy lost in friction, deformation of the escapement spring, etc. Without this resupply of energy the vibrations of the mass would be damped. This replenishment of energy is achieved by means of the escape wheel tooth during its run on the lifting surface.

The characteristic escapement values are as follows⁷:

(1) Period, Frequency, Number of Beats: The frequency, period, and number of beats in an escapement are related by Eq. 16-46

$$f_n = \frac{1}{T} = \frac{BR}{2} \quad (16-46)$$

where

f_n = natural frequency, Hz

T = period, sec

BR = beat rate (number of half vibrations of the oscillating mass)

For a flat escapement spring, the frequency is given in Eq. 16-22; for a torsion spring in Eq. 16-23. The period of a balance is given in Eq. 16-27.

(2) Escapement Constant: Since the rotational speeds of a timing mechanism with an escapement are determined entirely by the latter, a precise knowledge of the technical characteristics of the escapement and its effect on running of the mechanism is mandatory. Although in the case of air brakes, centrifugal governors, and the like, this effect can only be determined with difficulty, the relationship between the rotational speed of the escape wheel and the mechanical characteristics of the escapement—especially in the case of an escapement with a naturally oscillating mass—are much simpler to formulate.

When the oscillating mass (pallet) completes one vibration, the escape wheel has turned a distance of one tooth. If we designate the number of teeth on the escape

wheel by N_w the escape wheel will require for one rotation a time t of

$$t = TN_w \quad (16-47)$$

Thus the rotational speed ω of the escape wheel becomes

$$\omega = \frac{1}{TN_w} = \frac{f_n}{N_w} = \frac{BR}{2N_w} \quad (16-48)$$

The far right-hand side of Eq. 16-48 is called the regulator constant. It is an important quantity and is used as an output equation in the design of clockworks. However, this equation is not valid for escapements without a naturally oscillating mass because the quantities T and BR are then not "inherent" values.

(3) Relationship Between Rotational Speed and Regulator Period: The relationships which follow compare unregulated and regulated timing movements

$$\omega_u = \frac{\chi}{T_u N_w}, \text{ rad/sec} \quad (16-49)$$

and

$$\omega_r = \frac{\chi}{T_r N_w}, \text{ rad/sec} \quad (16-50)$$

hence

$$\omega_u = \omega_r \left(\frac{T_r}{T_u} \right), \text{ rad/sec} \quad (16-51)$$

and

ω_u = unregulated angular velocity, rad/sec

ω_r = regulated angular velocity, rad/sec

χ = gear ratio between driver and escape wheel

T_u = unregulated period, sec

T_r = regulated period, sec

N_w = number of teeth on escape wheel

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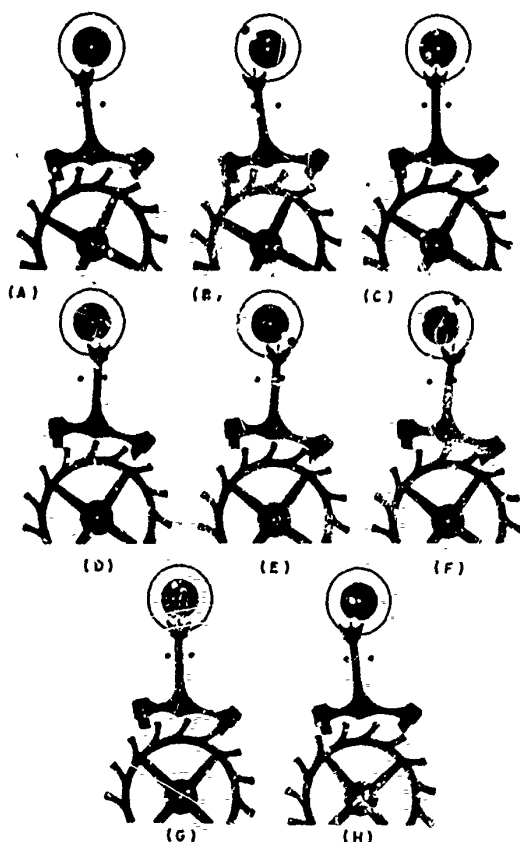


Figure 16-63. Operation Detached Lever Escapement⁷

Thus the deviation Δ from normal speed is

$$\Delta = \omega_r - \omega_u = \omega_r \left(1 - \frac{T_r}{T_u} \right) \quad (16-52)$$

If $T_u > T_r$, the timer runs slow (Δ has a positive sign) and if $T_u < T_r$, the timer runs fast (Δ has a negative sign).

16-4.5.3 Tuned Three-center Escapements

Components, functioning, and operation are described in the paragraphs that follow:

(1) Component Parts and Functioning, General: In this escapement, an intermediate link (lever) is placed between the escape wheel and the oscillating mass (balance). This

minimizes the drag torque imposed on the balance by the escapement. Important features of the tuned three-center escapement are (a) the energy is transferred over a relatively small angle during the rotary motion of the balance, (b) the balance must be free to rotate without any attachment, which is extremely important for a constant rate, and (c) this arrangement makes possible a greater speed of the escape wheel. The escapement is illustrated in Fig. 16-42 where the operating parts are labeled.

(2) Operation of Escapement: Fig. 16-63(A)⁷ shows the starting position. The balance executes a swing to the right. The impulse pin leaves the fork notch in the lever. A tooth has fallen on the lock at the entering pallet. The lever is spaced the "lost distance" from the banking pin. The lost distance is the angle of rotation from the pallet position after the drop to the end of the swing.

Refer to Fig. 16-63(B). The pallet is drawn deeper into the escape wheel by the escape wheel itself, due to its run angle, until the lever touches the banking pin. Here the lever traverses the lost distance. In this way the pallet is protected at least partly against repulsion (e.g., due to vibrations). During this time the balance swings fully into the end swing and reverses (right swing).

Refer to Fig. 16-63(C). After return of the balance, the impulse pin again enters the fork notch, strikes its right wall, and transmits an impulse to the pallet by its impact. The pallet is withdrawn from the escape wheel and escape begins. The escape wheel tooth slides over the locking point on the lifting plane. Lifting begins. In this phase the direction of impulse between impulse pin and lever changes. Up to this time the impulse pin has driven the lever. Starting with the beginning of lifting, the lever drives the impulse pin.

Refer to Fig. 16-63(D). This is the end of lifting on the entrance side. The tooth is about to drop. The impulse pin leaves the

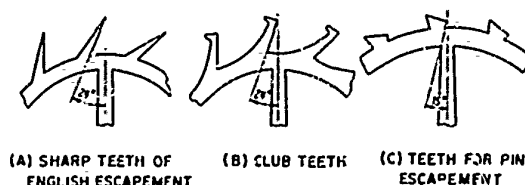


Figure 16-64. Escape Wheel Tooth Shapes⁷

fork notch; the balance moves free through the left swing.

Refer to Fig. 16-63(E). The tooth lying just in front of the exit pallet has fallen on the locking face. The balance swings farther into the end distance.

Refer to Fig. 16-63(F). The run angle on the exit side causes farther penetration of the pallet. The lever travels the lost distance on the exit side, until it meets the right banking pin. The balance reaches its extreme position and reverses its direction of rotation (it passes from a left swing to a right swing).

Refer to Fig. 16-63(G). The impulse pin strikes the fork wall and pulls the pallet out of the escape wheel. The escape on the exit side begins. After the escape, lifting begins and there is a transfer of energy through the lever and impulse pin to the balance.

Refer to Fig. 16-63(H). The tooth has reached the end of the lifting plane on the exit pallet and can fall away. The impulse pin leaves the fork notch. The tooth located in front of the entrance pallet drops on the lock.

(3) The Most Important Components and Their Function:

(a) Escape Wheel. There are three characteristic tooth shapes. Pointed teeth are used in the English lever escapement (Fig. 16-64(A)⁷). This escapement is less often used today because the tip of the tooth is very sensitive to shock, such as that following the drop. The club tooth predominates today (Fig. 16-64(B)). It has a greater mechanical

strength, ensures good oil retention, but tends to set more readily. The wheel of the pin escapement (Fig. 16-64(C)) is also very stable. It is relatively simple to cut with a milling machine, a fact of importance relative to cost.

(b) Pallet. A pallet with unequal arms mainly is used. The reason is to permit an equal distance of the locking planes from the center of motion and thus perform equal work on the entering and exit sides to release the pallet. Pallet insets are made of stone or steel.

(c) Draw Angle: The pallet locking planes, to do their job, must be arranged concentrically for minimum friction. Such a minimum, however, is not what is wanted here, because the lever, and therefore the pallet, would not be slowed down as the balance passes into the end of its swing. Thus the pallet could be dislodged from the escape wheel by vibration and shock. Only the escape wheel can supply the slowing action to the pallet during the time when the lever runs free of the impulse pin. For this reason, the circular shape of the pallet is abandoned, and its locking surfaces are replaced by planes. The position of these planes relative to the center of motion of the pallet is made such that the system tends to slide inward as a result of the pressure of the tooth until this "run" is halted by the banking pin.

The perpendicular force N at point R (Fig. 16-65⁷) due to pressure of the tooth corresponds to the friction force μN since there is bound to be friction. These forces act on the two lever arms l_1 and l_2 , and tend to turn the pallet in a positive or negative

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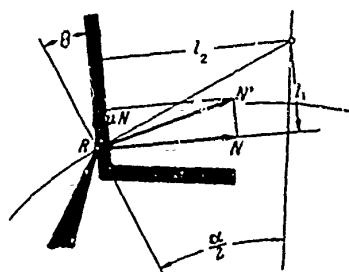


Figure 16-65. Determination of the Draw Angle⁷

direction (depending on the magnitude of the resultant moment or angle θ). If we assume constant friction coefficients, θ may not exceed a definite value in order for the sum of the moments of N and μN (or in other words, the moment of the resultant N') to be positive; and the pallet, therefore, to have a tendency to slide inward.

The length of the two lever arms is given by

$$l_1 = r \left(\tan \frac{\alpha}{2} \right) \sin \theta, l_2 = r \left(\tan \frac{\alpha}{2} \right) \cos \theta \quad (16-53)$$

Torque of the perpendicular force is

$$N l_1 = N r \left(\tan \frac{\alpha}{2} \right) \sin \theta \quad (16-54)$$

Torque of the force of friction is

$$\mu N l_2 = \mu N r \left(\tan \frac{\alpha}{2} \right) \cos \theta \quad (16-55)$$

If there is to be equilibrium, the two moments must be equal and opposite

$$N r \left(\tan \frac{\alpha}{2} \right) \sin \theta = \mu N r \left(\tan \frac{\alpha}{2} \right) \cos \theta \quad (16-56)$$

Hence

$$\mu = \tan \theta \text{ or } \theta = \tan^{-1} \mu \quad (16-57)$$

If we assume the coefficient of friction μ to be ≈ 0.17 (steel and stone) for the most unfavorable case (dry surfaces and average

polish), then we obtain an angle of 10 deg for θ . In order to ensure downward motion of the pallet, θ is made 12 deg. Further increase of the draw angle, however, must be avoided because, otherwise, the work of release and the return will be unnecessarily large.

(d) Lever. The lever serves to transmit the impulse from the pallet to the balance and vice versa. It is rigidly connected to the pallet and, therefore, moves together with it. The angle through which the lever turns is determined by the lifting angle, the lock, and the lost distance. Subtracting the lost distance, it amounts to about 10 deg. Shorter levers are preferred to longer ones. Longer levers mean greater mass and, therefore, heavier loading of the lever and pallet staff. Pallet and lever should be well balanced.

(e) Banking Pin. The purpose of the banking pin is to limit the run because, otherwise, the oscillating balance would have to expend too much work in release. Also the pallet should not touch the base of the tooth. The banking pin is positioned in such a way that the lost distance amounts to about 1 deg.

(f) Safety Pin. Only the extreme position of the lever can be delimited by the banking pin. It is conceivable, however, that the lever, during the phase when the impulse pin is outside the notch in the fork, might reverse as the result of a momentary shock in spite of the thrust due to the run angle. Premature reversal of the lever would cause the impulse pin to strike the outside of the fork on the way back; this would disrupt the system. In order to avoid this, a safety pin is attached to the lever that follows the center line of the lever and, if reversal should be induced, rides against the outer wall of the roller.

(g) Roller and Impulse Pin: The roller is in the form of a disk rigidly attached to the balance staff. Its purpose is twofold: (1) to act as a base for the impulse pin, and (2) to serve as a stop for the safety pin. The impulse

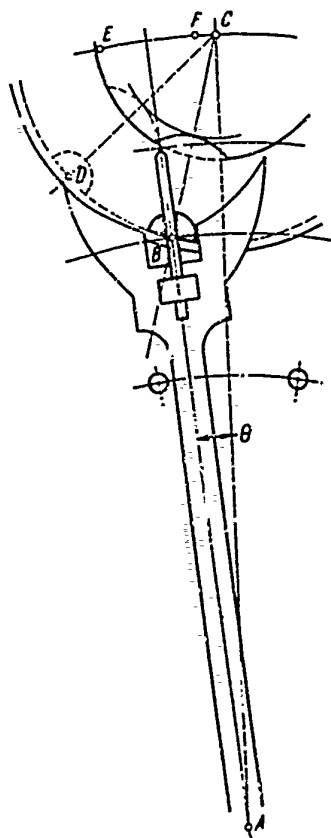


Figure 16-66. Lever With Safety Pin

pin is set into the steel roller. It may be sapphire, but in military timers it usually is made of steel.

A single roller, which is seldom used, could carry the impulse pin and also serve as a stop for the safety pin. With increase in roller size, however, there is increased risk that the safety pin will jam on the edge of the roller. For this reason the safety roller is made as small as possible. A double roller meets the requirements of a larger roller diameter for the impulse pin and a smaller roller diameter for restraining the safety pin. The diameter of the safety roller is about half that of the impulse pin roller (see Fig. 16-43).

The safety roller is cut away on its outside

face in line between the center of rotation and the impulse pin to permit the safety pin to pass during reciprocation of the fork. This slot should be only as large as absolutely necessary because enlargement will not leave sufficient stop area for the safety pin after the impulse pin moves out.

(h) Lever. The lever transfers the impulse of the pallet to the balance and vice versa. It carries a number of safeguarding features, the satisfactory functioning of which must be ensured. Fig. 16-66⁷ shows the lever at the end of lift on the exit side; information follows:

- Maximum lever swing angle

$$\theta = \frac{\text{lock} + \text{total lift}}{2} \quad (16-58)$$

- Width of Impulse Pin: about 5 deg (relative to point A).

- Diameter of Small Roller: about 3/5 of the impulse pin circle diameter.

- Distance of Safety Pin Point From Small roller: 0.5 deg.

- Distance From Side Face of Lever to Banking Pin (the so-called lost distance): about 1 deg.

- Slot to Pass Safety Pin: The slot must be situated in such a way that the safety pin has already entered the slot at the beginning of release. Its depth must be such that no contact is possible between the tip of the safety pin and the bottom of the slot.

- Arms of Fork: They must be long enough that the fork is prevented from a reverse stroke while the balance is traveling through the arc BD by their following the impulse pin. The safety pin cannot provide this safeguarding function in the sector BD. The inner surfaces of the fork arms are cylindrical surfaces. Their centers, for satisfactory movement of the impulse pin, should

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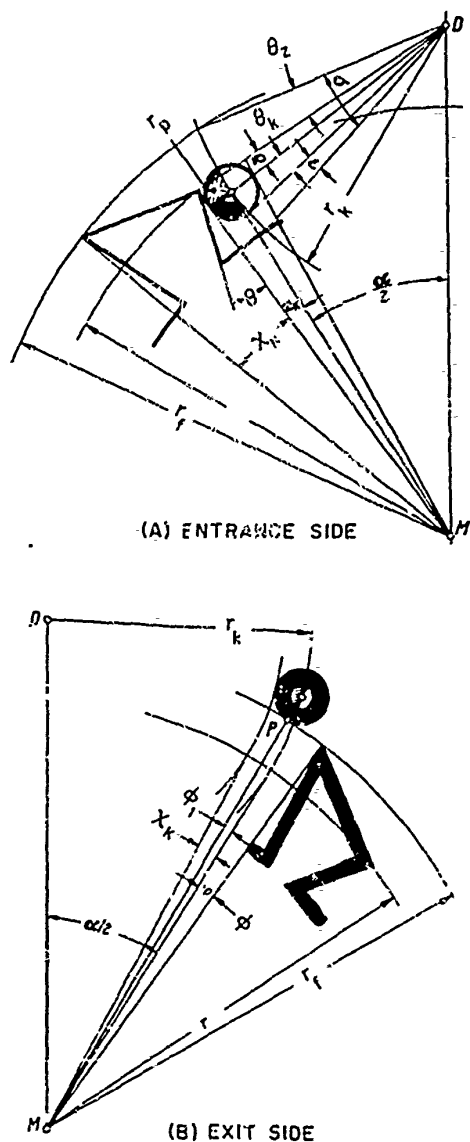


Figure 16-67. Pin Pallet Escapement Geometry⁷

not lie on the axis of the lever nor, in the center position, at the center C of the balance (points E and F).

• **Lever Length:** Length AB for short levers is $1.6 r_a$ and for long levers $2.0 r_a$; length BC is $0.5 r_a$ for each, where r_a is the outer pallet radius.

The short lever requires a heavy balance for dynamic reasons, while a balance with a smaller moment of inertia is preferred with a longer lever.

(i) **Fork Arms.** The fork arms on the lever provide added safety because the safety pin may still be in the roller slot when the impulse pin leaves the notch of the fork. In the single roller, the fork arms are not absolutely necessary because the safety pin can be restrained even after a slight rotation of the roller. In the double roller, the closer position of the safety pin slot to the center of rotation causes the angular distance over which the safety pin is in the slot, as measured from the center of rotation of the balance, to be considerably greater. During this time, the pallet is without adequate protection. The arms of the fork assume the protective function here. Incipient reversal of the lever causes the fork arms to ride against the impulse pin.

16-4.5.4 Detached Lever Escapements With Pin Pallet

In the pin pallet escapement (Fig. 16-43) the lift is effected almost entirely by the escape wheel. The pallet faces are replaced by round steel pins against which the escape wheel teeth act. On the average, the pin lift amounts to about one-fifth of the total lift.

While in the club tooth escapements the excursion of the lever is limited by the banking pin, in the pin pallet escapement the escape wheel itself performs this limiting function. As a result of the draw θ on the escape wheel tooth (Fig. 16-67(A)⁷), which is commonly 15 deg, the pallet is drawn so far in by the tooth draw (extra run θ) that the pallet pin strikes the foot of the tooth. This simplifies manufacturing appreciably but introduces a risk with respect to operation of the lever, namely, that the pallet pin tends to stick at the base of the tooth because slightly thickened oil can lodge in the corners of the teeth. In spite of this disadvantage, the pin pallet escapement has been used widely,

particularly in military timers.

Information on the design of this escapement follows:

(1) Pallet Pin Design:

The following notation, used for analysis, is illustrated in Fig. 16-67.

r = tooth heel radius of escape wheel, in.

r_f = tooth tip radius of escape wheel, in.

r_k = radius about which pallet pin turns, in.

r_p = radius of pallet pin, in.

α = escapement angle, rad

ϵ = run, rad

θ = total lift of pallet pin, rad

θ_k = pin lift, rad

θ_z = tooth lift, rad

ρ = lock, rad

σ = total pallet travel, rad

τ = pitch, rad

ϕ = drop of escape wheel, rad

ϕ_1 = small increase to drop angle, rad

χ_k = pallet lead, rad

χ_z = tooth lead, rad

Starting with the total lift, we obtain the pin radius

$$r_p = r_k \theta_k, \text{ in.} \quad (16-59)$$

Also

$$\chi_k = \frac{r_p}{r}, \text{ rad} \quad (16-60)$$

so that

$$\chi_k = \frac{r_k \theta_k}{r}, \text{ rad} \quad (16-61)$$

The tooth lead, obtained from Eq. 16-44, can be expressed as

$$\chi_z = \frac{\tau}{2} - \phi - \frac{r_k \theta_k}{r}, \text{ rad} \quad (16-62)$$

Since from Fig. 16-67(B)

$$r_k = r \tan \frac{\alpha}{2} \quad (16-63)$$

then

$$\chi_z = \frac{\tau}{2} - \phi - \theta_k \tan \frac{\alpha}{2} \quad (16-64)$$

The total rotation σ of the pallet and hence of the lever is

$$\sigma = \text{tooth lift} + \text{pin lift} + \text{lock} + \text{run}$$

or

$$\sigma = \theta_z + \theta_k + \rho + \epsilon \quad (16-65)$$

$$\theta_k = 2 \text{ deg} \quad \rho = 2 \text{ deg}$$

$$\theta_z = 8 \text{ deg} \quad \epsilon = 3 \text{ deg}$$

(2) Draw of the Pallet:

If the point of intersection of the tangent to the tooth-tip circle (instead of half the escapement angle) with the center line (MD) is taken as the center of motion of the pallet, the draw distances on the entrance and exit sides are different. This disadvantage is clearly seen in Fig. 16-68(A)⁷. (The figure is not to scale to emphasize this fact.)

There is no cause, however, to put the center of motion at this point. If the center of motion D is shifted toward the center of the wheel (Fig. 16-68(B)), the entrance draw becomes smaller and the exit draw larger. If D is moved close enough, the relationships are

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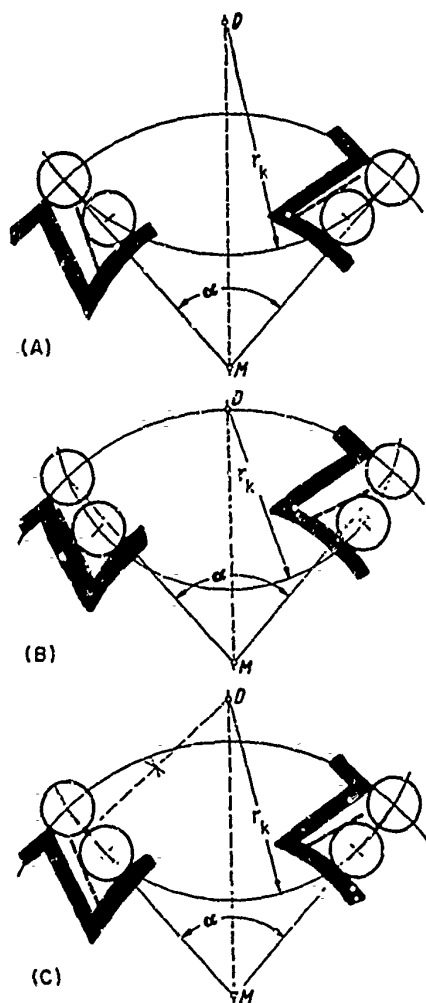


Figure 16-68, Entrance and Exit Draw Dependence on Pallet Center⁷

directly reversed. It should be kept in mind, however, that the center of motion of the pallet cannot be moved indefinitely close to the center of the wheel because this would require bending the pallet shaft. (The center of motion D in Fig. 16-68(B) already lies within the tooth heel circle.)

The center of motion of the pallet is positioned in such a way that the center of the pin lies on one leg of the escapement

angle at the beginning of the lift when the pin rests at the base of the tooth (end of the run) (Fig. 16-68(C)). Then the draw on both sides is completely equal. The center of motion of the pallet then lies on the perpendicular to the midpoint of the line joining the centers of the pins.

Attempts have been made to improve the design of the pin pallet escapement by a variety of modifications. It has been suggested, for example, that the penetration of the pallet to the base of the tooth can be avoided and its swing limited by locating the centers of motion of the balance, the pallet, and the escape wheel in a straight line. Then the lever, elongated toward the escape wheel, can serve a protective function, with its split end suitably shaped to ride on the escape wheel spindle. Suggestions for changing the shape of pin and tooth (bending the back of the tooth) were not acceptable because of their great cost.

(3) **Lever Design.** The lever for pin pallets is simpler than for club-teeth pallets; safety pin and small roller are omitted (Fig. 16-69⁷). By reducing the radius of the impulse pin and by properly shaping the arms of the fork, the impulse pin is made to move over a greater range inside the arms of the fork, so that the latter assume the safeguarding function. Outside this range the fork tips take over the safeguarding function. These can ride on the part of the balance staff which was not cut away to pass them earlier. Lateral banking arms limit the movement of the balance.

16-5 SETTING

16-5.1 GENERAL

Setting is that action which fixes the time interval measured by the mechanical timer. In some mechanical timers, a clock mechanism is used. In operation it is similar to a mechanical alarm clock. The ordinary alarm clock can be set for a time delay up to 12 hr, while the

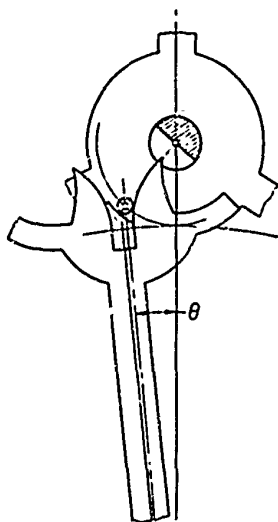


Figure 16-69. Simplified Lever⁷

clock mechanisms used in military timers usually can only be set for periods in the order of seconds or minutes. In order to set in a time delay, a knob on the face of the timer is turned so that the desired time is indicated on the dial. This action puts energy into the mainspring of the timer and corresponds to winding the alarm clock²⁹. When the time has elapsed on the military timer, a switch is closed (or opened according to the application of the timer), or some mechanical motion may take place.

The time delay set into a clock mechanism may not be used until some other event takes place, hence some sort of triggering linkage is necessary. The triggering linkage usually consists of a catch that can be released by energizing a solenoid. This type of timing device can be used only once without some external operation being required. With timers driven by motors (AC or DC), clutching mechanisms are used to disengage the drive motor from the actuator to allow the timer to reset to its start position³⁰.

In one version of a mechanical timer³¹, it is required to provide six specific times in the

interval of 40 to 120 sec by turning a single knob. The solution was to employ a "six-shot revolver" magazine arrangement of commercial odometer-type counters as shown in the exploded view of Fig. 12-4. This magazine permitted any counter to be coupled individually to the single timing movement by rotating the setting knob to any one of six positions. (A seventh "neutral" position also is provided.) The timer shown in the figure occupies about 6 in.³. The cylindrical magazine arrangement allows a simple, low cost, reliable mechanical setting mechanism while maintaining selectability for each of the six time intervals.

The readout is achieved by a mechanical switch contact on the hundreds or slowest moving wheel of the counter. The counter initially is set to the time desired (less 0.1 sec) and, when the timer is started, the counter counts backwards to zero. After the counter reaches zero on all wheels, the wheels turn to the 999.9 position in the succeeding tenth of a second; and this motion of the hundreds wheel closes the switch contact. Thus, all of the load to close the switch contact has been kept from the timing movement until a portion of the last 0.1 sec of timing. This digital system also increases the setting and readout resolution by at least 20 times over the traditional slow-moving cam and follower without having to resort to close tolerance components.

The power supply for this timer is a mainspring, and a detached lever escapement is used.

16-5.2 IMPROVED SETTING METHOD FOR MECHANICAL TIME FUZES

A mechanical time fuze to be adapted for tank-fired ammunition required a setting wrench to set the mechanism held in position by a high resisting torque (100 oz-in.). The fuze had a time range up to 100 sec, and each 0.1-sec setting represented a circumferential movement of only 0.007 in. Hence, a vernier

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Figure 16-70. Setting Mechanism for Fuze, MT, XM571

scale had to be provided. This fuze obviously was not suitable for firing from a tank.

Fig. 16-70¹ shows Fuze, MT, XM571 with setting mechanism redesigned for tank firing. The design has the following features:

(1) There is no need for time settings

beyond 10 sec for tank-fired ammunition. The range of the setting was, therefore, reduced from 100 sec to 10 sec so that each 0.1-sec setting represents a circumferential movement of 0.07 in. This increase eliminated the need for a vernier.

(2) The setting torque was reduced so that

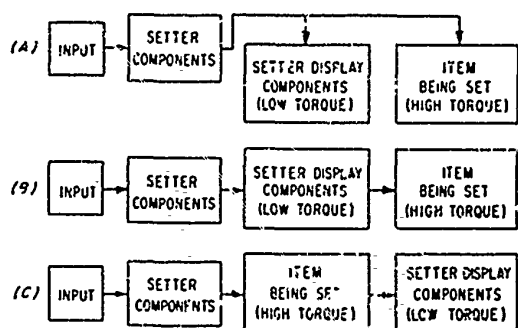


Figure 16-71. Linkage of Setter Components

the nose could be turned by hand. A wrench is thus no longer required. A knurl is provided on the nose to insure a good grip.

(3) The time setting is held by the release button. When the button is depressed, the nose turns freely. The button has five teeth that mate with an internal ring gear in the nose, whose pitch is such that each tooth represents 0.1 sec. When the button is released, it will lock the setting at any 0.1-sec increment.

(4) To eliminate the need for firing tables, the scale is calibrated directly in meters. Lines are numbered for every 200 m up to 4400 m. The intermediate 100-m settings have a tick mark. Incidentally, the scale is uneven because the even increments are on a time base.

(5) The size, shape, and thickness of the numbers and the numbered lines were selected experimentally so as to be readable under the red dome light during blackout conditions.

If one remembers the trying conditions under which the user must adjust a fuze, one can understand why this amount of attention is required for so simple a device as a time setting mechanism.

16-5.3 LINKAGE OF SETTER COMPONENTS

Designs of mechanical setter devices should include consideration of the linkage of the setter components and setter display components in conjunction with the device being set.

The parallel mechanical linkage (Fig. 16-71(A)) permits concurrent positioning of setter display components and the item to be set. This type of linkage could cause the display of a false reading because the setter display does not necessarily have to agree with the information actually set into item (the linkage to either the setter display components or item being set could be faulty). The series linkage (Fig. 16-71(B)) is little improvement over the first because the linkage to the item to be set could be deficient even though a setting is displayed. Deficiencies are more prone to occur in the high-torque gear trains of the item to be set rather than in the low-torque gear trains of the setter display assembly. The most reliable and safest linkage (at no increased cost) is a different series linkage (Fig. 16-71(C)) in which the setting actually positioned into item being set is displayed after the fact of setting (thus providing a true read-out).

16-5.4 SETTING MECHANISM FOR MECHANICAL TIME SETTER, XME77

The XME77 Fuze is shown on Fig. 16-72³². The mechanism of the fuze is housed in an upper body (fuze cradle) having a window area that indicates SAFE, "Point Detonating PD", or digital time sequences. A setting key (Fig. 16-73³²) is used to rotate the digital setting module to the desired function. The digital setting module consists of: a setting shaft, three digital counter wheels (hundreds wheel, tens wheel, and seconds wheel), two counter wheel index

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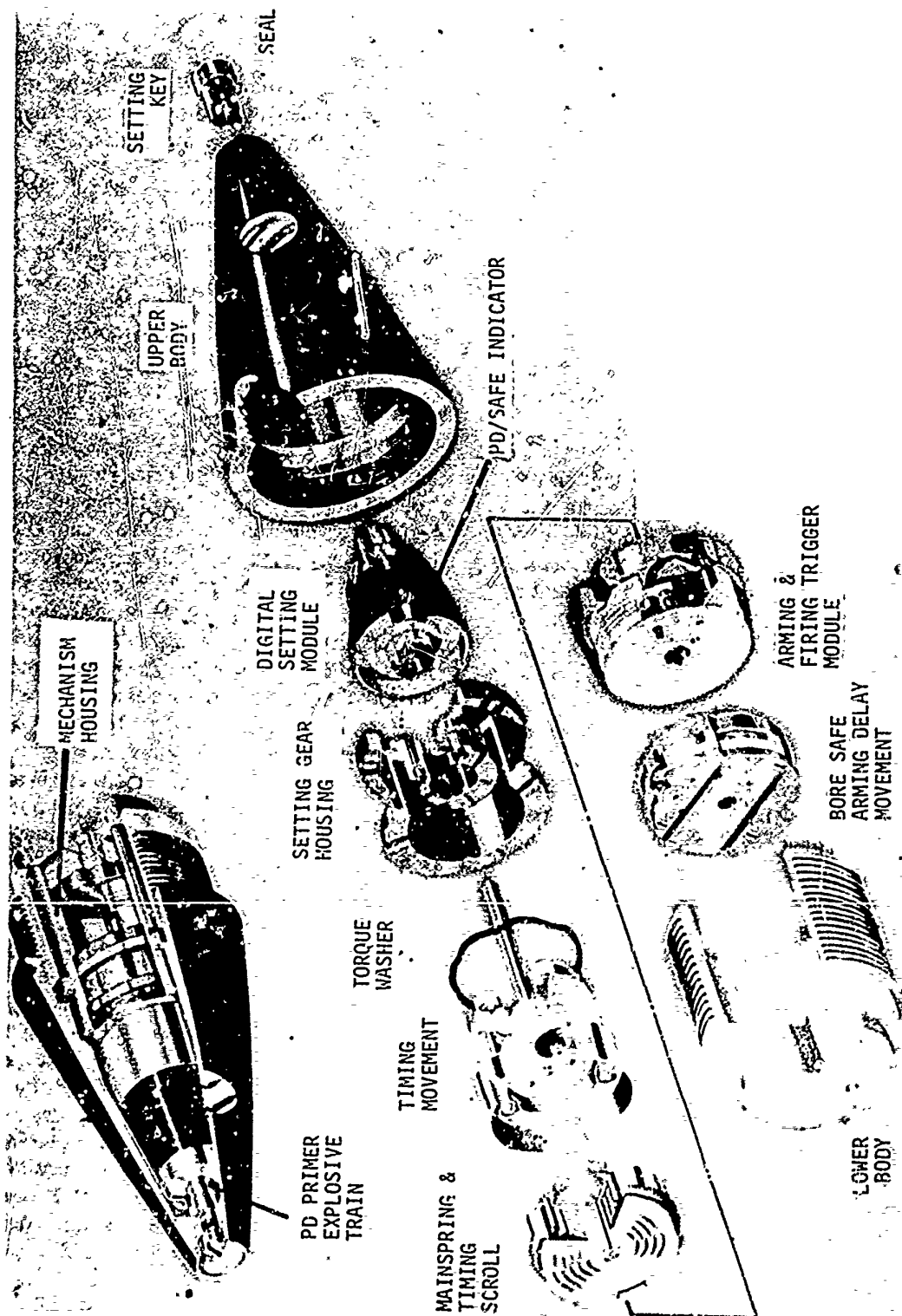


Figure 16-72. Mechanical Time Fuze, XM577

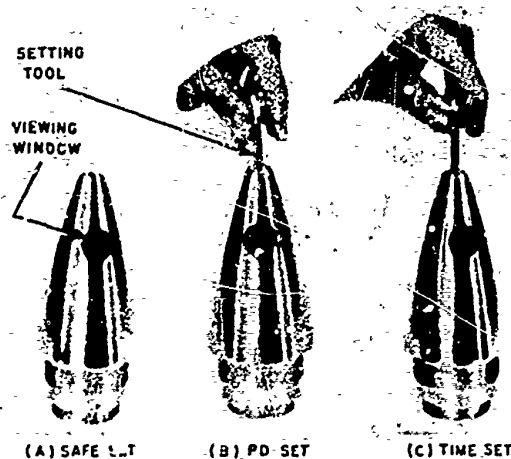


Figure 16-73. Setting Positions for Fuze, XM577

pinions, and a PD/Safe indicator flag. The setting shaft is coupled directly to the seconds wheel which in turn will index the tens and hundreds wheel, dependent upon the set time. Both the counter wheels and the indicator flag are observable through the fuze window when the fuze is set properly. Setting the fuze is accomplished by breaking the seal at the nose of the fuze and applying torque to the setting shaft with a setting key, as shown in Fig. 16-73. The applied torque rotates the timing mechanism module, displacing the scroll follower pin for the set time desired.

This fuze was developed to fill present requirements for artillery rounds. The fuze has demonstrated satisfactory performance under setback forces of 900 to 30,000 g, spin from 1600 to 30,000 rpm, and field settable time delays from less than 1 sec to more than 200 sec with better than 1% accuracy (0.06 standard deviation at a set time of 15 sec).

16-6 OUTPUT

16-6.1 ANALOG AND DIGITAL OUTPUTS

The overall objective of any timer output is to indicate the total number of oscillations of the time base occurring in a given interval of

time. The output can be either visual (readout) or physical (actuation of cam or switch). The output function (visual or physical) can be either analog or digital. An example of an analog mechanism is a dial of a watch which has continuous motion with infinite resolution. The digital output is a stepping motion having no resolution between steps. Visual readouts of each of them are illustrated in Fig. 16-74.

An analog output may be obtained by placing a disk on the slowest moving gear (mainspring barrel) of the timer. With this setup, the angular position of a slow moving shaft (output shaft) must resolve the displace-

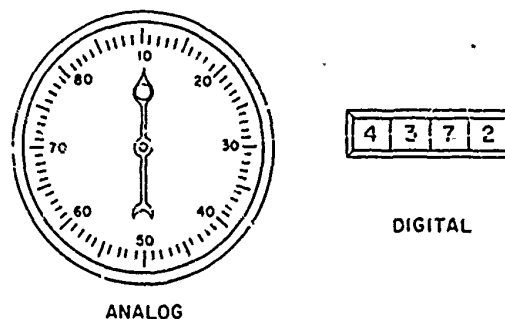


Figure 16-74. Two Types of Visual Output

ment of a fast moving shaft (input to gear train). For example, a 1-in. output disk that rotates once in 24 hr may be required to read out in intervals of 5 min of time. The 5-min interval on a disk 1-in. in diameter is an arc length of 0.01 in., and a specific point to be detected is moving at only 0.002 in./min. This makes it a problem to detect and set accurately.

Because of infinite resolution, the analog output is the most accurate device theoretically speaking. However, the practical considerations of precision manufacture, cost, and the need to detect extremely small angles limit its use for military timers. For these reasons a digital readout is better when high reading accuracy and incremental settings are desired.

The digital mechanism produces a discrete unit of output motion for each complete input pulse. A single pulse may represent a full 360-deg rotation of a shaft. The digital mechanism faithfully records each input pulse without error and is, therefore, accurate to the nearest pulse. For instance, again taking the 24-hr timer, suppose that the digital counter is arranged to record pulses that occur exactly every 30 sec. Then a time of 5 hr 10 min (18,600 sec) would be represented by a total of 620 pulses, and to an observer the figure 620 would be accurate to ± 30 sec when observed at any particular instant. This resolution is obtainable at any total time setting.

When the digital mechanism is used to provide a physical output at the end of the set time interval, it has an advantage of rapid transfer from one pulse to the next. Thus, the accuracy of the output at the set moment of transfer depends primarily on the accuracy of the time base. However, the digital device does not give the mechanical advantage of a gear train and, if a follower is applied to a cam surface on one of the counter wheels to sense a given time interval, it usually is found that performance is affected seriously because

the driving torques used to move these components are small compared with the load imposed by the follower. For this reason, the digital mechanism has been used in timers only for visual readout and the analog gear train usually provides the physical output.

16-6.2 SWITCHES AND RELAYS

During its operating interval, the timer may be called upon to operate a sequence of electrical contacts. In turn, these contacts may energize relays of any degree of complexity. It is better, where possible, to derive the useful output directly from the timer itself³¹.

Contact ratings are important. The required number of cycles in the life of the unit, and the capacity and rating of the load are the principal factors affecting contact design. DC circuits are far more injurious to contacts than AC circuits. A frequent specification is to guarantee the same life (say, 100,000 operations) for 115 V AC and 28 V DC circuits drawing the same rms current. With loads drawing high in-rush currents (inductive loading), contacts may be derated to 25% to 10% of their resistive load ratings.

Because of the special importance of the contact problem, it is often advisable to incorporate spark suppression circuitry. This generally takes the form of series RC circuits across the contacts, or reverse energized diodes that break down when their inverse voltage rating is exceeded, thereby limiting peak voltages across the contacts. Design of these circuits is best carried out on a trial and error basis. Although spark suppression circuits introduce time delays in the completion of contact operation, they are *extremely important* where long life under difficult but uniform load conditions is required. Obviously load duty cycle, which is related to the frequency of timer operation and to the temperature rise occurring in the contacts (or in the entire timing apparatus for that matter), affects contact pressure. Spring

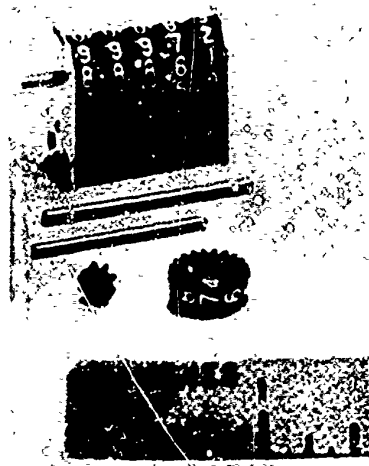


Figure 16-75. Digital Counting Device

constants establishing contact pressure are particularly sensitive to temperature.

In certain types of timers a constant speed motor may drive a set of brushes (contacts) over a printed circuit plate, where a pattern establishes the timing and contact closure sequences. At low brush speed, the contacts make and break so slowly that considerable arcing and pitting may occur. As a result contact rating may drop to 1% of the rating for contacts operating by snap action.

Other factors of importance include accuracy, repeatability, reliability, environmental conditions, and cost. Factors such as ease of adjustment, manner of setting, readout, and remote indication are more or less important depending on the specific application. Where a timer is to be used in a series of similar but not identical processes (where the timing will vary from one job to another), ease of setting up the timer is important. This set-up must include a check of accuracy which is best done by running through an approximate time cycle, and then making final adjustment. Where a timer is used over a long interval, readjustment may be necessary due to aging or wear of components.

It is important to be able to actuate the output circuit without taking too much energy from the escapement and associated components. For example, Ref. 31 discusses an experimental mechanical timer that uses commercially available digital counters as shown in Fig. 16-75³¹. The input shaft always is driven at the rate of 1 rps. The required time is preset into each digital counter which then is allowed to run down to zero. In the final 0.1 sec, all the wheels transfer as a single unit to read 999.9. At this instant a conductive knife blade attached to the hundreds wheel moves and completes an electrical circuit that provides an output signal. The advantage of this technique is that the switch closing load is not put on the timing movement until the final last 0.1 sec of timing. This contributes to the operational accuracy of the timer assembly.

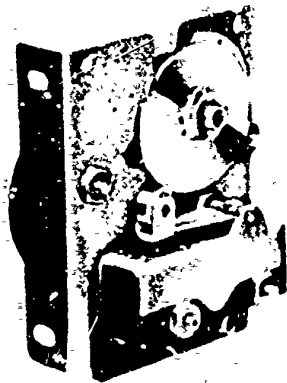
16-5.3 TYPES OF SWITCH

Snap acting switches rather than those types where gradual contact is made are usually more desirable. A slowly rotating output shaft closing and opening gradually a cam operated switch carrying currents on the order of amperes can lead to contact destruction. Contact destruction also may be a consideration where the contacting mechanism consists of an arrangement of a printed circuit board and brushes. Current ratings in this type of circuit must be reduced substantially below those values that could be tolerated in snap-action type switching.

Snap action switches in a timer are best set by trial and error since the precise switching point is somewhat indefinite. Further limitations are inherent in the cam geometry, wear of cam surfaces, and switch surfaces.

Mercury switches are another good choice if fast make and break contacts are desired. Arcing caused when breaking inductive loads within the switch rating is nondestructive. Another advantage of mercury switches is low constant resistance at low voltage and absence of contact chatter. Since the contacts are

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Figure 16-76. Adjustable Cam Timer³⁰

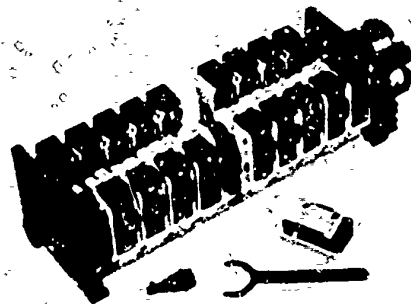
isolated (contained within a sealed volume), contact corrosion from damaging atmospheres is avoided as well as possible ignition of combustible gases by the switching arc³³. However, mercury switches are position and vibration sensitive and unable to operate under zero-g conditions.

A sealed dry reed switch may be actuated by a permanent magnet mounted on an output shaft or cam. It has advantages of small contact bounce, sealed contacts, and ability to operate in zero-g. Disadvantages are current limitations to a few amperes, glass-tube body, and susceptibility to vibration (but not at reed constant frequencies).

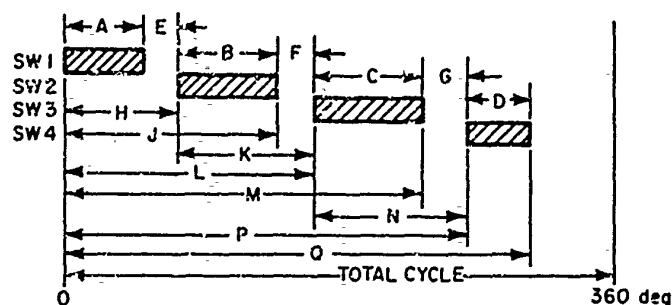
16-6.4 CAM OPERATED OUTPUTS

In these devices, rotating cams turn switches on and off according to a set program. The cams are driven by the output disk or shaft of the timer.

Cams fall into two classes, adjustable and nonadjustable. Nonadjustable cams are made of fiber, plastic, or metal disks into which a program is blanked or machined. The cams are attached to bushings, and the bushings are positioned in the drive shaft by set screws^{4,30}.

Figure 16-77. Cam Cycle Timer³⁰

Adjustable cams basically consist of two disks whose diameter is reduced over approximately 180 deg. Fig. 16-76³⁰ shows an adjustable cam timer. The desired program is set by adjusting the disks relative to one another. The disks may be clamped together by a screw or locknut, or connected by friction. The cams are staked to a bushing, and are marked in a variety of ways to facilitate setting. Both snap-action and leaf switches are available. Two types of follower are used with cam outputs, roller and knife. The roller follower gives longer life and lower drive torque requirements, and the knife follower gives greater accuracy but shorter life and higher drive torque requirements. In the cam operated cycle timer of Fig. 16-77³⁰, switches are mounted separately so that they can be replaced easily. Also, set screws are used for fine adjustment of the operating point. There are many designs for timer outputs, and prices vary considerably. When selecting a timer, the designer should analyze his needs relative to ease of adjustment, frequency of adjustment, and accuracy of setting required. In specifying cam output timers, it is best to lay out a timing chart as shown in Fig. 16-78³⁰. Remember, wide tolerances allow greater flexibility in the choice of actuators and switches, and reduce setting and testing costs.

Figure 16-78. Timing Chart for Cam-cycle Timer³⁰

16-6.5 READOUTS

Present-day mechanical time fuzes employ circumferential engraved scales and pointers for time settings and slotted screw buttons or segregated areas on the scale for optional function features. Usually, the rotary scales are limited to less than one full turn, with a secondary vernier scale to improve accuracy. This display is compatible with the internal setting portion of the fuzes and usually is achieved at low cost. Unfortunately, the display is difficult to read and can lead to gross setting errors by the operator. Significant improvement can be made by the design approach that follows.

placed on the inside of the scale, or outside as shown in Fig. 16-79(E). In the former case, the indicating arm may blot out a number; however, in the latter case, the scale is somewhat constricted to allow for the numerals to be placed on the periphery. On

16-6.5.1 Scale Layout

Fig. 16-79³⁴ shows the direction of increasing numbers for various scale types—i.e., for circular and curved, clockwise increasing; for vertical scales, bottom to top increasing; and for horizontal, left to right increasing. Except on multirevolution indicators such as clocks, a scale break should be included between the two ends of the scales as shown in Fig. 16-79(B). When pointer alignment is desired for check reading, the zero position should be at the nine o'clock position as shown in Fig. 16-79(C). For multirevolution indicators, the zero position should be at the top as shown in Fig. 16-79(D).

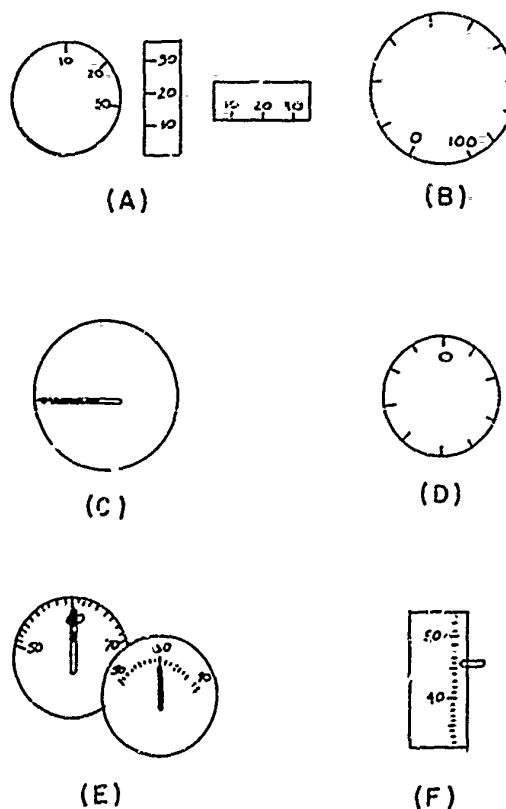


Figure 16-79. Recommended Readout Display Scales

On circular scales, the numerals can be

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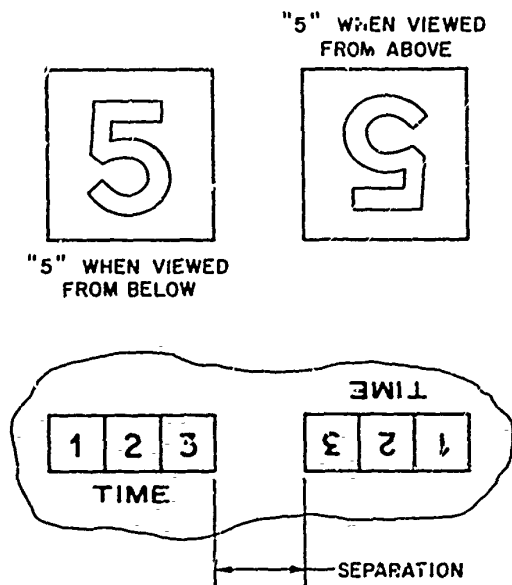


Figure 16-80. Multioriented Displays

vertical and horizontal straight scales, the numbers should be located on the side of the graduation as shown in Fig. 16-79(F).

The preceding general rules for scale layout may have to be modified in the use of fuzes to suit the particular circumstances imposed

by the oval shape and the random reading orientation between operator and round. If no definite orientation between operator and round is established, multioriented displays should be used as shown in Fig. 16-80³⁴.

16-6.5.2 Character Form

Table 16-3³⁴ shows a list of character type faces and their comparative legibility. This list should be used as reference when selecting a type face for display. From the chart, one can see that no one type face can be selected as being clearly superior to all others. For timer design, perceptibility and readability are more important than speed of reading because the amount of data is limited to several characters.

16-6.5.3 Grouping of Digits

The grouping of digits has a significant effect on the speed of perception. Thus the display arrangement should take full advantage of the most suitable grouping technique. The number of groups should be held to a minimum; and when minimized, should not be spread over wide areas.

TABLE 16-3

EFFECT OF CHARACTERISTICS OF PRINTED MATTER ON LEGIBILITY

Type Face Comparison: Scotch Roman Versus	Visibility		Perceptibility		Speed of Reading		Reader Opinions of Relative Legibility	
	Percent Difference	Rank*	Percent Difference	Rank*	Percent Difference	Rank*	Mean	Rank*
Astique	+56.3	1	-14.8	3	-0.2	3	2.4	2
Clarendon	+38.6	2	-22.2	2	-2.5	6	2.3	1
American Typewriter	+36.5	3	-37.7	1	-5.1	9	5.5	6
Cloister Black	+25.0	4	+2.3	10	-16.5	10	9.8	10
Bodoni	+18.5	5	-4.6	7	-1.1	4.5	4.2	3
Garamond	+16.9	6	-6.8	6	+0.5	1	5.4	5
Old Style	+15.8	7	-11.4	4	-1.1	4.5	4.6	4
Caslon Old Style	+11.1	8	-7.9	5	-1.3	6	6.4	8
Kabel Light	+8.2	9	+0.1	9	-2.3	7	8.2	9
Scotch Roman	0.0	10	0.0	8	0.0	2	6.2	7

*Increasing order of desirability

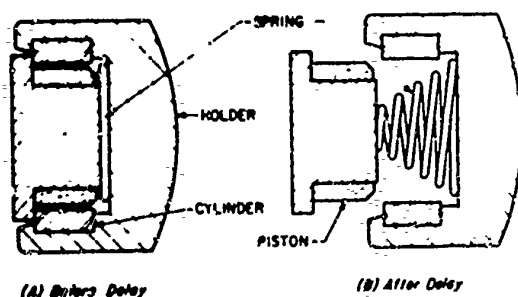


Figure 16-81. Pneumatic Dashpot for Arming Delay

16-6.5.4 Background

The background of the numerals or characters has an effect on reading speed and legibility. Distance is of secondary concern because in almost all situations the reading will be done at no greater than arm's length from the display. Black on white is superior to white on black from the standpoint of reading speed, distance, peripheral legibility, and eye movements. With respect to achromatic vs chromatic backgrounds, eye movements for black and white are far superior to color on color, a red on say green display. High contrast seems to be the most important factor with respect to reading speed.

Surface texture has little to no effect on reading speed or distance, but shiny surfaces or any highly reflective background should be avoided to reduce glare. If possible, windows or viewing ports should be nondistorting in nature.

16-6.5.5 Illumination

Since the nature of the process involved in setting a timer usually requires that the operator be in an outdoor environment, there is little the designer can do to reduce over-illumination when in bright sun conditions other than reduce obscurity due to glare. When nighttime operations are dictated

by the battlefield situation, the use of synthetic illumination should be considered either by self-illumination or by light provided by auxiliary equipment. Red light should be used when possible to preserve night vision.

16-7 FLUID TIMERS

In a fluid timer, a gas or liquid regulates the motion of mechanical parts. Fluid timers should not be confused with fluoric timers (Chapters 22-25) in which mechanical parts do not move. Rather, the fluid serves much the same purpose as the escapement, viz., to slow down the motion and to achieve a uniform rate. Fluid timers are not as accurate as clockworks but have found application in arming delays of fuzes. The two greatest problems with fluids are leakage and viscosity change over the military temperature range which lead to inaccuracies. However, both of these problems can be overcome through proper design. The application of two currently used fluids is described in the paragraphs that follow. Additional devices are covered in Ref. 1.

16-7.1 PNEUMATIC DASHPOT

An annular orifice dashpot is shown in Fig. 16-81³⁵. The "orifice" is the minute clearance between piston and cylinder. By selecting materials for piston and cylinder having different thermal coefficients of expansion, the orifice will change with temperature, thus affording a means of approaching a constant flow in spite of air viscosity changes with temperature. A glass cylinder can be produced accurately and the piston can be ground from ceramic or metallic materials.

The piston is pushed by a spring. The holder, of silicone rubber or polyethylene, holds and seals the parts. Models have been made from 1/8 in. diameter and 1/3 in. long to 1-1/2 in. diameter and 6 in. long. Time delay varies between 0.1 sec and 1 hr. The

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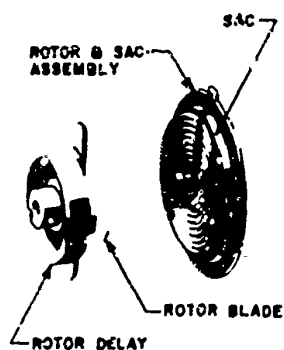


Figure 16-82. Delay Assembly of Fuze, XM218

dashpot has been used in experimental fuzes and is incorporated in Fuze, XM431, for the 2.75-in. rocket.

Theory of operation is based on the compressible flow of air through the orifice. The annular orifice, in this case, acts the same as a rectangular duct of the same dimensions; i.e., width equal to clearance, and length equal to circumference. The clearance is

$$h = \left[\frac{6\eta r \ell^2 P_1}{t (P_1^2 - P_2^2)} \right]^{1/3}, \text{ in.} \quad 16-66$$

where

h = clearance from piston to cylinder, in.

η = viscosity of the air, slug/ft-sec

r = radius, in.

ℓ = length of air travel, in.

P_1 = pressure in the cylinder, psi

P_2 = ambient pressure, psi

t = desired time delay, sec

16-7.2 SILICONE GREASE CAPSULE

The temperature-viscosity curve of silicone grease is flatter than that of other oils and greases. In the past, use of this substance therefore has been attempted to provide time delay. However, the leakage problem was severe, and the grease gummed up the arming mechanism so as to render it useless. This problem was overcome by sealing a silicone gum in a plastic sac made up of heat sealable Mylar tape.

Fig. 16-82 shows the sac and rotor delay mechanism of Grenade Fuze, XM218. The sac assembly consists of a metal backing disk and a plastic capsule, about 3/4 in. in diameter and 1/8 in. thick, containing silicone grease. The periphery and a segment of the plastic disk are heat sealed to the metal disk to form a pocket for the delay fluid. The sac assembly is placed against the delay rotor assembly (the space between the two assemblies in the illustration was introduced solely to show the sac assembly clearly). In operation, the delay is obtained when the four blades of the delay rotor, by virtue of a torsion spring, slide over the surface of the fluid sac, thus displacing and metering the fluid from one side of each blade to the other.

The design described was obtained by empirical means. The analysis is complex because the flow in the fluid sac passages varies as a function of rotor radius. Analytical techniques relating to the interactions of timer geometry, silicone fluid properties, and friction levels must be employed.

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PART FOUR – PYROTECHNIC TIMERS

CHAPTER 17

INTRODUCTION

17-1 GENERAL SYSTEMS

A pyrotechnic timer is a self-contained device in which a low explosive mixture burns linearly with respect to time to provide a controlled time delay. It is commonly called a delay element or just a delay. Its burning action often is likened to that of a cigarette, which also burns linearly. However, the delay housing sleeve is not consumed and air is not required for combustion. Low explosives are divided into two groups: (1) gas-producing low explosives that include propellants, certain primer mixtures, igniter mixtures, black powder, photoflash powders, and certain delay compositions; and (2) nongas-producing low explosives that yield the gasless type delay composition. Additional information on pyrotechnic timers is contained in other engineering design handbooks^{1,2}.

Pyrotechnic delays are the oldest military timers. Early descriptions of artillery tell of firing cannon balls with flaming wicks that served as pyrotechnic delays to provide for detonation after the ball arrived at the target. Whereas modern delays have been improved significantly, it is curious to note that black powder, the explosive employed originally, is still in current use for some applications.

Compared with electronic, mechanical, and fluoric timers, pyrotechnic delays are smaller, simpler, and less expensive, but they are also less accurate. Accuracy over the military temperature range is only about $\pm 10\%$.

In its simplest form, the delay element consists of a cylindrical housing containing the pyrotechnic composition. Sometimes a

primer is added at the input end to provide the initiating flame. The delay has a flame output that can be augmented into a detonation wave, if desired, by use of a relay.

Delay compositions are either gaseous or gasless depending on the quantity of gas generated when they burn. Combustion products of less than 10 or 15 cm³ of gas per gram are considered gasless; true gasless compositions do not exist. Provision must be made for the gas generated in gaseous delays by either venting or, in obturated delays, designing a free internal volume. For highest accuracy, gasless delays must have one of these two features. However, addition of these features makes the housing more complex. The current trend is toward the use of gasless delays. While delays adjustable in time have been used in the past, they also add complexity. Hence, most modern delays have a fixed delay time.

Advantages and disadvantages of pyrotechnic delays are summarized as follows:

(1) Advantages:

- (a) Normally, delays contain no moving parts.
- (b) Time delays are available ranging from microseconds to several minutes.
- (c) By comparison, they are smaller and lighter than equivalent mechanical, electrical, and fluoric delays.
- (d) The devices are rugged and can pass the standard military rough-handling tests. (Gas-

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less delays operate over a wide temperature range and withstand high impact acceleration.)

(e) Large amounts of energy are available in small weights and volumes.

(f) Usually, the fabrication cost is lower than that of other timing systems.

(2) Disadvantages:

(a) Since they contain pyrotechnic and explosive material, delays require that explosive safety precautions be taken.

(b) Pyrotechnic materials are sensitive to humidity and temperature, and careful control is necessary in processing, storage, and application.

(c) Time reproducibility at a given temperature is about 3% within one batch under the most controlled laboratory conditions. Batch-to-batch variation in production is considerably larger. This variation in burning time can be due to insufficient mixing, incomplete drying, difference in ingredient composition, variation in packing density, purity, particle size, and particle size distribution of the ingredients. Variations in column height also can introduce lack of reproducibility.

17-2 MILITARY APPLICATIONS

Pyrotechnic delays are used extensively in military devices, primarily in fuzes and demolition devices, to provide functioning or self-destruction delays. The *Fuze Catalog*³ describes many fuzes containing pyrotechnic delays and lists, in Volume 3, the delays themselves. Delays as elements of explosive trains are discussed in Refs. 4 and 5.

The classic use of these delays is in the time train of pyrotechnic fuzes. Fuze, M37A1³ is typical of the artillery fuzes employed during and before WW II. (Almost all of these fuzes are now obsolete for another reason, namely,

outdated arming safety.) The fuze contains a black powder delay column in the shape of almost a complete ring. One end of the ring is blind, the other has a relay leading to lead, booster, and main charge. A primer is mounted in the ogive, at right angles to the ring. The ogive turns so that the primer can be positioned anywhere around the ring. When it is at the relay, the delay is nil; when it is at the blind end, the entire column must burn before setting off the relay. A scale on the outside of the ogive permits setting the time from zero to 25 sec. Of course, the black powder in the column burns both ways when the primer is in the middle but the flame is extinguished at the blind end.

Fig. 17-1³ shows Detonator, Delay, T65, which is more typical of a simple modern application. The delay itself is the small center charge of a barium chromate/boron composition. The input end of the detonator consists of the electric contacts (pin and case), a carbon bridge, a spotting charge of lead styphnate, and an igniter mix. At the output end, the lead azide and RDX charges produce a detonation wave. It takes 50 msec for the flame to burn through the length of the delay composition.

17-3 REQUIREMENTS

The basic requirements for a military timer include reliability, ruggedness, and simplicity. The timer must function as intended when subjected to the correct stimuli. On the other hand, it must withstand the rigors of handling, transportation, and storage over the military temperature range. A pyrotechnic delay can meet these requirements.

To these general requirements must be added the important factor of safety. Of course, safety is a general requirement, which is certainly implied in ruggedness. Some of the delay compositions, like black powder, can burn very rapidly under certain conditions. Safety in pyrotechnic timers is therefore of primary importance. Safety aspects are discussed in more detail in par. 20-2 and in Ref. 6.

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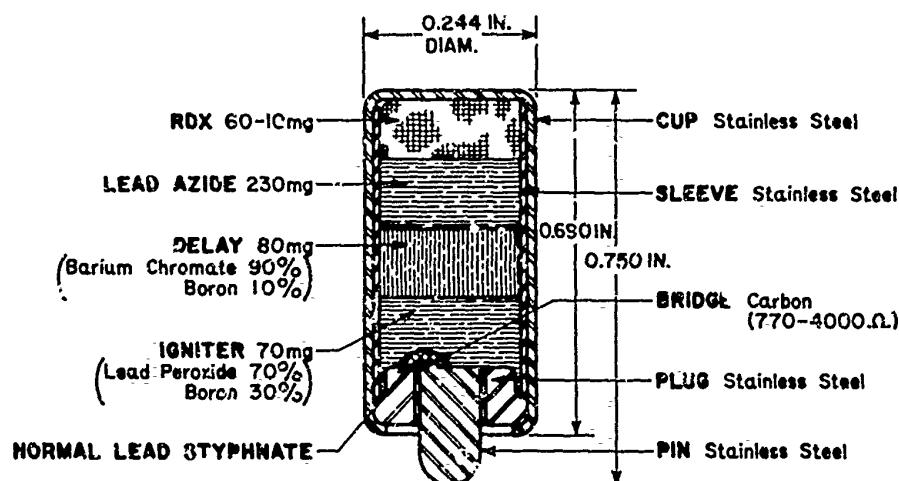


Figure 17-1. Detonator, Delay, T65

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CHAPTER 18

DELAY SYSTEM CHARACTERISTICS

No single pyrotechnic delay mechanism is suitable for all applications. Hence, the selection of a delay device must be based on the overall requirements of the particular military application in which it will be used. Considerations differ depending on whether the delays are vented or obturated and must take into account the space limitations imposed.

18-1 SPACE LIMITATIONS

The designer of a pyrotechnic timer always will be faced with space limitations when trying to fit the device into a military item. Factors affecting the amount of space required are the length of the delay column (a function of the time delay and the delay mix), the diameter of the column (each mix having a particular failure diameter below which propagation is not reliable), internal volume, the need for baffles and retainers, and the method of initiation (i.e., mechanical or electrical).

All of these factors must be taken into consideration and each factor balanced against the other so that an inexpensive, reliable, and rugged item results.

18-1.1 LENGTH

Length is a linear function of delay time: the longer the delay column, the longer it burns. Thus the burning rate of a particular delay composition and the total delay interval desired define column length. Whereas total delay time usually is specified, the determination of burning time is complex.

The delay time in a particular delay device is affected by numerous design parameters. These include delay composition, free volume, heat sink, igniter material, loading conditions, and space limitations. The user must specify the delay time required, the environment under which ignition must take place, and the severity of the environmental conditions from factory to field. Having this information, the designer is in a position to know approximately what delay compositions are required by referring to data on various delay mixes (see par. 21-2.1). Knowing the delay time required and the delay mix and its burning rate, the designer can now determine the approximate column height. If the resulting length exceeds the available space, substitution of another delay mix or the formulation of a new mix may be necessary.

Loading pressure also must be borne in mind in the design of a delay column. Data relating burning rate to density for barium chromate/boron compositions are given in Table 18-1¹. Almost all compositions demonstrate a slow but systematic change of burning rate with loading pressure, although not necessarily to the same extent. While this change suggests using an adjustment of pressure to compensate for lot-to-lot variation in burning rate, the practice of loading gasless delays at pressures between 30,000 and 40,000 psi (and at least 60,000 psi for gas producing compositions) has been established for considerations of ruggedness. It should be remembered that a crack in the delay column can result in a "blow-by" and hence instantaneous functioning. For best results, delay columns should be loaded in increments not over one-half diameter long.

TABLE 18-1
EFFECT OF LOADING PRESSURE ON BaCrO₄-B COMPOSITIONS

	Loading Pressure, 10 ³ psi					
<u>95/5 BaCrO₄-B</u>	<u>36</u>	<u>18</u>	<u>9</u>	<u>3.6</u>	<u>1.3</u>	<u>0.5</u>
Mean burning rate (sec/in.)	1.69	1.60	1.49	1.39	1.29	1.21
Mean burning rate (sec/g)	0.648	0.655	0.645	0.642	0.646	0.693
% Coefficient of Variation	1.2	0.6	0.7	0.7	0.8	0.8
<u>90/10 BaCrO₄-B</u>						
Mean burning rate (sec/in.)	0.670	0.653	0.619	0.586	0.558	0.544
Mean burning rate (sec/g)	0.272	0.276	0.280	0.287	0.297	0.308
% Coefficient of Variation	1.5	0.9	1.1	1.6	2.0	1.8

18-1.2 DIAMETER

The burning of a delay column can be retarded or even extinguished by radial heat losses. These losses become more serious as the column diameter, burning rate, and ambient temperature are reduced. The effects combine to result in a failure diameter associated with delay mix and temperature. For a manganese, barium chromate, lead chromate composition at -60°F, the failure diameter increases from less than 0.109 in. for a 3-sec/in. mix to between 0.156 and 0.203 in. for a 12.5-sec/in. mix¹. As shown in Table 18-2² the effect of column diameter proved to be significant for all 95/5 barium chromate-boron delay systems and for obturated 90/10 barium chromate-boron delays. Present usage indicates that for practical delay mixtures at -65°F, a 0.25 in. diameter is well above the limiting failure diameter¹.

18-1.3 WALL THICKNESS

The wall thickness of the body into which the delay is loaded is another important factor in the design of a delay column. This body serves as a heat sink because the metal body tends to have higher coefficients of heat transfer than the delay composition. It is desirable to have a body that acts as an

infinite heat sink—above a minimum wall thickness the body acts as an infinite heat sink—of sufficient mass to transfer at a constant rate enough of the heat generated so that the burning of the delay column remains approximately constant. If the surrounding wall thickness is increased, delay columns close to their low-temperature failure diameters tend to have larger thermal coefficients. However, the effects of wall thickness becomes less important for materials well above their failure diameters. Fig. 18-1 illustrates the change in delay time with the mass of the metal body³.

18-2 PHYSICAL CHARACTERISTICS OF BODY MATERIAL HOUSING

Another factor to be considered is the strength of the body material. Erratic delay times have been known to result due to yielding under the loading pressure. A conservative way to design the body is to consider it a tube stressed hydraulically and provide adequate strength to prevent yielding.

The quality of materials for the body or subassembly immediately surrounding the delay column is critical. Porosity of the metal envelope or contamination at the interface of body and delay column occasionally can

TABLE 18-2
EFFECT OF FUZE HOUSING MATERIAL AND DIMENSIONS ON BURNING
TIME OF BARIUM CHROMATE-BORON COMPOSITIONS

<u>Parameters</u>	<u>Effect</u>
1. Metal Housings	
a. Aluminum, Brass and Stainless Steel	a. No effect on burning times over test temperatures, internal diameter, wall thickness, and for either vented or obturated columns. b. No interaction between metal and composition.
2. Internal Diameter, in.	
a. 0.250 95/5 vented vs obturated	a. Results for vented columns significantly different at 95% confidence level.
b. 0.375 95/5 vented vs obturated	b. Results for obturated columns significantly different at 95% confidence level.
c. 0.250 90/10 vented vs obturated	c. No significant difference for either column at this diameter.
d. 0.375 90/10 vented vs obturated	d. Results for obturated column significantly different at 95% confidence level.
3. Temperature, °C	
a. - 54, Room Temperature, and 76	a. The effect of temperature was significantly different at the 95% confidence level for all metals, internal diameters, wall thickness, and for vented and obturated columns.
4. Wall Thickness, in. (0.05, 0.15, 0.30, 0.50, 0.75, and 1.00)	
a. 95/5 vented and obturated columns	a. Results for different wall thickness were significantly different, although no apparent trend was observed.
b. 90/10 vented and obturated columns	b. No significant differences or trends in results due to wall thickness for either type of column.

cause erratic performance due to impurities formed by traces of gas.

Many metals as well as plastics and ceramics have been investigated as delay element housings. However, aluminum and brass are the choice of most designers because of fabrication ease and availability, and also because of compatibility of these materials with most delay compositions. It has been shown that the burning times of delay compositions are not affected by the material used for the housing or its thickness above that necessary to resist melting provided that the inside diameter of the housing is well above the failure diameter of the delay composition.

18-3 VENTED DELAYS

Vented delay elements have openings to permit the escape of gases produced by their functioning. They are used when large quantities of gas are produced by the burning of the delay powder. They may even be necessary for gasless compositions when long delay times are required in order to eliminate the pressure build-up within the delay element and subsequent unpredictable burning rates. Venting exposes the burning delay composition to ambient pressure and, as a result, the burning rate is sensitive to changes in altitude except that manganese delay compositions show no significant effect. In addition, these vents require sealing up to the

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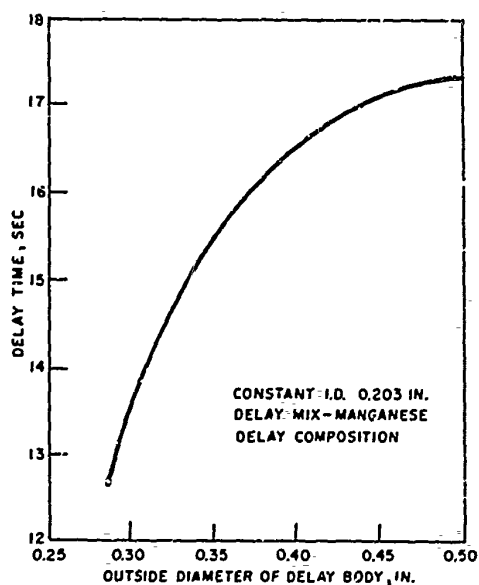


Figure 18-1. Variation in Delay Time With Body Diameter

time of functioning in order to protect the delay element from humidity. Two methods of sealing vented delays—by a disk, Method (A), and by a solder plug, Method (B)—are shown in Fig. 18-2².

18.3.1 INITIATION MEANS

The purpose of the delay initiator assembly, whether it is mechanically or electrically activated, is to produce hot gases and particles which will impinge on the delay column. Delays are easily ignited by the flame of a primer; however, slow-burning delays require an igniter. For ignition charges, see par. 21-1.1; for sensitivity characteristics, par. 21-4.

The initiator assemblies can take several forms. In some instances the assembly contains a charge holder that sits directly on top of the delay column (conventional),

allowing very little or no free volume, as shown in Fig. 18-3(A)⁵. Others use a chimney-type charge holder that may or may not sit on top of the delay column but provides for a free volume in which to vent gases (Fig. 18-3(B)). It also directs and concentrates the hot gases and particles into a definite area.

Another type of pyrotechnic delay assembly frequently uses a configuration employing a primer holder subassembly in which only the primer is held securely. This subassembly then is screwed into, staked into, or otherwise held rigidly in the main delay assembly. The igniter charge is made a part of the main pyrotechnic delay column. Fig. 18-6 illustrates the use of such a primer subassembly.

18.3.2 OUTPUT MECHANISM

The burning rate of a gas producing material is, in general, nearly proportional to pressure. For instance, a 95.4% barium chromate-4.6% boron composition was tested at various external pressures and the results are shown in Fig. 18-4². Examination of the figure shows that an increase in external pressure resulted in a decrease in burning times (an increase in burning rate). The relationship has been shown to be hyperbolic and can be represented by an equation of the form²

$$t = aP^n \quad (18-1)$$

where

t = burning time, sec

P = pressure, lb/in.²

a = factor depending on the mixture, (1/sec) (in.²/lb) ^{n}

n = factor depending on the mixture, dimensionless

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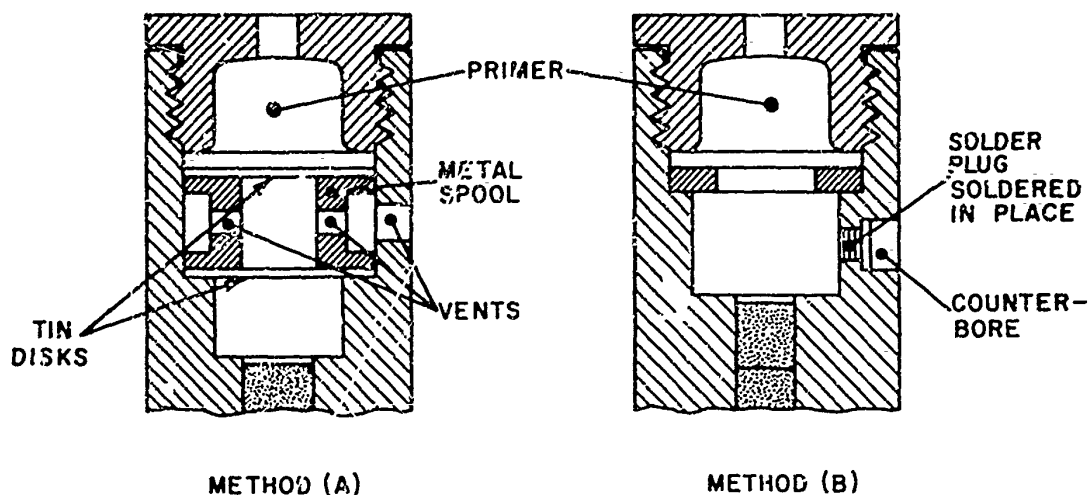


Figure 18-2. Sealing of Vented Delay Element

The numerical values of the factors are $n = 0.13$ and $a = 2.52 \text{ (1/sec) (in}^2/\text{lb)}^{0.13}$ for the 95.4/4.6 barium chromate-boron composition.

Two other barium chromate-boron compositions, 90/10 and 81/19, were investigated for external pressure effects and these results, also shown in Fig. 18-4, indicate no significant change.

As the delay column burns to the end, the base or output charge is ignited. This charge, called the relay charge, must be initiated by the delay mix and have the desired output characteristics as discussed in par. 21-3.1. While the delay column is burning, heat is being transferred through the metal body. In cases of long delay times (5 sec or greater) it may be necessary to insulate the output charge from the delay body if the output charge material is heat sensitive. This can be done by enclosing the output charge in a cup or ring made of insulating material.

18-3.3 BAFFLES AND RETAINERS

The design of a delay column must include means to resist forces such as spin, setback, shock, and internal gas pressure if they are present in the specific application. These forces can cause separation of the delay column and resulting failure, either in the form of no-fire or instantaneous functioning.

This separation usually occurs while the delay column is burning and at the burning front. Here, the material is usually molten and

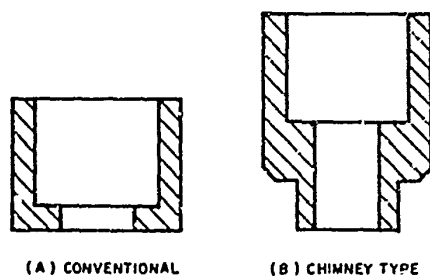


Figure 18-3. Charge Holders

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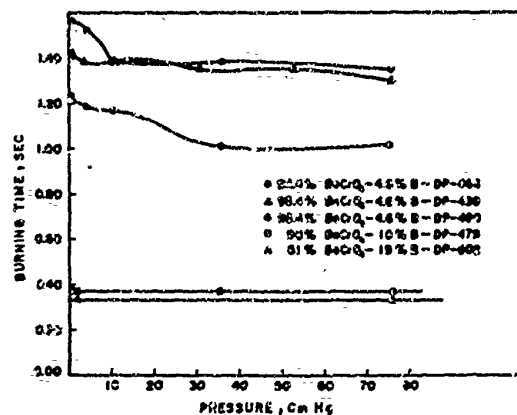


Figure 18-4. Burning Time of Barium Delay Compositions (M112 Fuze)

any of the forces can cause the column to separate on either side of the burning front. Means of alleviating separation include threading the inner diameter well, and using retainer rings and disks. A more successful solution is to baffle both ends of the delay column. These baffles can be in the form of slotted disks, washers, or porous metal disks. A typical baffled delay column is shown in Fig. 18-5³. The baffles are always force fitted into the delay body with approximately 0.002 to 0.005 in. interference fit.

Baffles also are employed between a delay and its primer to reduce blast effects and particle impingement. In general, increasing the free volume between the two will make initiation more difficult. Decreasing confinement of the delay column will have the same effect.

A retainer or delay holder is a separate member into which the delay column and relay element are pressed. When one of these elements is used, the designer may take advantage of a different material from that of the body, thus providing a better heat sink or other advantages such as good mechanical strength, while the body material can be selected for lighter weight, if desired.

18-4 OBTURATED DELAYS

An obturated delay element is constructed to retain all the gases produced by the functioning of the initiator and delay composition before the base or terminal

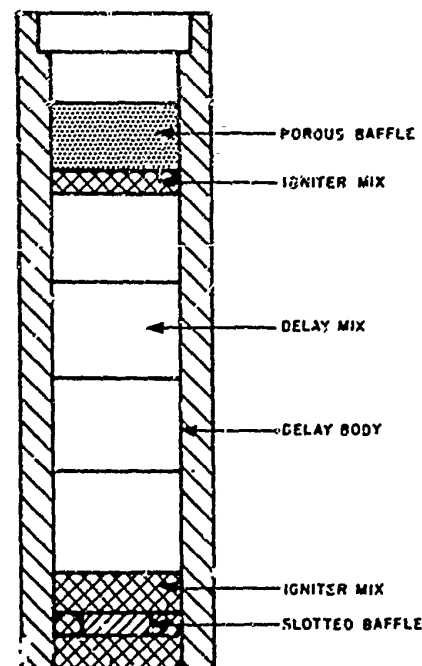


Figure 18-5. Typical Baffled Delay Column

charge is ignited, see Fig. 18-6². See par. 21-2.1 for delay charges.

Delays are considered to be obturated if the gases produced are vented internally into a closed volume in the pyrotechnic device. The effects of ambient pressure and humidity are eliminated in obturated delays because they are sealed from the external environment. Possible harm to other components of the system is prevented because the combustion products are contained. If a short time delay is required, an obturated delay often is used because obturation tends to increase the average burning rate of the delay composition.

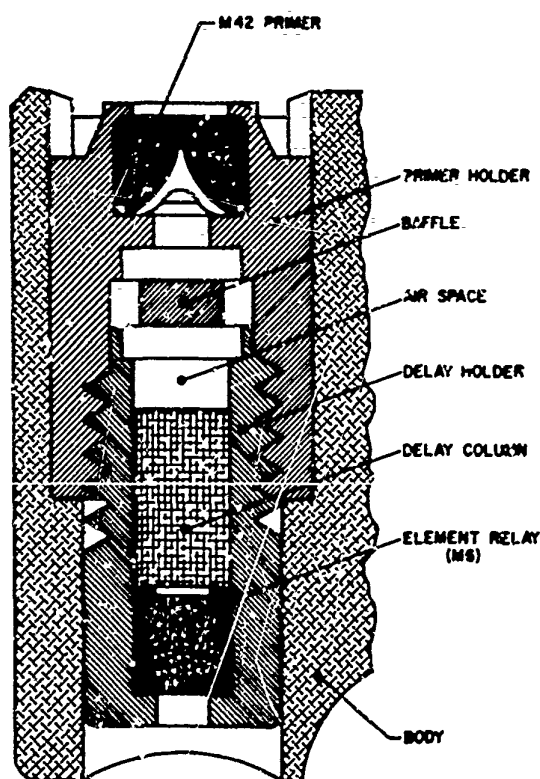


Figure 18-6. Delay Element, Obturated, M9

18-4.1 INITIATION MEANS

When the primer or flash charge is ignited in an obturated system, the pressure in the enclosed free volume is increased. At first, this happens very quickly and then the pressure is increased progressively by gas liberated by the burning delay column.

As a result, the burning rate accelerates continuously and is usually nearly proportional to pressure. Unless the free volume is increased along with the delay column length, the delay time does not increase directly. This requirement for a volume that is nearly proportional to the delay time limits obturated gas-producing delays to about 0.4 sec with a column diameter commonly in the range of 0.1 to 0.125 in.¹. In addition to its direct relationship to the free volume, the delay time of an obturated delay element is related inversely to the gas volume and heat of explosion of the primer, see Fig. 18-7¹. See par. 21-1.1 for ignition charges.

18-4.2 OUTPUT MECHANISM

The need for a volume proportional to delay time is discussed in par. 18-4.1. After the delay column burns to the end, it ignites the relay. See par. 21-3.2 for output charges.

18-4.3 BAFFLES AND RETAINERS

Baffles and retainers are included in an obturated design for the same reasons that they are used in the vented design. Design considerations are the same in either instance, see par. 18-3.3.

18-4.4 INTERNAL FREE VOLUME

The internal free volume is that volume formed by a cavity in the delay housing which is designed to contain the gases produced by the chemical reaction. Containing the gases makes the delay independent of the effects of pressure or humidity of the ambient atmo-

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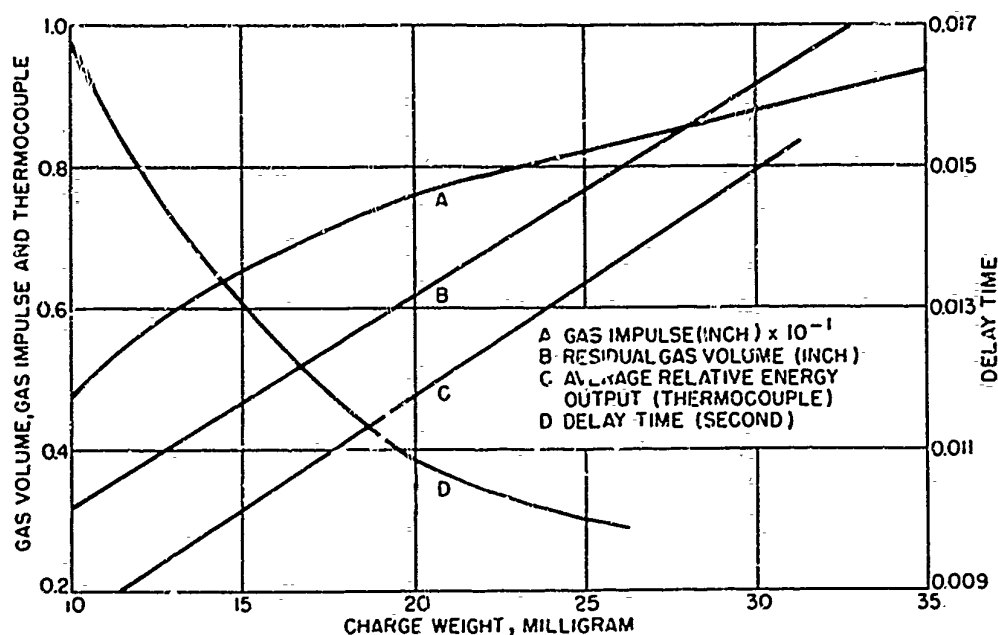


Figure 18-7. Characteristics of an Obturated Black Powder Delay Element

sphere and the fumes which might have harmful effects on other components of the system.

In an obturated system, the time will be greatly increased or the item may not burn through if the pressure rise is sufficient to cause bursting or significant leakage. The pressure can be calculated by defining the thermodynamic relationship between the heat and gas volume liberated by the primer, and delay column and the enclosed free volume in which the gases are confined. A reasonable estimate, for design purposes can be derived from the empirical equation¹

$$P = \frac{30 (W_p + W_d)}{V} \quad (18-2)$$

where

P = pressure, lb/in.²

W_p = weight of priming composition, mg

W_d = weight of delay composition, mg

V = enclosed free volume, in.³

Using this equation, the designer can run through a series of calculations, varying the weights of priming and delay compositions and the free volume in order to obtain a safe pressure.

18-4.5 SEALS AND CLOSURES

The three major elements of a pyrotechnic timer (initiator, delay column, and base charge) usually are integrated into one body or housing. It is good practice to design for hermetic sealing. Sealing is desirable even when venting is necessary and is achieved in a number of ways. Stab-initiated delay devices are sealed and obturated until initiation. The puncture caused by the firing pin allows venting. In percussion-initiated delays, venting, if required, may be obtained by use of blow-out disks or plugs (Fig. 18-2). A system

of double cups has been employed in electrically initiated devices which allows them to be hermetically sealed until, at initiation, the thin-walled cup is fractured by the initiator output allowing the gases to be vented. In some instances, hermetic sealing is required in addition to venting. It is possible to seal the delay device into a tube or container of sufficient volume to provide an adequate vent volume. Figs. 18-8⁴ and 18-9⁴ are typical examples of hermetically sealed delay actuator devices. An experimental percussion-initiated delay detonator is shown in Fig. 18-10⁵.

18-5 SYSTEM DESIGN AND PERFORMANCE

In delay system design, the delay compositions being the critical component of the delay element, should ideally have the following characteristics:

(1) They should be stable and nonhygroscopic; should have the highest purity consistent with requirements; should be readily available and inexpensive; and should be compatible with each other.

(2) They should be as insensitive as possible, meaning they should be capable of

being blended, loaded, and assembled into an item with minimum risk from impact, friction, moisture, heat, and electrical discharge.

(3) They should be readily ignitable, and should change little in performance characteristics with small changes in percentages of ingredients. Their burning rates should be reproducible within each batch and from batch to batch with a minimum of variation.

(4) They should be compatible with their container as well as with other contacting compositions. Performance characteristics should not change appreciably with long term storage.

(5) They should be relatively insensitive to changes in pressure and temperature.

(6) They should be capable of withstanding the vibration and shock of transportation, setback, rotation, and impact, and should be resistant to physical abuse inherent in the loading and firing of ammunition.

Pyrotechnic designers must continue to explore new compositions and investigate the effects of parameter changes when existing or new compositions are rearranged in their

All dimensions in inches

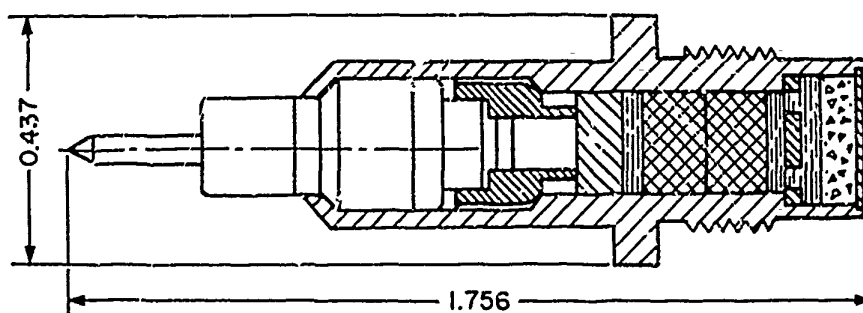


Figure 18-8. Stab Initiated Delay Actuator (MARK 14 MOD 0)

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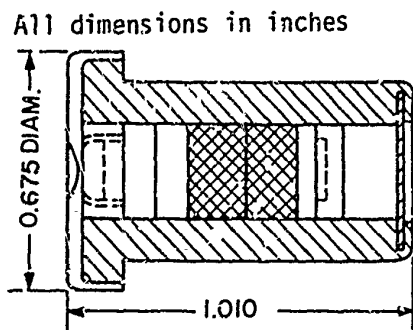


Figure 18-9. Electrically Initiated Delay Actuator (MARK 18 MOD 0)

metal parts, when metal parts themselves are varied in their geometry and metallurgy, and when combinations of these may yield a new end item.

The intended end-item requirement of the delay element will guide the choice of the most suitable type. If timing is to be controlled carefully, selection of obturated elements is called for; if operational physical abuse is severe, the inclusion of a binder seems the correct approach. Extreme climatic diversification or use outside the earth's appreciable atmosphere would call for prime consideration of obturated designs. Other considerations to be considered include the method of ignition, the delineation and tolerancing of housings, their physical properties, their costs or the costs of the assembly.

18-5.1 SYSTEM ASSEMBLY PROCEDURES

In the assembly of pyrotechnic timers the procedures vary according to the type of delay (i.e., vented or obturated). For instance, in an experimental obturated percussion delay (Fig. 18-10), the delay body is loaded before the detonator is crimped in place or the primer assembly is screwed into the body. The detonator cup is loaded before assembly. The seal is provided at one end by the

shoulder of the primer holder bearing on the primer flange and the soft metal primer washer. Sufficient igniter is loaded into each end of the delay space to transfer ignition to and from the delay.

In a vented delay, the vents often are sealed or plugged before the delay element is assembled to protect the element from adverse atmospheric conditions, to facilitate the ignition of the composition, or both (see par. 18-4.5). If the vent is not sealed, the requirement of surety of ignition of the delay column by the primer will limit the size of the vent, which in turn limits the time that the burning rate can be slowed down to conserve space. Any sealing of the vent should be broken as the primer is initiated, therefore, the seal cannot be too firm.

The delay body must be loaded before assembly. It is important that the delay composition be loaded flush with the end of the delay body. If this is done, the delay

All dimensions in inches

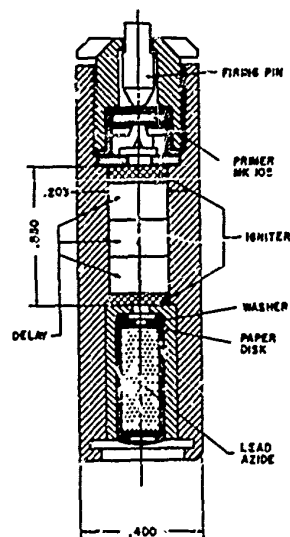


Figure 18-10. Experimental Obturated Percussion Delay Detonator

mixture is held firmly in place when the delay body is screwed tight into the holder. In cases where loaded black powder is pressed against metal, it is considered good practice to insert a thin paper disk between the powder and metal to serve as a cushion and thus to minimize the possibility of initiating the powder by friction.

Visual inspection of the bore surface of the delay body with a magnifying glass should disclose no tool marks or scratches running in an axial direction because these are conducive to blow-bys. Sharp edges (no burrs) are desirable at the ends of the bore. Concentricity between the bore and the expansion chamber, and smoothness of the bore are necessary to facilitate the use of a close-fitting loading ram with the bore⁵.

Information relating to the packaging of the assembled item either individually or mounted in the military end item are covered in par. 20-1.

18-5.2 PERFORMANCE REQUIREMENTS

There are a number of factors that influence the performance of a pyrotechnic delay timer. These include:

- (1) Quantity of charge (delay time)
- (2) Vented vs obturated design
- (3) Pressure and temperature environment
- (4) Output charge (relay)
- (5) Column diameter
- (6) Loading and production techniques
- (7) Storing and handling
- (8) Delay compositions.

The important aspects of factors (1)

through (5) have been discussed while factors (6), (7), and (8) are the subjects of Chapters 19, 20, and 21, respectively.

Because delay compositions contain all ingredients necessary for a self-propagating reaction, their burning is metastable. The effect of any factor that tends to cause an increase or decrease in burning rate is magnified. For this reason, satisfactory performance requires accurate control of all such factors. Control must be maintained from the procurement of raw materials until the end item, in which the delay is a component, accomplishes its intended use. The designer should be governed, therefore, by the following rules:

(1) Use delay compositions prepared by a well-established procedure from ingredients of known and controlled characteristics.

(2) Use obturated or externally vented construction when practical.

(3) Where obturated construction is impractical, use a seal that opens upon ignition.

(4) If a sealed unit is not practical, use delay compositions of demonstrated resistance to conditions of high humidity.

(5) Calculate the effect of cumulative tolerances upon such pertinent factors as external free volume.

(6) Provide for adequate free volume in obturated units.

(7) Analyze stresses induced by both internal and external forces that may be anticipated during loading, shipping, launching, and operation.

(8) Make sure that all components will survive these stresses, taking into account the elevated temperatures that result from burning of the delay columns.

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(9) Specify adequate loading pressures (at least 60,000 psi for gas producing compositions and at least 30,000 psi for gasless delay powders), and short enough increments (one-half diameter or less).

(10) Provide for proper support of the delay column.

(11) Use diameters well above the failure diameter at -65°F . (Usual practice is 0.2 or 0.25 in. for gasless mixtures; 0.1 or 0.125 in. for black powder.)

REFERENCES

1. AMCP 706-179, Engineering Design Handbook, *Explosive Trains*.
Fuze Committee, 5 December 1961 (AD-270 444).
2. AMCP 706-185, Engineering Design Handbook, *Military Pyrotechnics, Part One, Theory and Application*.
3. *Some Aspects of Pyrotechnic Delays*, Journal Article No. 22.0 of the JANAF
4. MIL-HDBK-137, *Fuze Catalog, Vol. 3, Fuze Explosive Components*, Dept. of Defense, 20 February 1970.
5. *Ordnance Explosive Train Designers' Handbook*, U S Naval Ordnance Laboratory, Silver Spring, Md., Report NOLR 1111, April 1952 (AD-029 151).

CHAPTER 19

PRODUCTION TECHNIQUES

19-1 GENERAL

The production of pyrotechnic timers involves a series of steps starting with selection and processing of the pyrotechnic ingredients, production of metal parts, and ending with final assembly. It is important in the selection and processing of the ingredients that their chemical and physical properties are known in advance, especially particular hazards to personnel and property caused by the reaction of these materials to various stimuli. For detailed information on the properties of pyrotechnic materials, see Ref. 1. The laboratory and plant procedures that must be followed for the safe production of pyrotechnic compositions are described in the *Safety Manual*², and processing procedures are listed in Refs. 3 and 4. The production of the metal parts that house the pyrotechnic compositions involves techniques that are covered in detail in pars. 14-1 and 14-2.

19-2 DESIGNING FOR MASS PRODUCTION

As a rule of thumb, small explosive components (initiators, delays, relays) are pressed. The most common procedure for pressing powdered explosives is pouring the powder into a mold and pressing it with a ram that fits snugly. The pressure most frequently specified for charges used in military items is 10,000 psi. Charges may be pressed directly into their containers or pressed into molds and ejected as pellets. When a container of length greater than its diameter is used, the explosive usually is loaded in increments that are one diameter long.

Explosive charges are first weighed or measured and then pressed either directly into place or into pellets. If the explosive is pelletized, the pellets usually are reconsolidated by being pressed into place.

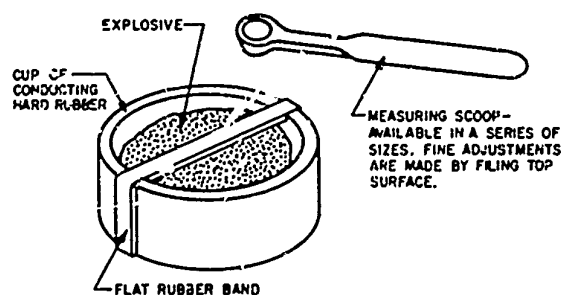


Figure 19-1. Scoop Loading

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19-2.1 MEASUREMENT OF EXPLOSIVE CHARGES

The desire is always to load a specific weight of explosive. For small test quantities or for some premium quality production, direct reading, one-pan balances are used that provide an accuracy within one percent⁵. The two most common volumetric measuring devices are scoops and charging plates. To obtain the desired weight, the loading plant must adjust the volume to account for bulk density. Scoops (Fig. 19-1⁵) are filled and leveled against a rubber band. Careful scooping is accurate within 4 percent⁵. Charging plates (Fig. 19-2⁵) lend themselves to production rates. After filling the holes in the top plate and scraping off the excess, plates are aligned with the cup holes.

19-2.2 DIRECT PRESSING

Fits and tolerances of explosive charge cases and loading tools must be determined by consideration of (1) production costs, (2)

clearances between run and case, and (3) binding resulting from interference between run and case. The cost of a set of loading tools is, of course, distributed over a large number of items.

Production loading tools should be hardened (60 Rockwell C is common), and the die should be lapped and polished. Cups are supported by close fitting loading tools while the charge is being pressed. Standard dimensions and tolerances of cups are listed in MIL-STD-320⁶. When loading explosives directly into an assembly, a pin is used to hold the component in alignment while loading. Fig. 19-3⁵ shows equipment for hand loading of leads.

A quantity of explosive can be pressed either to a controlled height (stop loading) or to the limit of an applied load for a given diameter (pressure loading). Stop loading is faster but not as accurate as pressure loading. In normal production, a reasonable weighing tolerance for initiator charges is three or four

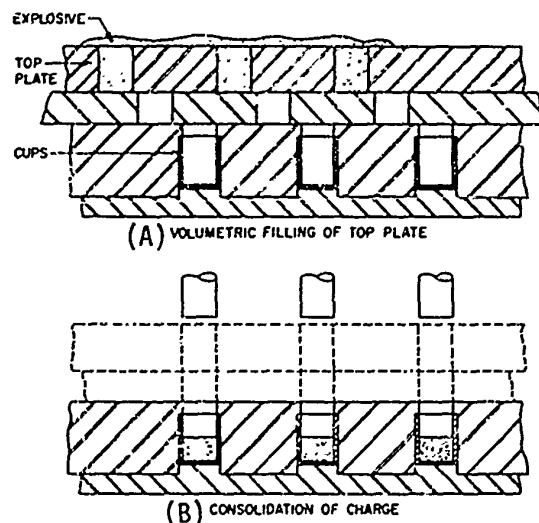


Figure 19-2. Charging Plate Loading

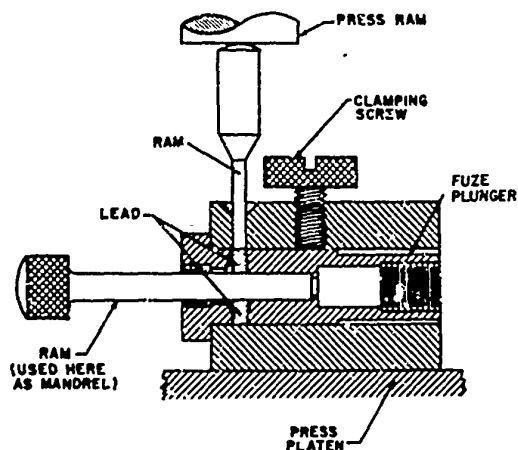


Figure 19-3. Tool for Direct Loading of Component

percent. In stop loading, if the height of an increment is exactly reproduced, the density may vary as much as seven percent⁵. In either type of loading, the density should be checked for each production lot.

19-2.3 PELLETIZING

Many powdered explosives are prepressed into pellets. Better finishes are obtained than for cases loaded by direct pressing. Quantity production of pellets is accomplished on automatic pelleting machinery, in which the explosive is metered volumetrically by controlled movement of punches. Single-stroke presses produce about 90 pellets per minute while rotary presses have rates of about 700 pellets per minute⁵. Immediate expansion upon ejection is about 0.3 percent. Pellet-to-pellet variations are usually less than 0.1 percent⁵. With frequent pellet density checks and adjustment of the pelleting press, pellets can be made reproducibly to one percent in an automatic pelleting press.

19-3 REQUIREMENTS FOR TECHNICAL DOCUMENTATION

Production requires complete documentation that is assembled into a technical data package. This documentation is to ensure that military items are capable of reliably performing the functions for which they were designed. See par. 14-4 for detailed information on the contents of a technical data package.

REFERENCES

1. AMCP 706-187, Engineering Design Handbook, *Military Pyrotechnics, Part Three, Properties of Materials Used in Pyrotechnic Compositions*.
2. AMCR 385-100, *Safety Manual*, Army Materiel Command, April 1970.
3. F. B. Pollard and J. H. Arnold, Eds., *Aerospace Ordnance Handbook*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1966.
4. AMCP 706-186, Engineering Design Handbook, *Military Pyrotechnics, Part Two, Safety, Procedures and Glossary*.
5. AMCP 706-179, Engineering Design Handbook. *Explosive Trains*.
6. MIL-STD-320, *Terminology, Dimensions, and Materials of Explosive Components for Use in Fuzes*, 3 August 1959.

CHAPTER 20

PACKING, STORING, AND SHIPPING PROCEDURES

20-1 GENERAL

Military materiel is packaged to protect it from harmful environments, including transportation. Packaging will protect the item after production, during storage, during transport, and until delivery to its ultimate user¹. During the transportation phase, which includes both handling and carriage, the Department of Transportation (DoT) regulations must be strictly observed for movement within the U.S. Since items must be stored for long periods, they must be protected against physical damage and deterioration; it may also be necessary to conduct periodic inspections of stored materiel.

From the military standpoint, good packaging methods protect the item through all phases and environments with minimum cost. Items must be protected for one of three required levels: overseas shipment (Level A), long-term storage (Level B), or interplant shipment (Level C).

The most damaging environments during transportation by truck, rail, ship, or aircraft are usually shock vibration. However, temperature extremes and other potentially harmful environmental factors should be considered as relevant to damage assessment or prevention.

These subjects are treated in more detail in Chapter 15; see par. 15-1 for packing, par. 15-2 for storing, and par. 15-3 for shipping.

20-2 SAFETY

Pyrotechnic timers like other military materiel also must be suitably packaged at

minimum cost. These timers, as well as the munitions of which they are a part, are subject to another important requirement: they must be safe during packing, storing, and shipping.

Explosives and pyrotechnics can be shipped and stored safely if they are handled correctly and carefully, and with all of the necessary precautions. The safety record of both the military and the explosives industry is a result of careful preparation, not chance. Pyrotechnics are set off by energy concentrations such as sparks, friction, impact, hot objects, flame, chemical reactions, and excessive pressure. Established safety practices will avoid these conditions in order to minimize hazards.

Probably the most important aspect of safety is a correct individual attitude. The *Navy Transportation Safety Handbook*² puts it this way:

"It is imperative that anyone who is engaged in the handling, transportation, or storage of ammunition, explosives, and other dangerous articles think safety, act safety, and live safety until it becomes a habit. Accidents usually result from failure to observe regulations, failure to understand hazards, or failure to take necessary precautions. In each case, the 'failure' denotes human error, and human error denotes ignorance, specific carelessness, or poor judgment. The individual must realize that when he does not comply with safety regulations, he not only endangers his own life, but also puts his fellow worker's life in jeopardy. In the military, safety responsibility follows the line organization.

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The commanding officer is responsible for the accident-free performance of his supervisors and their individual employees. A superior is not exonerated for an employee's poor judgment, carelessness, or failure to comply with safety regulations. The supervisor must advise and train his men so that they are constantly aware of the hazardous nature of their work. Further, he must indoctrinate his men with the philosophy that each individual is responsible for his own and his fellow worker's safety. And he must promote safety-mindedness by persuasion and by authoritative force when necessary."

The basic reference for safety is the *Safety Manual*³. It contains detailed discussions of the established safety practices for packing, storing, and shipping. These topics are discussed in the paragraphs that follow. The reader is referred to the *Safety Manual* for the following related safety topics that are outside of the scope of this Handbook:

- (1) Building construction features
- (2) Material handling equipment
- (3) Hand and machine tools
- (4) Electrical equipment and wiring
- (5) Lightning and static electricity protection
- (6) Fire fighting
- (7) Protective clothing and equipment
- (8) Good housekeeping practices.

The safety regulations have been slightly abbreviated and rearranged in two volumes for Department of Defense agencies⁴ and their contractors⁵. These separate publications, available from the Superintendent of Documents, U S Government Printing Office, are convenient references.

20-3 HAZARD CLASSIFICATION

Dangerous materials are arranged into eight classes according to their level of hazard. Pyrotechnics are divided into classes 1 and 7, depending on whether they merely burn or whether they can detonate. Class 1 items are those which have a high fire hazard but no blast hazard and for which virtually no fragmentation or toxic hazard exists beyond the fire hazard clearance distance ordinarily specified for high-risk materials. In contrast, class 7 items are those for which most items of a lot will explode virtually instantaneously when a small portion is subjected to fire, severe concussion, impact, the impulse of an initiating agent, or considerable discharge of energy from an external source⁵.

Pyrotechnic timers usually are packed, shipped, or stored as components of military ammunition. The ammunition assembly defines the hazard class. It is not feasible to specify here the hazard classes of all munitions that contain pyrotechnic timers. However, this information is tabulated in the *AMC Safety Manual*³, which lists ammunition classes, and in the *Navy Safety Handbook*², which lists every munition by Federal Stock Number.

The hazard and shipping class must be established before an item containing pyrotechnics can be packed, shipped, or stored. If the hazard class of a particular pyrotechnic delay has not been established, it must be obtained by means of standard tests devised for this purpose⁶.

20-4 PACKING

Pyrotechnic timers and ammunition containing them must be packed properly. Packing drawings and specifications have been prepared for essentially all military items containing hazardous materials. The drawings and specifications cover all applicable details of wrapping, boxing, bracing, palleting, and

handling. If such drawings and specifications are not available for a particular item, Department of Transportation regulations apply and they specify minimum requirements. Packing for different levels of protection are discussed in par. 15-1.

Federal regulations require all containers of hazardous materials be conspicuously marked and labeled.

20-5 STORING

Hazardous materials are stored in accordance with quantity-distance requirements. These requirements are defined as "the quantity of explosives material and distance separation relationships which provide defined types of protection. These relationships are based on levels of risk considered acceptable for the stipulated exposures and are tabulated in the appropriate quantity-distance tables. Separation distances are not absolute safe distances but are relative protective or safe distances"⁴.

Quantity-distance tables are contained in the safety manuals³⁻⁵; a typical excerpt is shown in Table 20-1³. The largest minimum distances are required where a hazard exists to personnel, i.e., inhabited buildings. Intraline refers to the minimum distance between any two buildings within one operating line or assembly operation. The magazine distances given in the excerpt are for above-ground storage, which is the least desirable. Earth-covered, arch type magazines are preferred because they are safer; their required separation distances are much less than those of above-ground magazines. Note that separation distance is roughly proportional to the quantity of explosive, and that a barricade of proper construction cuts in half the distance used for unbarricaded storage.

To determine distances between different types of magazines, Ref. 4 is the easiest to

use. It contains a group of diagrams like the following:



It states that the minimum distance from a barricaded above-ground magazine to the door end of an earth-covered, arch type magazine is found in Table 5-6.3, column 5 in the reference.

In addition to quantity-distance, compatibility also must be considered in storage. Only compatible hazardous items may be stored together in one magazine. Compatibility is established by consideration of the following factors³:

- (1) Effects of explosion of the item
- (2) Rate of deterioration
- (3) Sensitivity of initiation
- (4) Type of packing
- (5) Effects of fire involving the item
- (6) Quantity of explosive per unit.

20-6 SHIPPING

The safe transport of hazardous materials is the responsibility of the shipper. It has become expedient to pack and label hazardous cargo to meet requirements for all kinds of transportation. The Navy is the largest shipper of military cargo because most of it ultimately ends up aboard ship. If a commercial shipper is used, he should be properly licensed in all states and countries involved. Shipping regulations are complex and a qualified shipper is needed to cope with them.

All safety regulations are enforced in the

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TABLE 20-1

EXCERPT FROM QUANTITY-DISTANCE TABLES

Pounds of Explosive	Distance, ft							
	Inhabited Building		Highway & or Railway		Intraline		Above Ground Magazine	
	<u>bar.</u>	<u>unbar.</u>	<u>bar.</u>	<u>unbar.</u>	<u>bar.</u>	<u>unbar.</u>	<u>bar.</u>	<u>unbar.</u>
Class 1								
No limit		100		100		100		80
Class 7								
1	40	80	25	50				
10	90	180	55	110	30	40		
100	190	380	115	230	40	80	28	51
1,000	400	800	240	480	95	190	60	110
10,000	865	1730	520	1040	200	400	130	235
100,000	1855	3630	1115	2180	415	830	280	510
500,000	4510	4510	3245	3245	715	1430	475	875

shipment of hazardous materials to protect life, property, and the cargo itself. All cargo must be properly blocked and braced during shipment. For some hazard classes, the vehicle must be placarded and inspected. Mixed shipments in the same vehicle must be compatible. In case of an accident on any mode of shipping, Form F5800 must be filed with the Department of Transportation when the incident involves death or serious injury, \$50,000 property damage, or continuing danger.

Considerations for specific modes of shipping follow:

(1) Rail Transport. Railroad shipment of hazardous materials is covered in Department of Transportation Tariff No. 25⁷.

(2) Truck Transport. Motor Vehicle shipment of hazardous materials is covered in Department of Transportation Tariff No. 11⁸. Motor vehicle shipment is more complex than

rail shipment. A train is made up of many cars watched over by the engineer in front and caboose personnel behind. The engineer is in voice communication with the tower. The railroad controls traffic flow over its route. It provides trained inspectors. In contrast, each truck solos. It has no control over traffic on the public highway, and the driver must cope with any situation that may arise.

For these reasons, drivers of hazardous materials are given careful training and detailed instructions (e.g., Ref. 9), and the vehicle is carefully inspected for safety (e.g., lights and brakes) and compliance with local laws (e.g., weight limit).

(3) Ship Transport. All water shipment is regulated by the Coast Guard¹⁰. There are many restrictions to the transport of hazardous materials by ship which must be taken into account. Some dangerous articles are not permitted on passenger carrying vessels. Also, many ports do not permit the anchorage of

vessels carrying dangerous articles. The Army Corps of Engineers therefore has established suitably isolated explosives anchorages at various ports.

(4) Air Transport. Aircraft shipment of

hazardous materials is covered by Department of Transportation Tariff No. 6-D¹¹. As in ship transportation, dangerous cargo is prohibited on passenger carrying craft.

REFERENCES

1. AMCP 706-121, Engineering Design Handbook, *Packaging and Pack Engineering*.
2. OP 2165, *Navy Transportation Safety Handbook*, Naval Ordnance Systems Command.
3. AMCR 385-100, *Safety Manual*, Army Materiel Command, April 1970.
4. DOD 4145.27M, *DOD Ammunition and Explosives Safety Standard*, Dept. of Defense, March 1969.
5. DOD 4145.26M, *DOD Contractors' Safety Manual for Ammunition, Explosives and Related Dangerous Material*, Dept. of Defense, October 1968.
6. TE 700-2, *Explosives Hazard Classification Procedures*, Dept. of Army, 19 May 1967.
7. R. M. Graziano, Agent, *Hazardous Materials Regulations of the Department of Transportation*, Tariff No. 25, Association of American Railroads, Washington, D.C., 1972.
8. Tariff No. 11, *Regulations for Transportation of Explosives and Other Dangerous Articles by Motor, Rails, and Water, Including Specifications for Shipping Containers*, published by Agent F. G. Freund, American Trucking Assoc., Inc., 1616 P St., N.W., Washington, D.C. 20036.
9. OP 2239, *Drivers Handbook - Ammunition, Explosives, and Other Dangerous Articles*, Naval Ordnance Systems Command.
10. CG 108, *Rules and Regulations for Military Explosives and Hazardous Munitions*, U S Coast Guard.
11. Tariff No. 6-D, *Official Air Transport Restricted Articles Tariff*, published by C. C. Squire, Airline Tariff Publishers, Inc., Agent, 1825 K Street N.W., Washington, D. C. 20006.

CHAPTER 21

PYROTECHNIC DELAY COMPONENTS

The delay element is the heart of the pyrotechnic timer. The timer also includes an initiator and a relay or output charge. A knowledge of (1) the various ways of applying input stimulus, (2) the delay compositions currently in use and their characteristics, (3) the relay or output charge, and (4) the sensitivity of the delay compositions to external stimuli will aid the designer in meeting the system specifications.

21-1 INITIATORS

The first element of the explosive train of a pyrotechnic timer is the initiator or primer. It is categorized according to its input stimulus as (1) stab, (2) percussion, or (3) electric and according to its output as (1) pressure or (2) flame. Stab and percussion primers are known as mechanical primers.

The primer is a transducer that converts mechanical or electrical energy into explosive energy. It contains materials sensitive to stimuli such as heat or impact, has a relatively small explosive output, and is not designed to initiate secondary high explosive charges.

21-1.1 STAB PRIMER

21-1.1.1 Construction

The stab primer is a rather simple item consisting of a cup made of aluminum, stainless steel, copper, or gilding metal. It is loaded with explosives and covered with a closing disk that is crimped in place. MIL-STD-320¹ describes design practices and specifies standard dimensions, tolerances, finishes, and materials for initiator cups. Two examples of stab primers are shown in Fig. 21-1². For more detailed information on the

design of initiators, see Ref. 3.

21-1.1.2 Ignition Charge and Loading

Stab primers are initiated by a pointed firing pin that punctures the cup. The energy required to fire stab primers increases nearly linearly with the thickness of the metal which the firing pin penetrates. It is also a function of the firing pin dimensions and tolerances, and the composition and density of the priming mix. Table 21-1³ lists the common primer mixtures.

Most explosive charges are loaded by pressing them directly into cups at pressure between 10,000 and 20,000 psi. It is the usual practice, when the charge of an explosive is longer than its diameter, to load in increments

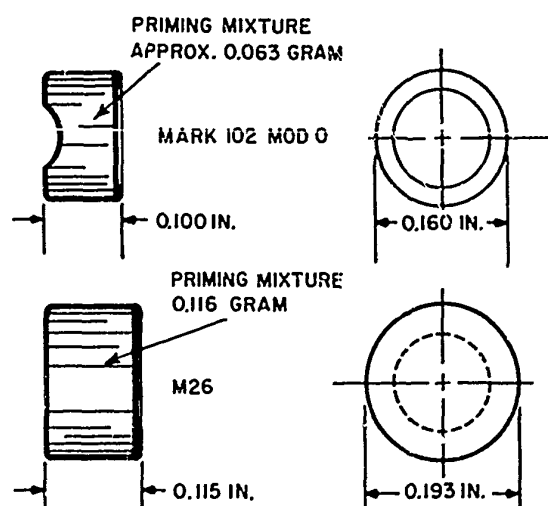


Figure 21-1. Typical Stab Primers²
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TABLE 21-1
COMMON PRIMING COMPOSITIONS

Ingredients	Composition, (percent by weight)					
	FA956	FA982	PA100	PA101	NOL50	NOL130
Lead Styphnate, basic	—	—	—	53	60	40
Lead Styphnate, normal	37	36	38	—	—	—
Barium Nitrate	32	22	39	22	25	20
Lead Azide	—	—	—	—	—	20
Tetracene	4	12	2	5	5	5
Lead Dioxide	—	9	5	—	—	—
Calcium Silicide	—	—	11	—	—	—
Aluminum Powder	7	—	—	10	—	—
Antimony Sulfide	15	7	5	10	10	15
PETN	5	5	—	—	—	—
Zirconium	—	9	—	—	—	—

not over one diameter long (see par. 18.1.1).

21-1.2 PERCUSSION PRIMER

21-1.2.1 Construction

The percussion primer differs from the stab primer; it is fired by a firing pin that does not puncture the container. The essential components of a percussion primer are a cup—commonly brass—a thin layer of priming mix, a sealing disk, and an anvil. Percussion Primer, M42 is shown in Fig. 18-6 and Percussion Primer, M39A1 is shown in Fig. 21-2³. In general, percussion primers require more input energy to function than stab primers. For more detailed information see Refs. 1 and 3.

21-1.2.2 Ignition Charge and Loading

Priming compositions for percussion

primers are shown in Table 21-1. The loading pressures of percussion primers are similar to those of stab primers. Loading pressure has a negligible effect upon sensitivity of percussion primers in the range from 10,000 to 60,000 psi. Firing energy requirements can be expected to increase with thickness and hardness of the primer cup, and with thickness of the primer mix between anvil and cup.

21-1.3 ELECTRIC INITIATOR

21-1.3.1 Construction

Electric initiators contain the initiation mechanism as an integral part. A plastic plug holding the initiation mechanism makes up one end of the cylindrical housing. Electrical connection is by means of lead wires or pins. Electric Squib, M2 is shown in Fig. 21-3³. As a group, electric initiators are more

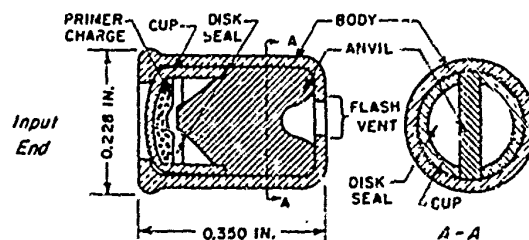


Figure 21-2. Percussion Primer, M39A1

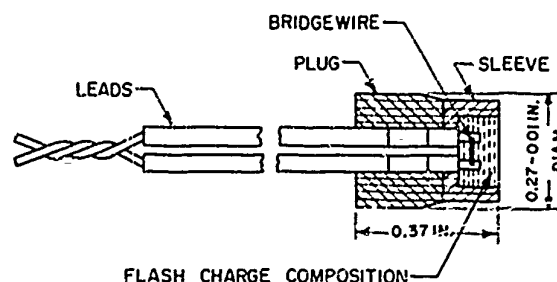


Figure 21-3. Electric Squib, M2

sensitive than mechanical primers. While several types of transducers have been employed—viz., hot wire bridge, exploding bridgewire, carbon bridge, conductive mix, and spark gap—the hot wire bridge is the most common initiation mechanism. See Ref. 3 for detailed design information.

21-1.3.2 Ignition Charge and Loading

The input characteristics of electric initiators are subject to precise control over quite remarkable ranges. Firing energies can be selected to range from less than one erg to thousands of ergs, current requirements from hundredths to hundreds of amperes, and resistance from a few hundredths of an ohm to tens of megohms. The input sensitivity varies with the type of transducer and each type must be considered separately.

The explosive in direct contact with the bridgewire is known as the spot charge. Whereas normal lead styphnate has the broadest general use, lead azide has been used for applications where extremely rapid response is needed. Information is given in MIL-L-17186⁴ for normal lead styphnate and MIL-L-3055⁵ for lead azide. Basic lead styphnate, as procured under specification MIL-L-16355⁶, has particle sizes in the range between 5 and 95 micron which is highly satisfactory for spot charges.

Loading pressure may either increase sensitivity by improving contact between wire and explosive or decrease it by increasing the rate of heat dissipation through the explosive.

In lead styphnate, loaded at pressures between 1000 and 4000 psi, the latter trend apparently predominates. On the other hand, lead azide loaded at pressures between 3000 and 90,000 psi becomes more sensitive as loading pressure is increased.

The response times of hot bridgewire initiators fired by capacitor discharge vary with spot charge material as well as bridgewire characteristics. Information that is needed to design hot bridgewire initiators is available, including design data on bridgewire material, size, diameter, and resistance as well as firing energy and power³.

21-2 DELAY ELEMENTS

The delay element consists of a metal tube, usually aluminum or brass, loaded with a delay composition. It is placed between the initiator and the relay or other output charge. Sometimes all three are combined into one unit. See pars. 18-2 and 18-3 for design details of vented and obturated delays. Fig. 18-2 shows an example of a vented delay element while Fig. 18-6 shows an example of an obturated delay element. Data on representative delays covering various time ranges have been compiled. In the paragraphs that follow there is a discussion of the basic chemistry of delays and the characteristics of various compositions that are used.

21-2.1 BASIC CHEMISTRY OF DELAY COMPOSITIONS

The basic ingredients of a delay composi-

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TABLE 21-2
FUELS FOR DELAY COMPOSITIONS²

Ingredients		Percent of Ingredients		Avg. burning rate at 70°F, sec/in.	Coefficient of		Variation
					Temp msec/ deg C/sec	Pressure msec/ mm/sec	
BaCrO ₄ -KClO ₄ -W	40	10	50	8.53	1.5	0.73	
	70	10	20	31.31	1.0	0.40	
CuO-B	90	10	—	1.74	2.56	0.52	1.72
MoO ₃ -B	88	12	—	2.75	1.77	1.14	8.5
	92	8	—	5.21	0.58	—	2.11
Co ₂ O ₃ -B	90	10	—	4.17	1.47	1.89	1.92
MnO ₂ -B	87	13	—	4.35	3.88	1.44	1.88
	90	10	—	6.41	6.02	—	2.18
V ₂ O ₅ -B	91	9	—	4.50	—	0.57	1.11
WO ₃ -B	91	9	—	5.40	3.68	0.15	3.4
	93	7	—	9.90	2.12	0.02	1.2
Fe ₂ O ₃ -Ti	69	31	—	0.84	2.9	—	3.0
	73	27	—	1.41	2.4	—	1.9
Fe ₂ O ₃ -Ti-SiO ₂	69	31	1	1.39	1.0	—	3.4
BaCrO ₄ -Zr	79	21	—	5.11	2.1	—	5.6
BaCrO ₄ -Ti	82	18	—	1.39	2.6	—	0.9
	87	13	—	3.35	2.0	—	0.9
	89	11	—	10.30	1.7	—	2.7
Mo-BaCrO ₄ -KClO ₄	30	60	10	9.0	1.25	0.54	
	20	70	10	23.0	0.33	1.4	
	40	50	10	5.5	—	—	
Zr-MoO ₃	49	51	—	0.18	0.66	—	

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tion are a fuel, an oxidant, a binder, and a lubricant. Delay compositions react when oxidant and fuel in the proper ratio are mixed intimately, and then ignited. The rate of burning is dependent on the proportions of the ingredients and their particle size. For a general discussion of the chemistry and technology of primary explosives, see Ref. 8.

21-2.1.1 Fuels

Principal fuels for delays are finely powdered metallic elements, nonmetallic elements, and their alloys. Ideally the fuel should have a high heat of reaction, yield reaction products stable at high temperature,

be resistant to moisture, and be nonpyrophoric. Fuels finding the greatest use are boron, silicon, zirconium, manganese, tungsten, zirconium-nickel alloys, and sulphur. Table 21-2² lists common fuel ingredients as well as their burning rate and the coefficients of temperature and pressure.

21-2.1.2 Oxidants

To be suitable for delay compositions, an oxidant must be stable at relatively high temperatures, reactive, nonhygroscopic, and yield solid reaction products. These criteria limit oxidants to those shown in Table 21-3².

TABLE 21.3

OXIDANTS FOR DELAY COMPOSITIONS²

<u>Chromates</u>	<u>Perchlorates</u>	<u>Oxides</u>	<u>Peroxides</u>	<u>Nitrates</u>
Barium	Potassium	Ferric	Barium	Potassium
Lead		Cuprous		
Strontium		Tungsten		
		Lead		
		Manganese		
		Bismuth		

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21-2.1.3 Binders

For a delay composition to resist setback forces or acceleration, a small quantity of binder may be added to reduce the changes of the charge breaking. A minimum quantity of binder is added to minimize the amount of gas generated and when it becomes necessary to granulate the mixture to provide a free-flowing powder for pelleting. Binders used include linseed oil, glycerine, and vinylalcohol-acetate copolymer². Delay compositions adequately supported have resisted over 100,000 g setback without a binder. It is necessary to minimize additives, such as binders, to minimize evolution of gas.

21-2.1.4 Lubricants

A composition may be difficult to pelletize or press if it contains a hard material if it sticks to the punch. A minimum quantity of a lubricant may be added to alleviate these difficulties. Those used include graphite, stearic acid, and stearates².

21-2.2 DELAY COMPOSITIONS

21-2.2.1 Early Compositions

A discussion of early delay compositions follows:

(1) Black Powder:

Black powder is not favored by most

engineers for use in new designs. Still there are instances where the unique ballistic properties of black powder are difficult or impractical to duplicate. Formed into compressed pellets, columns, or ring segments, black powder has been used to obtain delay times from milliseconds to a minute.

The advantages of black powder are great sensitivity to ignition even at low temperature, economy, multiplicity of uses, and relative safety in handling. The disadvantages are hygroscopicity and limited stability, excessive flash and smoke, undesirable solid residue, difficulty in controlling burning rate (high pressure increases the rate), poor burning qualities under diminished pressure, and finally, limited supply⁹.

Perhaps the main reason that black powder is considered for new designs is its relatively high burning rate at low pressure and small-pressure burn-rate exponent. An empirical relation that has proven satisfactory for predicting performance with an interior-ballistic computer program is⁹

$$r = 0.133P^{0.325} \quad (21-1)$$

where

r = burning rate, in./sec

P = pressure, psia

Experimental data indicate that a transition

in burning rate occurs in the region of 100 psia. It should be noted that powders produced by different manufacturers exhibit different ballistic properties.

(2) Studies of Gasless Compositions:

To overcome the disadvantages of black powder as a delay composition, research was initiated to develop nongaseous delay powders, making use of inorganic exothermic reactions similar to those used for thermite mixtures. Reactions which were studied are summarized in Table 21-4¹⁰.

A large number of these compositions have been considered and many subjected to experimental investigations^{11,12}. However, most of them have been discarded for one or another of the following reasons³:

- (1) Erratic burning rates
- (2) Too large a column diameter necessary for reliable propagation
- (3) Failure at low temperatures
- (4) Hygroscopicity
- (5) Rapid deterioration
- (6) Unavailability of reproducible supply of raw materials
- (7) Large pressure coefficient of burning rate
- (8) Failure at low pressure
- (9) Reaction products that are liquid or otherwise subject to movement by projectile acceleration during burning of the delay column.

It was found that for each oxidizing agent used, under the standard test conditions, very fast burning times were obtained with magnesium, aluminum, zirconium, and titanium. Slower burning times were obtained with

silicon, manganese, and chromium; while still slower ones occurred with iron, tungsten, and others. Metals that gave fast burning times with silver oxide, silver chromate, barium peroxide, and lead chromate gave slower burning times with cuprous oxide, barium chromate, and iron oxide.

21-2.2.2 Current Gasless Compositions

Table 21-5¹⁰ lists the gasless delay combinations in current use. The range of compositions given for some of the combinations allows for adjustment of the burning rates over wide ranges. The powdered mixtures are pressed into tubes at high loading pressures.

Two types of fast delay mixture have been used at US Army Harry Diamond Laboratories for producing delays in the millisecond range¹⁴. One of these is a mixture of zirconium/ferric oxide/Superfloss and the other a mixture of zirconium and barium chromate. (Superfloss is a pure form of diatomaceous earth produced by Johns-Manville Corp.) A gasless igniter study has shown that the addition of about 10% Superfloss improves the loading characteristics of zirconium/barium chromate mixtures and its use in these delay mixtures is recommended¹³. Although both of these compositions have been tested in the M9 Delay Element (Fig. 18-6), they may be readily adapted to other designs.

Two slow burning mixtures have been used or investigated at Harry Diamond Laboratories¹⁴. These include (1) manganese/lead chromate/barium chromate and (2) tungsten/barium chromate/potassium perchlorate/Superfloss. Details of these compositions as well as a barium chromate/barium composition follow:

(1) Manganese Delay Compositions. Mixtures of manganese, lead chromate, and barium chromate can be produced with controlled burning times varying from about 2 to 13.5 sec/in. Generally, a standard

TABLE 21-4
HEATS OF REACTION OF INORGANIC MIXTURES CONSIDERED FOR DELAYS

Metals	Silver Oxide $-\Delta H^\circ / n$	Silver Chromate $-\Delta H^\circ / n$	Barium Peroxide $-\Delta H^\circ / n$	Lead Chromate $-\Delta H^\circ / n$	Cuprous Oxide $-\Delta H^\circ / n$	Barium Chromate $-\Delta H^\circ / n$	Iron Oxide $-\Delta H^\circ / n$
Magnesium	139.1	69.6(I)	126.7	63.4(I)	103.6	51.8(5)	239.8
Aluminum	378.0	63.0	340.8	56.8(I)	271.5	45.3	200.5
Zirconium	244.1	61.0	219.7	54.9(I)	172.1	43.3	377.3
Titanium	211.0	52.8	186.2	46.6(I)	140.0	35.0	278.0
Silicon	187.0	46.8	164.8	41.2(I)	116.0	29.0(N)	206.0
Manganese	89.5	44.8	77.1	32.6(4)	54.0	27.0(10)	91.0
Chromium	252	42.0(N)	214.8	35.8(5)	145.5	24.3	74.5
Zinc	76.5	38.3	63.9	32.0	41.0	20.5	52.0
Tin	124.1	31.0	99.3	24.8	53.1	13.3	17.3
Iron	177.5	29.6(8)	140.3	23.4	7.3	11.8(N)	0
Cadmium	58.2	28.1	45.8	22.9	22.7	11.4	-2.9
Tungsten	174.7	29.1	137.5	22.9	68.2	11.4	-C.5
Molybdenum	155.5	25.9	118.3	19.7	49.0	6.2	
Nickel	50.5	25.3	39.0	19.5	15.9	8.0	
Cobalt	51.4	25.7	38.1	19.1	15.0	7.5	
Antimony	145	24.2	107.8	18.0(6)	36.5	5.4	
Bismuth	116.1	19.4	78.9	13.2	9.6	1.6	
Copper	31.5	15.8	16.4	8.2	22.7	2.3	
Nonmetals							
Phosphorus	195	39(I)	487.5	48.8(I)	213	21.3	35.3
Sulfur	142.1	23.7	158.2	26.4(4)	95.9	4.8	-15.1
Selenium	67.9	11.3	86.6	14.4	-6.2	-0.3	-0.5

$-\Delta H^\circ$ heat of reaction.
 $-\Delta H^\circ / n$ equivalent heat of reaction (heat of reaction per electron charge).
 (N) no reaction observed.
 (I) very fast burning rate.
 () burning time, sec.

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TABLE 21-5
GASLESS DELAY COMPOSITIONS IN CURRENT USE

<u>Fuel, %</u>	<u>Oxidants, %</u>		<u>Inert, %</u>
Manganese 30 to 45	Barium Chromate 0 to 40	Lead Chromate 26 to 55	None
Boron 4 to 11 13 to 15	Barium Chromate 89 to 96 40 to 44	Chromic Oxide — 41 to 46	None
Nickel-Zirconium Alloy 26	Barium Chromate 60	Potassium Perchlorate 14	None
Nickel-Zirconium Mix 5/31 5/17	Barium Chromate 22 70	Potassium Perchlorate 42 8	None
Tungsten 27 to 39 39 to 87 20 to 50	Barium Chromate 59 to 46 46 to 5 70 to 40	Potassium Perchlorate 9.6 4.8 10	Diatomaceous earth 5 to 12 3 to 10
Molybdenum 20 to 30	Barium Chromate 70 to 60	Potassium Perchlorate 10	
Silicon 20	Red Lead 80		Diatomaceous earth Max 8 parts by weight
Zirconium 28	Lead Dioxide 72		

pressure of 30,000 psi is used to load the dry mixtures in a column of 0.203 in. diameter¹⁴. Burning rates are affected markedly by the ratio of barium chromate to lead chromate. Increasing the barium chromate content decreases the burning rate. Experimental data on this effect are shown in Table 21-6². Burning rates also are affected by particle size; the finer sizes burn faster.

Table 21-7² shows the effect of the housing material on the burning rate while Table 21-8¹⁴ shows the effect of dry storage on burning time of manganese delay mixtures.

(2) Tungsten Delay Compositions. Tungsten delay compositions were developed to satisfy the requirements for reliable, long burning times (40 sec/in.). Potassium perchlorate was added to the binary mixture of tungsten and barium chromate to increase the

heat of reaction, increase ignitibility, and to insure propagation at low temperatures². Burning times, gas volumes, and heats of reaction for various mixtures of these ingredients are shown in Table 21-9². Variation in the burning rate of a 55/10/35 barium chromate/tungsten/potassium perchlorate composition, loaded at 36,000 psi in vented bodies—as a function of tungsten particle size—is given in Table 21-10².

The effects of the potassium perchlorate level on the burning characteristics of tungsten delays modified with a ceric oxide flame sustainer have been studied¹⁵. The results indicated that there is an optimum level of potassium perchlorate (9%) at which minimum delay time variability occurs. Increasing potassium chloride sublimation introduces delay failures and higher burning times.

TABLE 21-6
EFFECT OF INGREDIENTS ON BURNING RATE OF MANGANESE DELAY COMPOSITIONS²

Comp.	Ingredients	%	Nominal burning rate, sec/in.	Heat of reaction, cal/g	Gas volume, cm ³ /g	Gas analysis,		5-sec value	Ignition temp, °C
						% H ₂	% CO		
A	Manganese*	45.0							
	Lead chromate	55.0	2.1	260	15.4	550.0	45.0	608	382
	Barium chromate	...							
B	Manganese*	33.0							
	Lead chromate	37.0	8.4	256	18.3	77.7	22.3	660	522
	Barium chromate	30.0							
C	Manganese*	32.8							
	Lead chromate	30.2	13.5	262	11.4	65.4	34.6	702	478
	Barium chromate	37.0							

*Micron size 5.7

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(3) Barium Chromate/Boron Compositions. A series of mixtures based on barium chromate and amorphous boron has been found to be easy to manufacture, readily ignitable, and capable of withstanding storage under adverse conditions with a high degree of reliability. Burning time values, heats of reaction, gas volume, and ignition temperature with increasing percentages of boron are shown in Table 21-11². Increasing the loading pressure results in a small decrease in burning rate. Typical data for 95/5 and 90/10 compositions loaded in M112 Fuze Housings are shown in Table 21-12².

21-3 RELAYS

The output charge of a pyrotechnic delay timer is usually a relay. The relay is either the

last charge increment in the delay element, or a separate component inserted into the delay assembly. Typical relays are shown in Fig. 21-4³.

The usual relay consists of a cup into which lead azide is pressed at 10,000 psi. In some relays, a sealing disk is crimped over the open end, while in others, the end is left open; but the skirt left by partial filling is crimped at an angle. When such relays are inserted into delay elements and crimped in place, the crimp is compressed just enough to obtain a firm and snug fit.

21-4 SENSITIVITY

21-4.1 NEED FOR CHARACTERIZATION

To be able to minimize the hazards of pyrotechnic delay compositions, it is necessary to determine their reaction and sensitivity characteristics. This information forms a basis for the establishment of optimum safety procedures in processing pyrotechnic devices. The goal looked for is minimum risk to personnel who prepare, handle, test, and transport the compositions.

Sensitivity is established by tests that simulate such external stimuli as impact, friction, heat, moisture, and electrostatic discharge³. The tests also are used to (1)

TABLE 21-7
**EFFECT OF HOUSING MATERIAL ON
BURNING RATE OF MANGANESE
DELAY COMPOSITIONS**

	<u>Aluminum bodies</u>	<u>Brass bodies</u>
Nominal avg burning time, sec	8.15	10.3
Column length, in.	0.676	0.845
Nominal avg burning rate, sec/in.	12.1	12.2

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TABLE 21-8

EFFECT OF DRY STORAGE ON BURNING TIME OF MANGANESE DELAY COMPOSITIONS

Batch ^a	Burning Time ^b (sec) After Indicated Exposure in Sealed Flasks at +165°F									
	Before Storage		1 Wk Storage		2 Wk Storage		4 Wk Storage		8 Wk Storage	
	Avg. ^c	Std. Dev.	Avg. ^c	Std. Dev.	Avg. ^c	Std. Dev.	Avg. ^c	Std. Dev.	Avg. ^c	Std. Dev.
1	6.56	0.123	6.73	0.089	6.73	0.095	6.85	0.127	6.86	0.117
2	5.35	0.122	5.46	0.028	5.50	0.036	5.56	0.077	5.62	0.064

^a33% Mn, 30% BaCrO₄, 37% PbCrO₄.^bMixtures loaded at 30,000 psi with 2-100 mg increments of DM-3 igniter in delay bodies 0.203 in. I.D., 0.500 in. O.D., 0.750 in. long.^cAverage of ten tests.

determine the energy required to initiate a delay composition, (2) serve as a quality assurance gage, and (3) to indicate the effect of storage under adverse conditions.

21-4.2 SENSITIVITY TO INITIATION

There are a number of tests that measure how easily explosive materials are initiated. They use various stimuli that are capable of setting off the explosive. The stimulus most widely used is impact by dropping, others used are friction and rifle bullet impact.

21-4.2.1 Impact

The impact test consists of dropping a weight on a sample of explosive. In practice, two types of tests are used, each requiring a special type of equipment. The two most prevalent impact tests are the Picatinny Arsenal and the Bureau of Mines tests. The method of the Bureau of Mines consists of dropping on the sample a known weight in guided free fall from a preselected height. The method developed by Picatinny Arsenal (PA) uses the same procedure except that the sample fills a hardened steel cup that is covered by a brass cap. A vented steel plug that is centered on the brass cap is hit by the falling weight. Fig. 21-5³ shows the PA test apparatus.

The main difference between the two tests is that the PA test involves greater confine-

TABLE 21-9
BURNING RATES OF VARIOUS TUNGSTEN
DELAY COMPOSITIONS¹

Ingredient, %			Nominal avg burning rate, sec/in.	Gas volume, cm ³ /g	Heats of reaction, cal/g
W	BaCrO ₄	KClO ₄			
85	..	15	1.6	....	....
80	..	20	2.5	....	304
28	62	10	48.6	8.5	....
30	60	10	31.2	10.4	....
32	63	5	28.7	3.3	
35	30	35	24.1		
40	47	13	5.9		346
50	40	10	7.8	4.3	305
65	20	15	3.0	2.1	
70	10	20	7.3	1.6	

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TABLE 21-10
VARIATIONS OF BURNING RATE DUE TO
CHANGE IN PARTICLE SIZE OF
TUNGSTEN DELAY COMPOSITION²

Tungsten, Micron Size	Average Burning Rate, sec/in.
4	9.0
8	17.2
15	28.1

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TABLE 21-11
DELAY CHARACTERISTICS FOR VARIOUS PERCENTAGES OF BORON²

Boron, %	Nominal* avg burning time, sec	Heat of reaction, cal/g	Volume of gas, cm ³ /g	Impact test PA, in.	Ignition temp, °C 5-sec value
3.0	7.56	Incomplete reaction		40+	....
4.0	1.72	354	5.0	40+	....
5.0	1.09	420	8.0	40+	app. 700
6.0	0.77	431	8.4	37	....
8.0	0.56	462	7.9	28	....
10.0	0.47	515	7.3	21	680
13.0	0.40	556	8.9	20	....
15.0	0.39	551	7.0	16	....
17.0	0.38	543	11.6	13	....
19.0	0.37	535	8.8	16	....
21.0	0.38	526	8.6	34	....
23.0	0.41	503	4.2	40+	....
25.0	0.43	497	10.2	40+	....
30.0	0.57	473	10.4	40+	....
35.0	0.97	446	12.7	40+	....
40.0	2.19	399	14.1	40+	....
45.0	5.25	364	15.0	40+	....
50.0	14.5	Incomplete reaction		40+	

*Loaded in M112 Fuze Housings at 36,000 psi

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ment of the sample, distributes the translational impulse over a smaller area, and involves a frictional component (between cap and sample). Hence, PA test values are affected greatly by sample density.

21-4.2.2 Friction

To measure sensitivity to friction, a 7-g sample (50-100 mesh) is rubbed by a steel or fiber shoe swinging at the end of a long rod. The behavior of the sample is described qualitatively to indicate its reaction to this stimulus. The most energetic reaction is explosion, it decreases in the order of severity to no effect³.

21-4.2.3 Rifle Bullet Impact

The traditional bullet sensitivity test consists of firing a cal .30 bullet into the side of a 3-in. pipe nipple that contains approxi-

mately 0.5 lb of the explosive being tested and is capped at both ends. Because of the curved target surface, test results can be affected greatly by the condition of the weapon, the characteristics of the ammunition and the impact angle³. An improved test with a flat target plate was devised at PA¹⁶.

21-4.3 SENSITIVITY TO THE ENVIRONMENT

Pyrotechnic compositions are subject to degradation or initiation by several environmental conditions. Burning rate can be adversely affected by absorption of moisture. Initiation may be caused by heat or electrostatic discharge.

21-4.3.1 Heat

A heat test is used to determine a threshold temperature below which there is no readily

TABLE 21-12
VARIATION OF BURNING RATE WITH
LOADING PRESSURE OF BARIUM
CHROMATE-BORON COMPOSITIONS²

Loading pressure, psi	Composition			
	95/5		90/10	
	Nominal burning rate, sec/in.	Density, g/cm ³	Nominal burning rate, sec/in.	Density, g/cm ³
200	1.21	1.88	0.53	1.89
500	1.21	1.91	0.54	1.95
1,300	1.29	2.22	0.56	2.08
3,600	1.39	2.41	0.59	2.26
9,000	1.49	2.55	0.62	2.43
12,000	1.60	2.70	0.35	2.57
36,000	1.69	2.89	0.70	2.73

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detectable reaction and above which a reaction takes place within some short time interval. Several ways of doing this are²:

- (1) Measuring time to explosion or time to ignition
- (2) Isothermal heating
- (3) Adiabatic heating
- (4) Differential thermal analysis
- (5) Thermogravimetric analysis.

21-4.3.2 Moisture (Hygroscopicity)

In this test, the absorption of, or reaction with, external moisture by an ingredient or

composition is determined because variations in moisture can cause changes in sensitivity. Basically, a known weight of sample is placed in a vessel prepared to have a known relative humidity at a specific temperature. At predetermined intervals, the percent gain or loss of weight of the sample is calculated².

21-4.3.3 Electrostatic Discharge

The relative ease of initiation of a pyrotechnic composition by an electric spark is termed its sensitivity to electrostatic discharge². In this procedure, the sample is loaded in a cylindrical depression in a heavy metal plate that serves as an electrode. A second electrode, whose height is adjustable, is placed above the sample which is then subjected to a high-voltage spark. The maximum, 50%, and minimum energy levels at which initiation occurs then are determined. Humidity levels must be controlled in this test.

21-4.4 INPUT AND OUTPUT SENSITIVITY

21-4.4.1 Input

A discussion of the input sensitivity of initiators follows:

(1) Mechanical Initiators. The input sensitivity of stab and percussion primers is determined by the impact test (see par. 21-4.2.1).

(2) Electric Initiators. Depending upon the application, the sensitivity of electric initiators should be characterized in terms of the

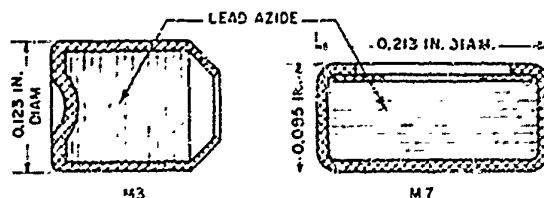


Figure 21-4. Typical Relays

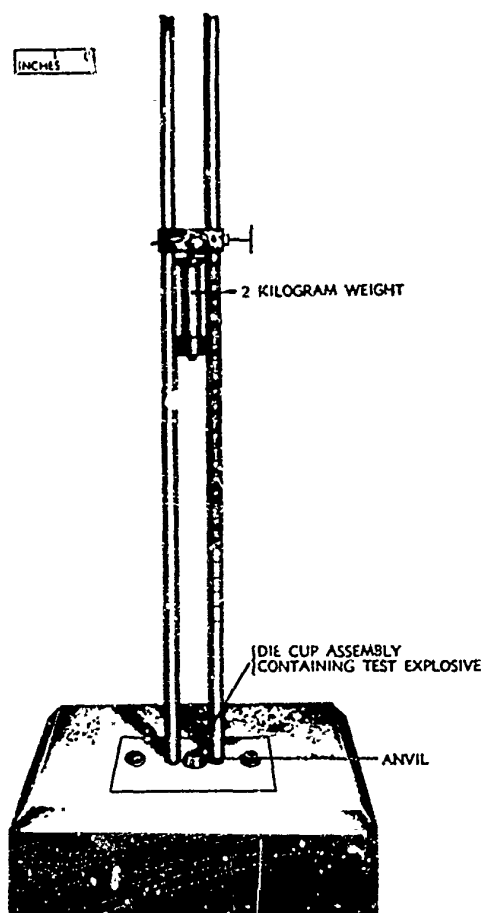


Figure 21-5. Picatinny Arsenal Impact Test Apparatus

threshold current, voltage, power, energy, or some combination of these. Tests used for sensitivity of electric initiators include³:

- (1) Capacitor discharge test
- (2) Voltage sensitivity
- (3) Steady current functioning.

21-4.4.2 Output

The output of a delay is a flame or hot slag. Tests for flame output include (1) light output, as measured by a photocell, (2) a

modification of the lead disk test (amount of lead displaced by output of device), (3) a test to measure flame temperature and length, and (4) a closed chamber test using a manometer to measure flame output momentum³. A stop watch is often satisfactory for measurement of relatively long burning times. However, the electronic chronometer is suitable for all ranges of burning time². In this method, the timing instrument starts when the initiator functions and stops when the charge flashes. Correction must be made for the burning times of the initiating source and the relay charge.

21-4.5 ANALYSIS OF DATA

The sensitivity of an explosive charge is the magnitude of the minimum stimulus that will result in its initiation. Stimuli too weak to initiate charges can alter them, sometimes in a readily noticeable way and sometimes by changing the sensitivity of the charge to the stimulus. In recognition of this variability a number of statistical plans have been devised for sensitivity studies. Some of the following plans are designed to characterize sensitivity in terms of an assumed normal distribution and still others determine some point in the distribution of particular interest:

(1) Staircase Method, the Bruceton Test

In the Bruceton test¹⁷, the magnitude of the stimulus used in each trial is determined by the result obtained in the immediately preceding trial. If the preceding trial was a misfire, the stimulus for the next trial is made one step higher, and if it fired, the stimulus should be one step lower. The step used is a difference between stimulus levels, such as 5 V or 2 in. of drop height. Misfires are discarded because their sensitivity could have been affected by the previous test.

The validity of this procedure depends on whether the assumptions are valid that (a) the steps are of a uniform size, and (b) the frequency of explosions is distributed normally.

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(2) Frankford Run-down Test Method. A run-down test has been developed by Frankford Arsenal¹⁸ that, with the expenditure of a much larger sample, makes possible a greatly improved assessment of the distribution of the underlying population. The number of trials is constant at each energy level. The maximum level for all samples activated, the minimum level for no samples

activated, and several points in between are determined.

(3) Other Procedures. Other procedures include the Probit¹⁹, Normit, and Logit²⁰ which are analytical methods of determining the underlying statistical distribution of a measured parameter. They are not data collecting schemes.

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21-15/21-16

PART FIVE — FLUERIC TIMERS

CHAPTER 22

INTRODUCTION

Flueric devices represent those elements that perform control or logic functions by means of a fluid (liquid or gas) in motion without the use of moving or mechanical parts. Flueric timers are timers fabricated from fluid elements to provide an "output" pulse after some known time interval has elapsed following an "input" pulse.

A flueric timer can be constructed by series interconnection of binary stages that are driven by a fluid oscillator. In order to construct a useful timer, e.g., one which indicates the elapse of a pre-programmed time interval, additional auxiliary components are required. A typical digital interval timer is shown in block diagram form in Fig. 22-1¹. As indicated in the figure, such a system may include a power supply, a time base oscillator, a multistage counter, a setting mechanism, a decoder to determine when the set time has elapsed, and an amplifier stage which feeds the output transducer. At present the feasibility of flueric timing has been demonstrated by several independent investigators.

Standard flueric terms and symbols are covered in Ref. 2 and a bibliography appears in Ref. 3.

22-1 ADVANTAGES

The use of flueric devices instead of the more conventional electromechanical types is attractive for the following reasons:

(1) High Reliability. Due to the lack of moving parts, flueric elements in general can operate for almost indefinite time periods. No

parts are subjected to flexure, bending, wear, or sticking. If the supply fluid is filtered, erosion practically is eliminated and fluid flow in the element itself produces a self-cleaning effect. Even with the addition of some contaminants (dirty air), tests have indicated that an oscillator performed satisfactorily for two weeks before cleaning was necessary⁴. Of course, the degree to which a circuit can tolerate contaminants will vary with size and circuit requirements. A sound design principle is always to employ contaminant free supply fluid.

(2) Large Temperature Range. Although temperature will play a most significant role in system fluid whose dynamic properties are inherently temperature dependent (and this fact will alter element function), the element itself (fabricated from metals, glass, ceramics, etc.) can be made to withstand extreme temperature ranges extending from -100° to 700°F . At high temperatures, the problems associated with sealing, connecting, or joining various elements can be more important than the fact that the system fluid is at a high temperature.

(3) Not Affected by Electromagnetic and Nuclear Radiation. The components of a flueric element, if properly made, are in general not affected by RF fields or nuclear radiation. Flueric elements can be constructed to represent a complete Faraday shield that will minimize effects of electromagnetic waves. Extending this line of reasoning, a nuclear radiation shield also can be applied over the final design to minimize penetration of gamma and X rays. Effects of local

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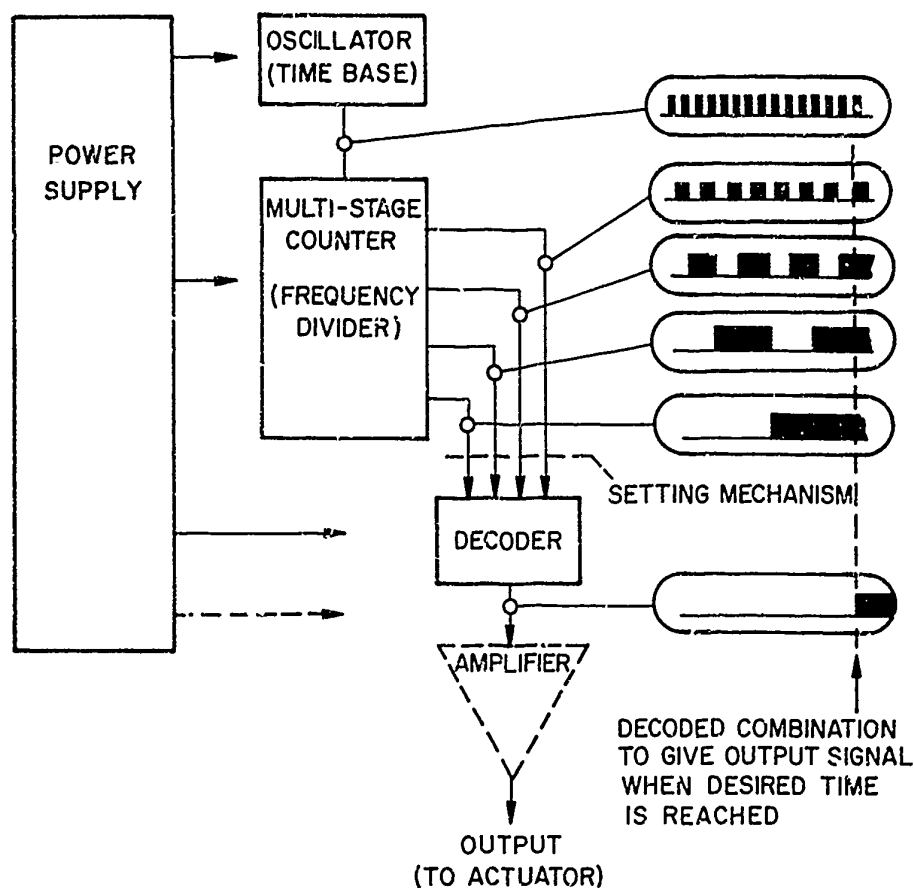


Figure 22-1. Digital Interval Timer Block Diagram

environment can be eliminated by proper design and fabrication.

(4) Shock and Vibration. The effect of shock and vibration on a stored element or a standby element can be reduced to practically zero, by initial choice of fabricated materials. The shock effect on an operating unit, however, is another matter. Generally it is agreed that the relation between the density of the working jet compared with the density of the fluid surrounding the jet is of prime importance. Many devices, however, require shocks in excess of 1000 g's to affect their performance. Other devices, such as a properly adjusted turbulence amplifier, can be "upset" by acoustic shock signals at one

discrete frequency and remain relatively unaffected by other frequencies. One could conceivably capitalize on this phenomenon in designing an acoustic switching device.

(5) Reduction of Interfaces. Fluoric devices can simplify or reduce the number of interfaces in a system because the fluoric circuit can operate using the medium of liquid or gas being controlled, thus reducing interfaces and the need for expensive transducers. This not only adds to the simplicity of the system but increases reliability⁵.

(6) Low Cost. As the technology develops, undoubtedly the system cost will decrease.

Potential savings often overlooked are the lowering of

- (a) Cost of maintenance
- (b) Servicing expenses
- (c) Down time.

(7) Not Affected by Corrosive Fluids. If a proper choice of fabrication material has been made, fluoric circuits can function with corrosive fluids, and within corrosive atmospheres.

(8) Miniaturization. The three major advantages of miniaturization are:

- (a) Speed of response can be increased.
- (b) Smaller components require less power.
- (c) Smaller dimensions and less mass are desirable so that payload can be increased.

22-2 DISADVANTAGES

Some of the most common disadvantages associated with the use of fluoric circuits and elements are:

(1) Limit of Response Time or Switching Speed. Response time or switching speed is very important in digital application⁵. Changes in design will affect the switching speed of the element, but for various wall-attachment devices having a nozzle width of 0.010 in. and using air at pressures below 50 psi, an average range is 100 to 1000 Hz, or response times of 0.005 to 0.0005 sec (switching occurs twice per cycle). Higher speeds have been achieved at higher supply pressures but at the expense of unacceptable power consumption. Due to the present limits of output transducing devices, it is questionable whether speeds in excess of several hundred hertz can be used effectively. Units (fluid oscillators) have operated at 100,000 to

200,000 Hz, but the outputs were not used in a meaningful manner.

(2) Limit of Signal Propagation. The limit of signal propagation for a gas operated system is equal to the local speed of sound through the gas. For dry air at ambient temperature, the propagation speed is about one foot per millisecond.

(3) Large Power Consumption. Fluoric elements require a continuous supply of fluid while in operation, and considerable amounts of power may be required⁵. This can be offset to some extent by micro-miniaturization. The power consumption of an element generally depends upon the flowing fluid, jet velocity, and nozzle size. In wall-attachment devices, these variables can be related to two nondimensional parameters: the Reynolds number and the ratio of nozzle depth to width (aspect ratio). Bistable operation of the device requires a minimum Reynolds number, below which attachment no longer occurs. However, this occurs only at very low Reynolds numbers.

Pressure recovery in the output receivers is also important in determining the power consumption. Efficient geometries will require less power.

In fluid timer applications, power consumption is an important consideration. If the timer is being supplied from a bottled source or pyrotechnic gas generator, the power consumption of each stage must be known more critically than if ram air is used. This is because bottled supplies have a limited useful life, but ram air is available in almost unlimited amounts once the projectile or missile is air-borne.

(4) Need For Contaminant Free Supply. Micro-miniaturization of circuits has created a need to employ pure bottled fluids to prevent clogging and malfunctioning, etc. Ram-air power supplies will require a closure to exclude water and other contaminants prior

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to firing. The closure will be opened or removed prior to or during firing. This can be done automatically by the firing cycle, such as setback opening the ram tube or by having a plastic cap that is blown off by blow-by as the projectile leaves the muzzle. A small separator such as the cyclone type will be included in the ram-air power supply to eliminate rain, snow, and dust in flight. The use of a ram-air power supply increases safety since the system is completely inert until it achieves a minimum velocity.

(5) Dependence on Temperature and Pressure:

Although a fair degree of temperature and pressure insensitivity has been accomplished, especially with compensated flueric oscillators, perfect insensitivity has not been achieved. This is discussed fully in Refs. 6 and 7.

Theory and experiments indicate that temperature insensitivity in the resistance-inductance type of oscillator is obtained at the

expense of pressure sensitivity, and a compromise is necessary in the actual oscillator. With fluid oscillators of the RCR feedback type, claims of $\pm 1\%$ have been reported over a pressure range of 6 to 30 psig and 77° to 175°F ⁶. At the present time, RC oscillators have been operated from -60° to $+170^\circ\text{F}$, using power jet pressures from 6 to 30 psig with only a $\pm 1\%$ change in frequency. The oscillator must be miniaturized for practical use in a fuze. Hybrid systems (such as the torsion bar oscillator) that use vibrating mass systems are virtually temperature and pressure insensitive, but are not strictly flueric devices. All uncompensated flueric oscillators are temperature sensitive because they depend on the velocity of sound of the operating fluid which is, in turn, temperature sensitive. The sonic velocity is proportional to the square root of the absolute temperature.

Since the precision of the basic oscillator governs the overall precision of the flueric timer, its temperature and pressure sensitivity is a major consideration.

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CHAPTER 23

FLUERIC SYSTEMS DESIGN

23-1 FACTORS

Among the factors to consider before developing a fluid system are gain, signal-to-noise ratio, frequency response, ease of interconnection of individual components, output pressure, flow and power. A discussion of each factor follows:

(1) Gain:

The three types of gain are pressure, flow and power. Gain is defined differently for digital and proportional devices.

Digital-amplifier *flow gain* is the ratio of change of flow output to change in control flow necessary for switching to occur. *Pressure gain* is the ratio of change in output pressure to change in control pressure required for switching. *Power gain* is the ratio of change in output power to change in control power required to initiate switching.

(2) Signal-to-noise Ratio:

This is the maximum output-signal amplitude divided by the maximum noise amplitude. Good signal-to-noise ratio is not as important for the devices used in timers as it is for proportional amplifiers.

In timing devices, output is at one of two discrete levels, each of which has a tolerance band. Provided the noise riding on the output signal does not exceed limits of the tolerance band, the flueric device can be relatively noisy and still function properly. However, care must be taken to avoid spurious switching by a noisy input signal.

(3) Frequency Response:

Response for flip-flops is given by the switching time; the time interval that begins when the changing input signal reaches 50% of its final value and ends when the subsequent output signal reaches 50% of its final value. In each instance the output signal can be flow, pressure, or power.

(4) Interconnectability

A good measure of the ease with which a digital flueric device can be staged is its *fanout* capability—how many downstream devices it can control. In determining fanout capability, all of the devices should be identical in size, input impedance, gain, and power-supply conditions.

Fanout applies primarily to digital systems where the flueric devices are used as logic elements to handle information. Gain between successive stages is not a primary objective.

Another approach to interconnection is to match input and output impedances. If output impedance of the driving element is matched to input impedance of the driven element, maximum power transfer occurs. The impedance of the elements is adjusted by such techniques as providing output flow dividers, vents, bleeds, and varying duct cross sections.

Table 23-1 compares types of digital devices with respect to power range, switching time, geometry and ease of interconnection.

TABLE 23-1

CHARACTERISTICS OF DIGITAL FLUERIC DEVICES

<u>Type of Device</u>	<u>Power Range</u>	<u>Switching Time</u>	<u>Geometry of Ducts</u>	<u>Ease of Interconnection</u>
Wall-attachment	Low to high	Medium	Rectangular	Difficult
Edgewise	Low to high	Fast	Rectangular	Moderate
High-pressure low-flow	Low to medium	Medium	Circular	Moderate
Turbulence	Low	Slow	Rectangular or circular	Easy

23-2 MODULAR COMPONENTS

In order for a flueric timer to replace other types in fuze applications, the overall size must be reduced to a minimum. The use of photoetching and other recent processes has made it possible to fabricate microminiature flueric elements. These are usually thin wafers of rectangular or circular shape made from metal (phosphor-bronze). The external shape of these wafers is held constant and various geometries are etched through the entire wafer thickness. These elements can then be stacked together readily to form a final package. This idea typifies the modular component concept.

With modular components, the aspect ratio of nozzles readily can be changed simply by stacking two or more elements of similar shape together. Also an entire stage can be removed and replaced quite readily. Fig. 23-1 shows two typical element wafers, a relaxation oscillator (A) and its binary amplifier (B). These measure about 0.5 in. by 0.75 in. and are 0.003 in. thick. The corner holes on each wafer are used to clamp the wafers together (by use of long screws) and the hole spacings are standardized. The top and bottom of the center holes are supply pressure manifold holes (power supply) which may be used at a particular stage or may carry flow through to another stage. Output arms

feed through other holes to become inputs to subsequent stages. The small, centrally located holes are bleed-off ports, as is the etched section open to the side of the element. It is quite obvious that the proper order of stacking must be maintained throughout.

Experiments have shown that if the proper torque is applied to each mounting screw and the wafers are etched properly, the use of gasket sealing material between each wafer is unnecessary. In fact, the use of a sealant is to be discouraged because the tiny nozzle openings can easily clog.

Mechanical strength of the wafer also must be considered since high pressures permanently can deform overhanging sections of the etched element.

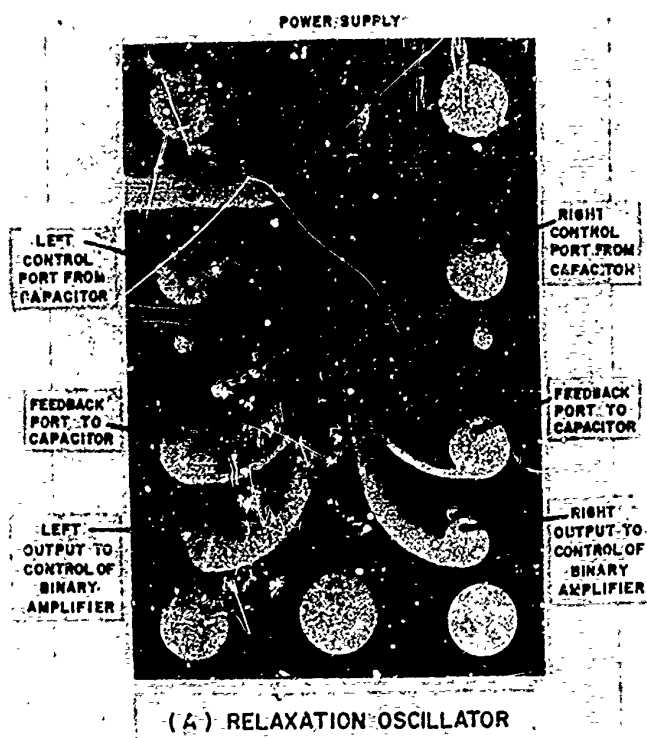
At both ends of the stacked elements (as well as at any intermediate location) one may use thicker plates of similar external size which serve to introduce or remove fluid signals, and also give mechanical strength for clamping by the through screws.

A complete timer package employing modular components is shown in Fig. 23-2.

23-3 INTEGRATED CIRCUITS

Integrated circuitry as applied to flueries is

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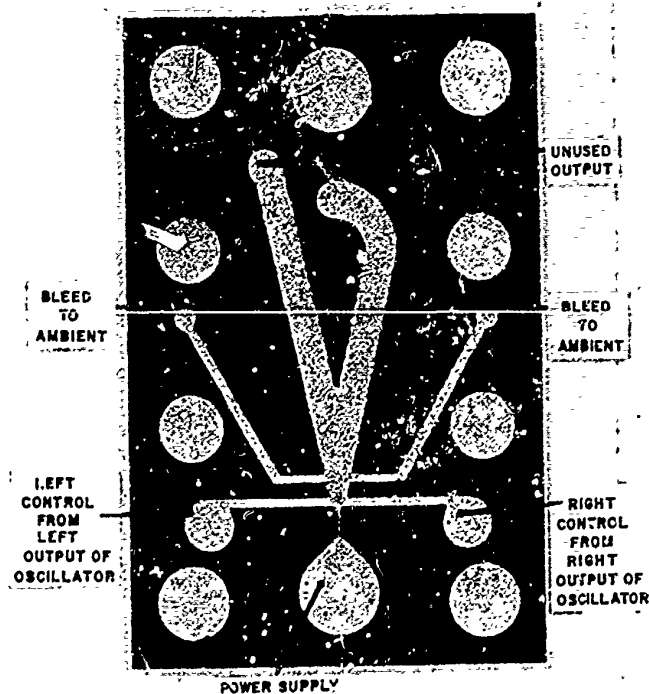


Figure 23-1. Miniaturized Modular Circuit Elements

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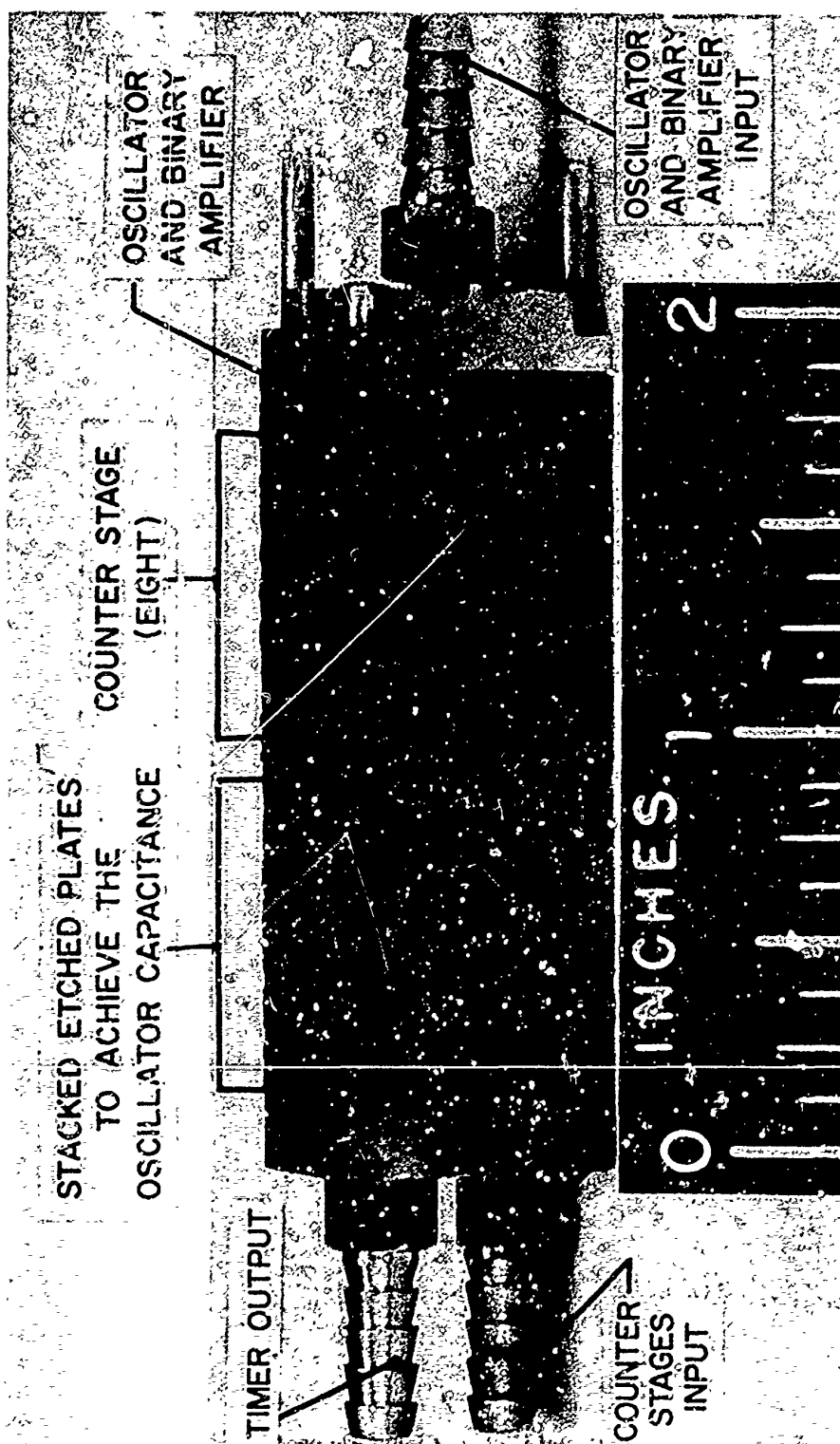


Figure 23-2. Fluid Timer Assembly Illustrating Modular Design

the incorporation of two or more functional geometries on a single planar sheet. This concept has several desirable features: (1) space can be used fully on any given wafer, (2) overall size of the final unit can be reduced, and (3) more efficient interstage matching can be accomplished. The desirability of (1) and (2) cannot be overemphasized. In par. 23-4 the importance and significance of source and load impedance matching are discussed. Integrated circuitry offers a way for better inter-stage impedance matching since the input and output channels can be controlled more critically and fluid flow need not confront any discontinuities that may be present from wafer to wafer.

Since the geometries of the etched wafer cannot be altered after fabrication, the designer must know beforehand the effect of each part of the element. At present a design problem cannot be tackled straightforward from a purely analytical technique, and usually a large-scale model initially is fabricated, and development proceeds from this model by empirical methods. Once the geometries have been defined and the elements function as desired, the model is reduced proportionately to its final size.

Integrated circuit concepts can produce elements of high reliability. Some integrated circuit devices have been fabricated which include 10 or more individual elements on a single planar sheet.

23-4 MATCHING TECHNIQUES

The coupling of fluid elements, stage to stage, may introduce a matching problem. Matching may not be necessary with bistable flip-flops having bleed ports and in devices where each stage receives a supply pressure from a common manifold. However, in staged amplifiers, matching must be considered¹. The main difficulty is that the performance of a stage depends not only on its own configuration but also on the geometries of the previous and the following stages. A

means is needed to predict the performance of a stage in a system without actually assembling the components. Since system conditions vary widely and generally are not known in advance, it is necessary to simulate a large number of operating conditions when testing a single stage. In addition, the system may be required to operate over a range of frequencies and power supplies. Thus units may have to be matched dynamically as well as statically.

In general, the matching of fluid components is analogous to matching in the design of vacuum-tube and transistor circuits in electronics, which usually is accomplished by using static characteristic curves. It is also possible to approach the interconnection of fluid amplifiers in this way. Indeed, in view of the mathematical difficulties involved in describing fluid motion in complex geometries, it may provide the only feasible approach.

Before applying characteristic curves to fluid amplifiers it is necessary to understand the general case of a fluid flowing from one black box to another. The first box may be called the *source* and the second box the *load*. Under steady flow conditions, the flow supplied from the source must equal the flow delivered to the load.

With any source of energy there is associated an impedance, limiting the flow rate at which a quantity of energy can be removed from the source. This is called the *source impedance*. Similarly, every load has an impedance that determines the flow rate at which energy can be supplied to the load. This is called the *load impedance*. The most useful parameter to describe the performance of a source or load is, therefore, its impedance. In steady-state flow, the impedance is considered as purely resistive. Resistive impedance, for incompressible flow, is defined as the total pressure drop across the source or load divided by the volume flow through it. Very often the impedance of a

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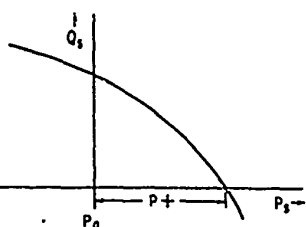
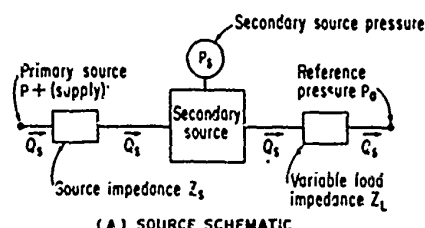


Figure 23-3. Characteristics of the Source¹
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fluid component is nonlinear, i.e., it is a function of the volume flow. For this and other reasons associated with the complexities of fluid motion, it is very difficult to derive an analytical expression for the resistance of a fluid component. Resistance, however, can be determined readily from the experimental characteristic curves. In discussing fluid devices it is convenient to use primary and secondary sources, as shown schematically in Fig. 23-3¹. A primary source is the constant-pressure source or manifold which supplies fluid to the secondary source. The impedance of the primary source is zero, i.e., it can supply an unlimited amount of flow at constant pressure. The secondary source is the active fluid interaction device on which characteristics are desired. To obtain these characteristics the secondary source is connected to a variable load impedance Z_L . The primary source supply pressure P_+ is connected to the secondary source through the secondary-source impedance Z_s . In steady flow the mass flow in the circuit is constant. When density changes are small, the volume flow Q_s may also be considered constant. A typical source characteristic is shown in Fig.

23-3(B). This curve is obtained experimentally by measuring the volume flow and secondary source pressure over a range of load impedances. Each load impedance provides one point on the source characteristic curve. The complete source characteristic is the locus of these individual points over the entire range of load impedances that could possibly occur in practice. Points on this characteristic curve which fall in the first quadrant represent passive loads (resistances). The curve can be continued into the second and fourth quadrants by using active loads (pressure sources) that lower or raise the reference pressure P_a .

A schematic drawing of the method of measuring load impedance is shown in Fig. 23-4(A)¹. To obtain the characteristics of the load, one must connect it to a variable source that might occur in practice. Again, for small density changes, the volume flow Q_L passes from the source through the load impedance to the reference pressure P_b . Experimentally, the total pressure P_L is measured upstream of the constant load impedance Z_L . A typical load characteristic is shown in Fig. 23-4(B).

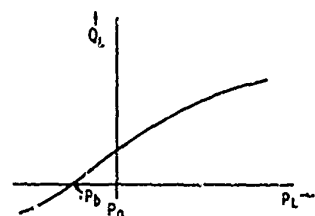
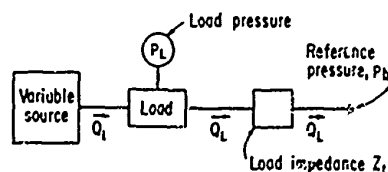


Figure 23-4. Characteristics of the Load¹
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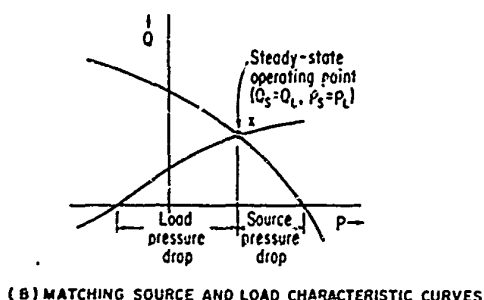
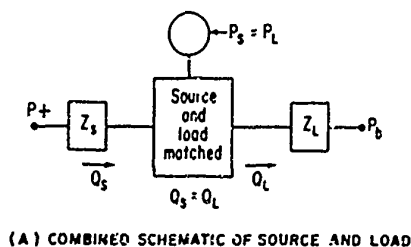


Figure 23-5. Matching Source and Load Characteristics¹
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To obtain each point on the load characteristic, it is only necessary to set the load pressure at some level by varying the source and to measure the resulting flow. When the load pressure is equal to the reference pressure, the load flow is zero. Increasing the load pressure increases the flow. If the load pressure is maintained below the reference pressure, a reverse flow will occur. Thus the curve represents the locus of possible operating points for this one particular load subjected to a wide variety of source conditions.

Fig. 23-5(A)¹ is a schematic drawing of a specific load connected to a specific source. As previously mentioned, under steady flow conditions the source must equal the load flow to maintain continuity. It is also necessary for the source pressure to equal the load pressure since they are measured at the same point in the circuit. The connection of a specific source to a specific load, therefore, results in

one particular value of flow and one particular value of pressure. Graphically this means that the source and load curves intersect at one point when they are superimposed on each other as shown in Fig. 23-5(B). This point is called the operating point. Very often, in fluid amplifiers, the load must be adjusted for a particular source, so that the operating point falls in a desirable operating region. The coordinates of the operating point shown in Fig. 23-5(B) are

$$P_x = \frac{Z_L}{Z_L + Z_s} \left(P+ + \frac{Z_s}{Z_L} P_b \right), \text{ psi} \quad (23-1)$$

$$Q_x = \frac{P+ - P_o}{Z_L + Z_s}, \text{ in.}^3/\text{sec} \quad (23-2)$$

where

P_x = pressure at the operating point, psi

Z_L = load impedance, $\frac{\text{lb}}{\text{in.}^2} \frac{\text{in.}^3}{\text{sec}}$

Z_s = source impedance, $\frac{\text{lb}}{\text{in.}^2} \frac{\text{in.}^3}{\text{sec}}$

$P+$ = primary source pressure, psi

P_b = reference pressure, psi

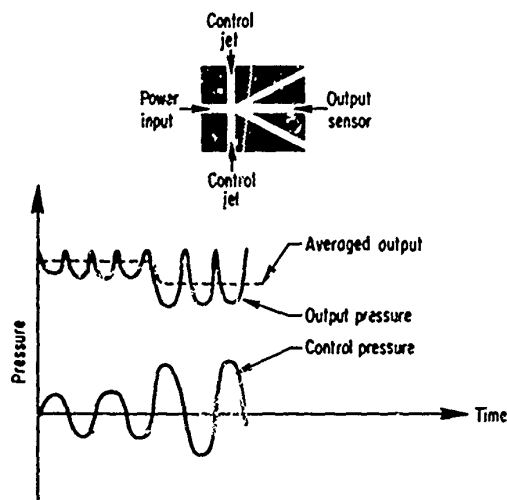
Q_x = flow at the operating point, $\text{in.}^3/\text{sec}$

Thus the operating point depends upon the source and load impedances as well as the supply and reference pressures.

23-5 DC AND AC SYSTEMS

The concept of direct-current (DC) in electrical phenomena implies flow of current (electrons) in one direction, the amount of flow being controlled by the driving force (voltage). This concept applies equally well to the field of DC fluidics wherein the fluid flow is the current and the driving force is the pressure applied to the fluid. Since the control of air flow is in many respects similar to the control of unidirectional electric

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Figure 23-6. AC Rectification Fluoric Device³

current, the design principles of DC fluorics have grown to parallel closely those of DC electronics. Unfortunately, some types of fluoric circuits also have limitations similar to those of DC electronics. Weak signals are difficult to transmit and detect, and noise from turbulent flow in fluidic systems is even more troublesome than thermionic noise in electrical systems. To help alleviate this problem, AC fluoric systems are being developed². The use of the term AC applied to fluoric signals may be misleading to those who carry the analogy between electrical and fluoric circuits too far. A more precise description might be *undulating or oscillatory flow superimposed on a steady flow*. The important difference between electric and fluoric AC signals is that the fluoric signal always has a DC component in addition to the AC component. In some ways, however the features of the new AC fluorics often parallel those of AC electronics, and the terminology is also similar. Designers of AC fluoric systems speak of inductance, frequency modulation, phase shift, and pulse width in the manner as do designers of electronic systems.

In AC fluorics the term signal refers to the pressure changes occurring in the circuit. These pressure variations can be either referenced to local atmospheric pressure, or to some other point in the circuit. The signal is therefore a differential pressure. Signal amplitude in an AC circuit generally ranges from 0.01 to 10 psi. More typical values are between 0.1 and 1 psi. Speculation on the ultimate frequency limit for fluoric devices ranges from a conservative 10 kHz up to a rather optimistic 100 kHz.

The transmission speed for an AC fluoric device is about equal to the velocity of sound in the fluid medium, or about 1000 ft/sec in air which is commonly used. The corresponding time delay is about 1 msec/ft.

The specific advantages of AC over DC fluoric systems include faster response, greater accuracy, and less vulnerability to system noise. Present indications are that AC fluorics is especially well suited to the measurement and control of speed, temperature, and pressure in environments that are too extreme for conventional sensors or control devices. The present types of fluoric timers which incorporate oscillators and counters are a form of AC fluorics. A widely used component that well illustrates AC fluoric operation is the rectifier or absolute-value amplifier. This device has an output port centered downstream from the supply nozzle as shown in Fig. 23-6³. Two opposing control nozzles impinge on the power stream and direct it away from the outlet port to a degree proportional to the imbalance in the opposing control streams. When the two control pressures are equal, the power stream is centered on the outlet and the pressure output is maximum, as shown in the figure. When the differential between control pressure is highest, the beam is deflected away from the outlet by a maximum amount, and the resulting power output is a minimum. Sinusoidally varying control pressures thus flip the power stream back and forth across

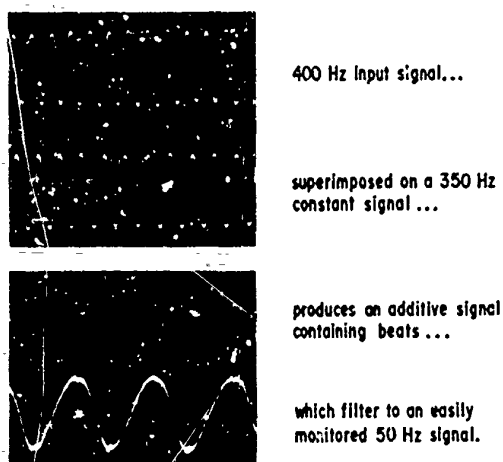


Figure 23-7. Heterodyning a Flueric Signal³

the outlet port to produce output pulsations of the type shown in the figure. These pressure pulses are then usually filtered to produce an average constant DC signal having an intensity inversely proportional to the amplitude of the AC signal.

Another example of AC flueries which has its counterpart in AC electronics is in heterodyning a flueric signal. In the wave forms shown in Fig. 23-7³, a 400-Hz input signal is superimposed on a constant carrier frequency of 350 Hz to produce an amplitude-modulated wave that can then be filtered to produce a beat frequency of 50 Hz. This principle has been used to produce a flueric/acoustic transceiver, each unit powered by inflated balloons. In the transmitter unit the power supply air is passed through an ultrasonic whistle, and the tone generated is amplitude modulated by acoustical interaction with a human voice. At the receiver, which receives the line-of-sight signal, demodulation occurs back to audible frequencies by AC flueric devices also powered by an inflated balloon. A successful transceiver developed by H. H. Unfried of Genge Industries Inc. transmitted voice information over several hundred feet with fidelity approaching a pocket radio. The acoustic

radio, however, is very limited. It is generally known that to get high directivity, one must use high frequency flueric signals. These signals are severely attenuated by atmospheric conditions, and air currents can deflect the beam direction. One possible use, however, could be in short range communications in explosive environments where the use of electrical energy would be prohibited.

One of the major difficulties facing developers of AC flueric systems is the need to strengthen the analytical basis of the present design technology. As a result, a considerable amount of work is now done by empirical methods. The lack of analytical tools makes it extremely difficult to optimize a device, or in fact to analytically design a system to serve the particular intended function. Continued effort and work with flueric systems will alleviate this problem.

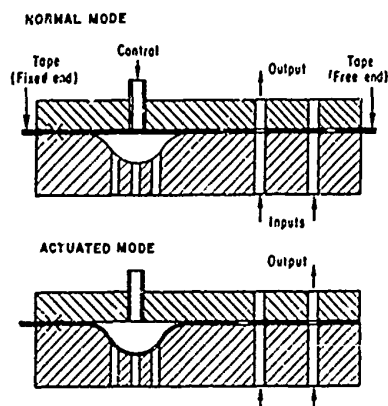
An analysis of an AC flueric circuit follows very closely the approach used in electrical-network analysis. The circuit is first subdivided into active and passive components. Active elements include amplifiers, power supplies, and auxiliary sources. Passive elements are components composed of idealized resistive, capacitive, and inductive elements. A simplified approach then assumes that the characteristics of the individual components combine in a linear manner. This simplified analysis does not completely define the real situation over all operating conditions but does provide an adequate bench mark for initial circuit design.

For a more detailed comparison of flueric and electronic logic, see Appendix A.

23-6 HYBRID SYSTEMS

Hybrid systems use flueric elements together with mechanical elements (diaphragms, etc.) to make an efficient final unit. For example, output from a flueric circuit can be used to deflect a diaphragm that is connected to mechanical linkage to perform switching,

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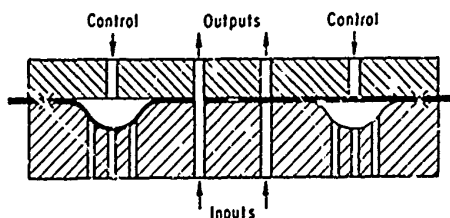
Figure 23-8. Monostable Coded-tape Valve⁴

etc. Some typical hybrid devices are:

- (1) Coded tape valves
- (2) Tape actuators
- (3) Vibrating-reed frequency sensors
- (4) Moving part detectors
- (5) Flow control devices
- (6) Pneumatic switches.

23-6.1 CODED TAPE VALVES

A coded, flexible strip can be used as a moving element in a valve, Fig. 23-8⁴. The strip is actuated by pneumatically deflecting the strip into a profiled cavity. When pressure is applied to the control port, the tape

Figure 23-9. Bistable Coded-tape Valve⁴

deflects into the cavity and the free end moves in its groove. Holes in the tape are arranged so that, when the tape is deflected into the actuating cavity, the formerly open port is blocked and the opposite port is opened. Consequently, the device acts as a switch.

The vent holes in the bottom of the actuating cavity allow the fluid to escape as the tape is deflected by control pressure. Since the tape is of an elastic material, when the control signal is removed, the tape snaps back to the original position. Consequently, this device is monostable.

Between application of control pressure and completion of switching to the deflected position, some of the control signal leaks around the tape and out of the venting ports. When the tape is completely deflected, the tape seals the venting port and blocks the leakage.

The same principles also can be the basis for a bistable device, Fig. 23-9⁴. Essentially the same as the device shown in Fig. 23-8, it incorporates two actuating cavities, and both ends of the tape are clamped. The tape is just long enough to lie flat across one cavity when it is completely depressed into the other. The configuration is stable and the tape remains deflected into one cavity until a control signal is applied to the other cavity. Thus, this device can be used both as a switching device and a storage element.

The coded-tape device has two important characteristics:

(1) The element is capable of controlling many inputs. In the sketches shown, only two ports are indicated. In practice, however, many ports could be controlled by a single tape.

(2) The output is isolated completely from the input.

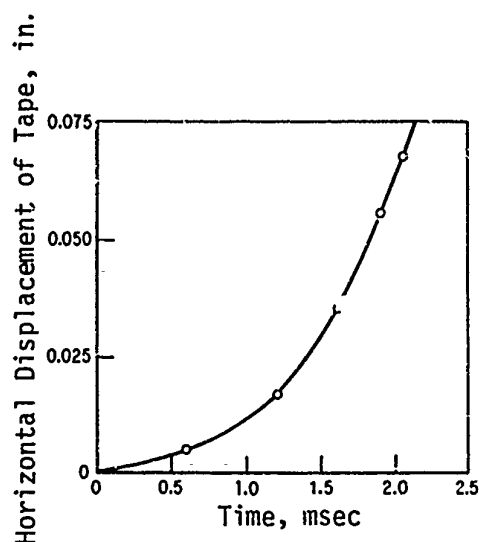


Figure 23-10. Displacement-Time Relationship for Tape-element Switching⁴

Although the coded-tape device has moving parts, the moving part is of light weight. Furthermore, the device is simple and inexpensive. In practice, Mylar tape has been found to be a suitable material.

Switching time of the device depends on the signal pressure applied and the mass of the flexible member. In working devices, switching times of 2 or 3 msec can be obtained. A typical time-displacement relationship for a control pressure of 20 in. water is shown in Fig. 23-10⁴.

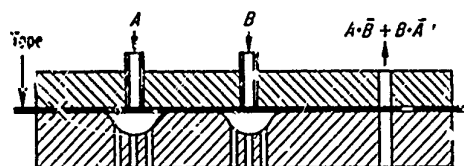


Figure 23-11. Exclusive OR Coded-tape Element⁴

In digital-circuitry applications, coded tape devices can generate logic functions, Fig. 23-11⁴. Here a flexible tape with two cavities is actuated by control ports, A and B. This is an exclusive OR circuit; i.e., the signal port is open when the pressure is applied to either control port A or B, but not both. A variety of other logic circuits also can be generated with devices of this type.

Digital code-translators have been made by placing several of these logic units in parallel. When so arranged, all the inputs are in parallel. As they switch, they produce parallel outputs, but in a different code.

23-6.2 TAPE ACTUATORS

The coded-tape device also can be used as an actuator; i.e., when the tape is deflected, the moving end of the tape can be used to apply a force rather than to switch signals, Fig. 23-12⁴. Here, the actuating cavity does not limit tape deflection.

A sketch of the forces F acting on such a tape is shown in Fig. 23-13⁴. Output force is given by⁴

$$F = Pb \left(\frac{\ell^2}{8d} - \frac{\Delta}{2} - \frac{\ell\mu}{2} \right), \text{ lb} \quad (23-3)$$

where

P = supply fluid pressure, psi

b = width of the tape, in.

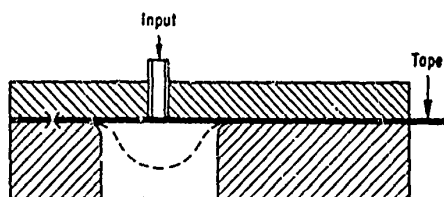
ℓ = span of the cavity, in.

μ = coefficient of friction between tape and cavity, dimensionless

Δ = tape deflection, in.

From this equation, as the deflection increases, the force should decrease. An experimental measurement of force vs displacement for a typical device is shown in Fig. 23-14⁴.

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Figure 23-12. Tape Actuator⁴

23-6.3 VIBRATING REED FREQUENCY SENSORS

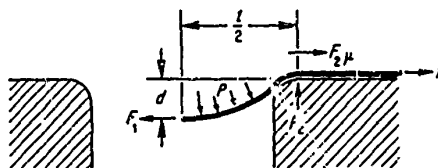
Vibrating reed frequency sensors may be used in applications where there is a requirement for the measure of a time-variable, repetitive, mechanical motion. A typical application of this type of sensor is shown in Fig. 23-15⁴ where it is used with a wobble-plate signal generator. This signal generator has two nozzles 180 deg from each other (with reference to the shaft) which can be used as shown to provide pressure pulse outputs 180 deg out-of-phase with each other.

The outputs from the wobble-plate signal generator are directed against the sides of a vibrating reed, Fig. 23-16(A)⁴, and act as out-of-phase, sinusoidal driving forces. When the reed is at rest, the paddle deflects all the flow from the supply nozzle and none of the pressure is recaptured in the output tube. As the reed vibrates, the intermittent opening between the supply nozzle and the output tube permits a portion of the supply pressure to be recaptured and used as an output signal.

When the frequency of the driving jets is not close to the resonant frequency of the reed, the reed is not deflected appreciably. However, as the driving frequency goes through the resonant frequency of the reed, the reed deflections increase and the pressure in the output tube goes through a maximum, Fig. 23-16(B).

Frequency error can be sensed by use of two reeds tuned to slightly different frequencies, Fig. 23-17(A)⁴. Pressures P_1 and P_2 are the signals from a wobble-plate generator.

23-12

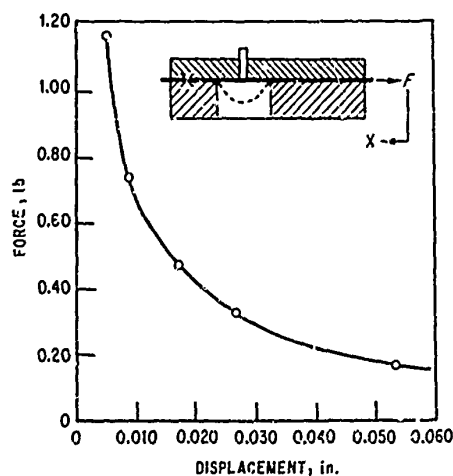
Figure 23-13. Forces Acting on Tape Segment⁴

Output pressures as a function of input frequency are shown in Fig. 23-17(B). The two signal pressures are applied to opposite sides of a stream interaction or other proportional amplifier. A curve of the pressure differential between the two output ports is shown in Fig. 23-17(C).

Test results on such a device, with air as the working fluid, are shown in Fig. 23-18⁴.

23-6.4 MOVING PART DETECTORS

Mechanical motion or flow can be detected by a tightly covered foam-rubber filled cavity, Fig. 23-19⁴. An impregnated rubber-fabric diaphragm is placed across the surface of the cavity. When moving parts hit the diaphragm of the foam-filled cavity, they create an

Figure 23-14. Force-Displacement Relationship for Actuator⁴

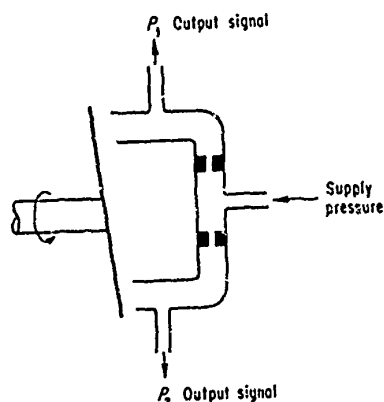


Figure 23-15. Wobble-plate Signal Generator With Out-of-phase Signal Outputs⁴

output fluid pulse. This output pulse can be used to actuate a pneumatically operated switch; it can be amplified by fluoric amplifiers for other uses; it can operate fluoric counter circuits; or it can be incorporated

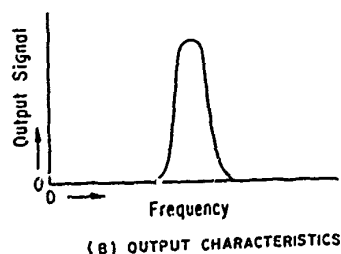
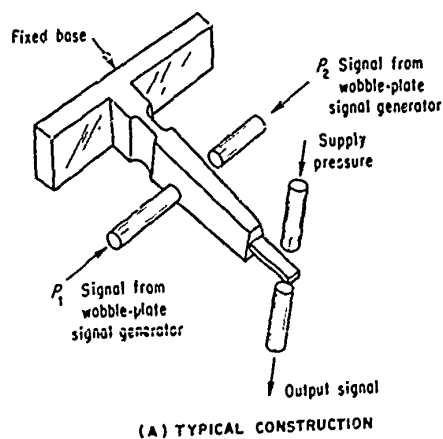


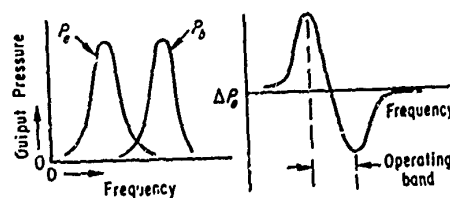
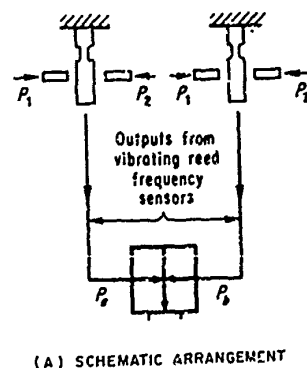
Figure 23-16. Vibrating-reed Frequency Sensor⁴

with an oscillator to determine time between events or rate of production.

A large variation in the sensitivity of the detector can be obtained by varying the density of the foam. Sensitivity varies inversely with density. Sensitivity can be made so high that a few grams of material striking the surface give usable output-pressure pulses, or the sensitivity can be so low that several pounds are required to give a usable output pulse.

23-6.5 FLOW CONTROL DEVICES

In principle, most flow controllers are usually variable fluid resistors whose resistance depends on some external parameters such as pressure or temperature. These controllers often involve moving parts and are thus subject to wear. As a general rule of thumb, an element that employs deformable parts is generally more reliable and longer lasting than an element that uses moving parts.



(B) OUTPUT CHARACTERISTICS (C) DIFFERENTIAL OUTPUT FROM FLUORIC AMPLIFIER

Figure 23-17. Double-reed Frequency Sensor⁴

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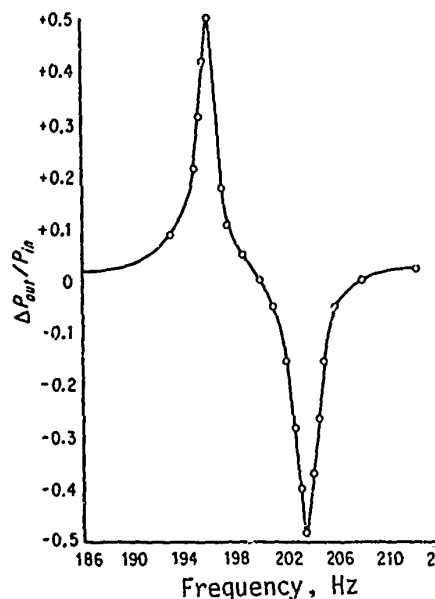


Figure 23-18. Test Results for Double-reed Frequency Sensor⁴

One type of temperature-controlled variable fluid resistor is shown in Fig. 23-20⁴. Silicon rubber has an unusually high coefficient of volumetric thermal expansion. As the valve body and the O-ring increase in temperature, the O-ring expands and decreases the clearance between itself and the tapered needle screw. As the clearance decreases, the fluid resistance increases. The lateral position of the tapered needle screw can be adjusted so that the valve shuts off completely at any desired temperature. Thus, as temperature is increased, resistance increases until, at some predetermined temperature, the resistance becomes infinite.

A typical curve of flow vs temperature for this type of resistor is shown in Fig. 23-21⁴. A constant pressure of 20 psi was applied to the element. The tapered needle screw was so adjusted that the valve shut off completely at approximately 65°C. With this design, fluid flow varies linearly with temperature over a relatively wide range.

A patented adjustable, laminar-flow vari-

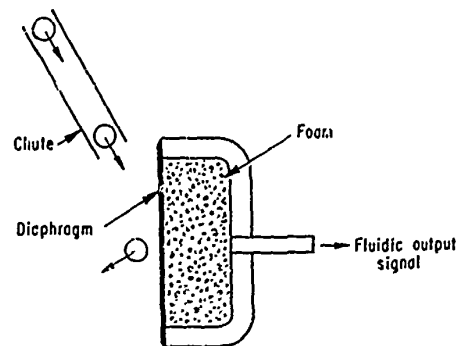


Figure 23-19. Flueric Moving-part Detector⁴

able fluid resistor consists of two flat plates sealed by O-rings, Fig. 23-22⁴. Resistance is varied by varying the spacing between the plates.

Spacing of the plates can be controlled by temperature-responsive elements, Fig. 23-23(A)⁴, when used in conjunction with the variable fluid-resistor. Here the dimensions of the inner rod and the casing vary with the temperature changes, varying the spacing between the two plates. An example of this resistor circuit is shown in Fig. 23-23(B). Output pressure depends on the resistance of the adjustable, laminar-flow restrictor. Typical relationships of output pressure and temperature for this device are shown in Fig. 23-24⁴. Both plots show significant ranges of temperature variation over which the output pressure varies linearly with temperature.

23-6.6 PNEUMATIC SWITCHES

Historically, pneumatically operated

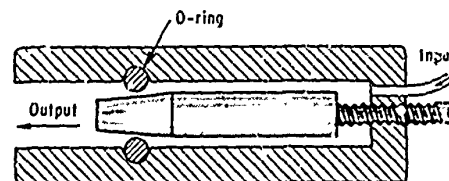


Figure 23-20. Temperature-sensitive Flueric Resistor⁴

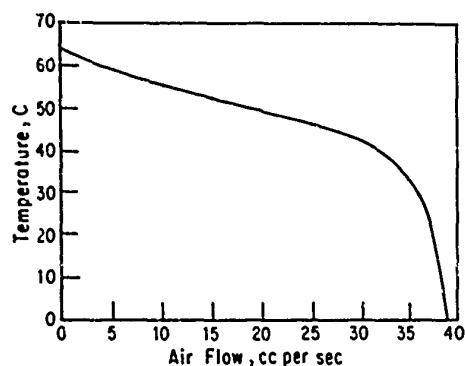


Figure 23-21. Flow-Temperature Characteristics for Resistor Shown in Fig. 23-20⁴

switches have been used extensively throughout industry and have the potential for wide applications in hybrid fluoric circuits. In principle, most of these switches include a membrane or other flexible part which is deflected by applied pressure to actuate electrical contacts. Some of these switches, even though insensitive to external shock and vibration, sense pressures of 0.5 in. water or less⁴.

23-7 TEST AND EVALUATION

An initial effort in any new fluoric design problem is usually made with a breadboard setup in which various parameters of the circuit easily can be changed. At this time the use of pressure and flow meters and special test equipment will aid in the development. Once a circuit design is developed, it most likely will be scaled down to a size that will not permit further measurement. Because of this, the designer must have a thorough

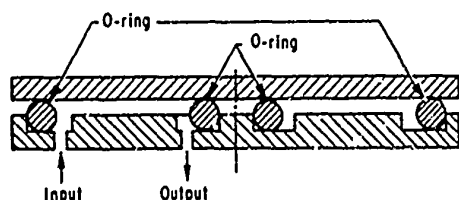


Figure 23-22. Adjustable Laminar-flow Fluoric Resistor⁴

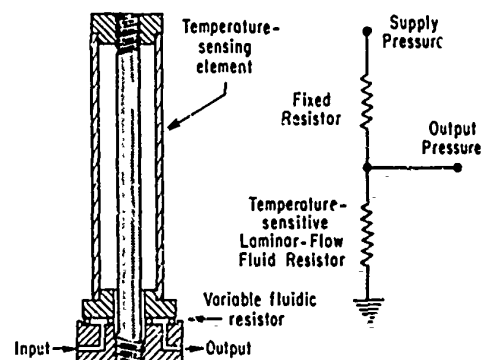


Figure 23-23. Temperature-sensitive Fluoric Resistor⁴

knowledge of the effects of scaling down a large model to one of greatly reduced size. Furthermore, in his evaluation of the breadboard, he will most likely conduct static as well as dynamic tests. He should be aware in the dynamic tests that even a short tube, such as a pressure connector, can add a significant shunt capacity as the frequency is increased and thus alter circuit response. Due

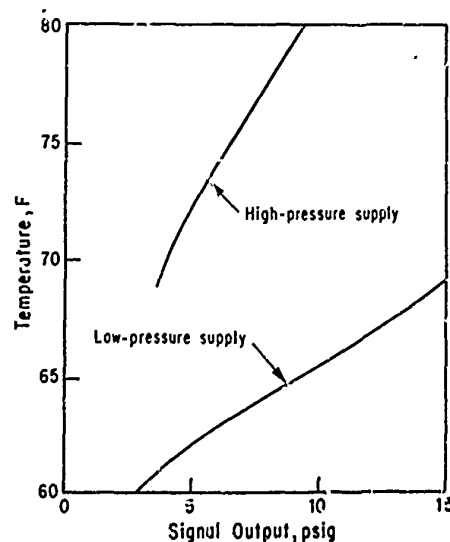


Figure 23-24. Output Pressure-Temperature Characteristics for Circuit Shown in Fig. 23-23⁴

to the nonlinear behavior of most flueric circuits, an analytical solution to system design, at the present time, has not been as practical as the cut-and-try method. As fluid technology develops, however, it is hoped that much of the work being done will be documented in the form of handbooks and textbooks which might then facilitate the design process.

23-7.1 FLOW METERS

Fluid flow can be recorded as volume flow per unit time, or mass flow per unit time. If the fluid is compressible, the flow is usually corrected to SCFM units (standard cubic feet per minute), generally at a reference level of 14.7 psia and 59°F^s.

There are two types of fluid flow of interest to the flueric designer: laminar flow and turbulent flow. Laminar flow is characterized by fluid particles in a tube moving in straight parallel lines down the tube. Turbulent flow is characterized by an unpredictable tumbling, churning flow as the fluid progresses down the tube. If the Reynolds number of the flow in a tube is below 2000, the flow will be laminar; if the Reynolds number of the flow is above 4000, very probably it will be turbulent. The Reynolds number R_e may be determined by

$$R_e = \frac{vd}{\nu}, \text{ dimensionless} \quad (23-4)$$

where

v = mean velocity of the fluid, ft/sec

d = tube diameter, ft

ν = kinematic viscosity, ft²/sec

For air, ν is 1.57×10^{-4} . The flow laws for the laminar and turbulent regions are well known, but in the transition region the flow is complex and no known law describes the fluid behavior.

An expression for Reynolds number which

is more useful for flueric circuitry is

$$R_e = \frac{Q}{Q_r}, \text{ dimensionless} \quad (23-5)$$

where

Q = actual weight flow, lb/sec

$Q_r = \frac{\pi g d^3}{4\mu}$ = reference weight flow, lb/sec

g = sea level acceleration due to gravity, 386.4 in./sec²

μ = fluid (dynamic) viscosity, lb-sec/in.²

d = tube diameter, in.

Thus for each size of tube and for a given fluid, there is a definite reference current. If the actual fluid current through the tube is less than 2000 times this reference current, the flow is in the laminar region. If the actual current is greater than 4000 times the reference current it will be turbulent flow. Between these values is the transition region. Fig. 23-25⁶ shows a plot of tube diameter versus flow for air and water constructed from Eq. 23-5. The fluid viscosities used were $\mu_{air} = 2.6 \times 10^{-9}$ and $\mu_{water} = 1.46 \times 10^{-7}$. Similar figures can be easily constructed for any working fluid if the viscosity is known.

The product of fluid pressure and flow is power

$$H = kPQ \quad (23-6)$$

where

H = power (see note)

k = a factor

P = fluid pressure, lb/ft²

Q = flow, ft³/min

Note: When $k = 1$, power is in ft-lb/min. For

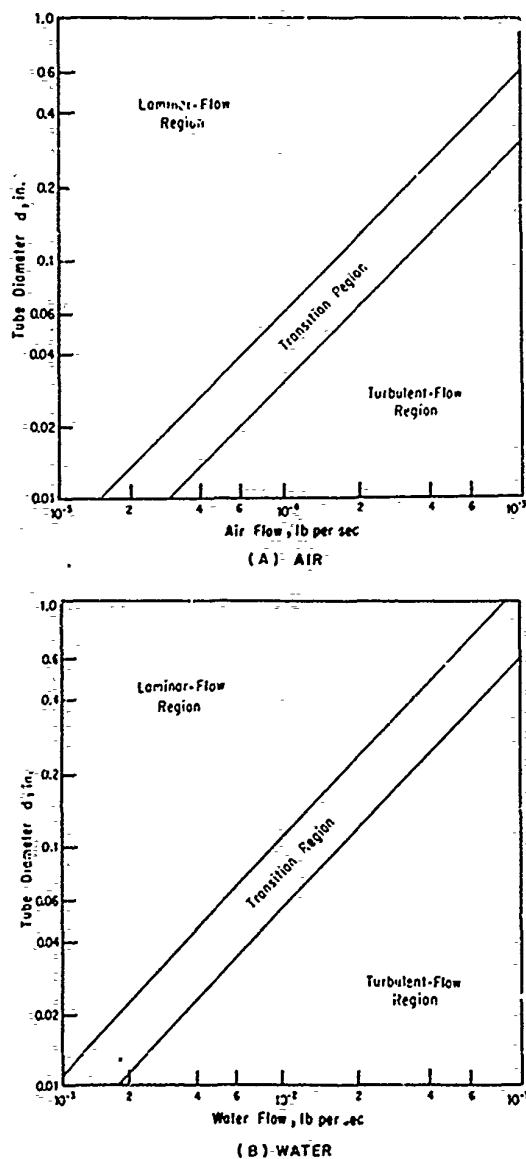


Figure 23-25. Flow Regions for Air and Water in Round Tubes⁶

power in watt, use $k = 0.5645$ when air is the fluid.

Fig. 23-26⁵ shows the air power, in watts, of various size nozzles with rectangular cross section as the pressure and flow are varied at constant temperature. Exit is to the atmosphere. Fluid power need not be converted to

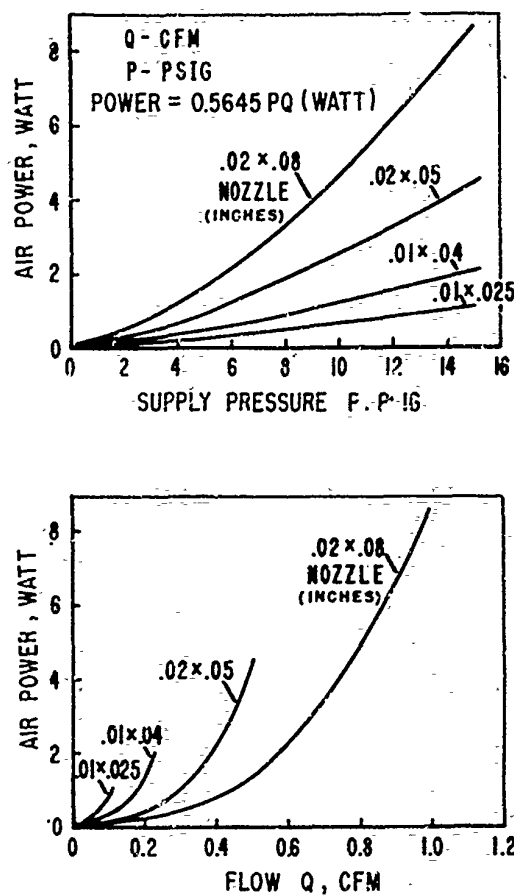


Figure 23-26. Air Power Expended in Typical Rectangular Nozzles

watts unless some form of electrical analogy is desired. In some types of applications the product $P_A Q$ (P_A is absolute pressure), is used as a measure of fluid *current*. This term commonly is called *throughput*.

A wide variety of flow meters is commercially available. Many of them place a known fluid resistance in the flow stream and monitor the pressure drop across it. Others use rotating cups and vanes whose rotational velocity can be related to flow rate. Some of these latter types are in reality volume meters from which a Q can be calculated.

Another type is an electrical flow meter

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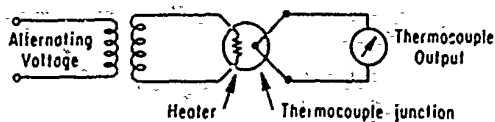


Figure 23-27. Indirectly Heated, Single-thermocouple Flow Meter⁷

shown in Fig. 23-27⁷. In this type of a thermocouple with an adjacent heater is placed in the flow path. Output of the thermocouple can be related to flow rate; i.e., for a fixed heater current, voltage output will decrease for an increase in flow since the fluid will capture more heat from the heater-thermocouple bulb. This type must be calibrated with a given fluid and a similar fixed geometry. For a given flow, output readings will change if the fluid temperature changes. To eliminate this, a compensation thermocouple can be integrated into the circuit as shown in Fig. 23-28⁷. Thermocouple C is the compensating thermocouple. A and B are heated, C is not.

Changes in the ambient temperature of the flowing fluid affect all three thermocouples. Since the output of thermocouple C opposes that of the other two, temperature-fluctuation effects of the flowing fluid are cancelled. The compensation is so effective that no correction need be made for fluid temperatures from 40° to 200°F when measuring the flow of air. Instruments of this sort are commercially available. The circuit of Fig. 23-28, although normally used as a steady-state flow meter, can measure flow fluctuations up to 10 or 12 Hz.

23-7.2 VELOCITY METERS

When fluid flows in a tube, the velocity is not constant along any radial line, but usually varies from zero at the tube walls to a maximum at the centerline. The shape of the velocity profile is a function of the surface roughness, fluid viscosity, and diameter of the

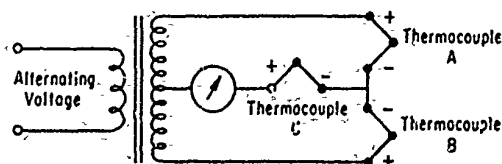


Figure 23-28. Three-thermocouple Compensated Type Flow Meter⁷

tube. This applies to laminar flow. With turbulent flow, a different velocity profile exists. In many cases, with laminar or turbulent flow, the designer is interested in an average velocity that can be assumed uniform over the cross-sectional area of interest, so that flow rate can be related to this velocity and the area through which it acts.

The basic principle of the flow meters just described can be used to measure fluid velocity, but most velocity meters employ a light weight metallic film or thin wire. These are known as hot-wire or hot-film anemometers. They work on the following principle: A hot wire (or film) in a moving fluid stream loses heat energy to that stream, if the stream is at lower temperature than the wire. The amount of heat loss and resulting temperature drop of the wire depend on the temperature and velocity of the moving fluid stream. Resistance of the wire changes with the temperature. Energy loss or temperature of the wire can be monitored, and is a direct measure of the velocity of the fluid.

Due to the small mass of the sensing element (5-micron tungsten wire, 1 mm long), response is fairly fast and velocity fluctuations to 60 kHz are possible. This is far above the frequency range of interest in most fluidic circuit designs. To eliminate the fragile nature of tiny wires of brittle materials, metallic film deposits on cylinders of quartz or glass are the heart of the hot-film anemometers. With the introduction of these types, fluid velocity measurements from 150 m/sec (a maximum for hot-wire types) to above 500 m/sec were realized.

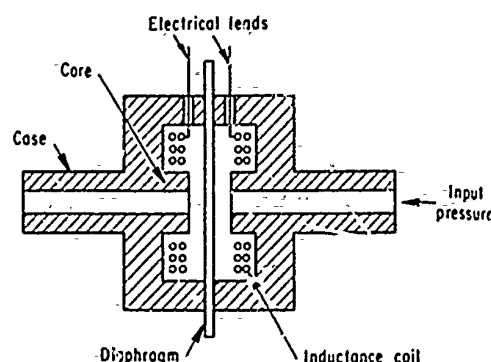


Figure 23-29. Stretched-metal Diaphragm Pressure Meter⁷

Under conditions of thermal equilibrium, the rate of heat loss from the wire must be equal to the electrical power supplied to the wire. A useful empirical equation has been developed as follows

$$I = A + B(v)^n, \quad A \quad (23-7)$$

where

I = current supplied to wire or film, A

A , B , and n = constants

v = velocity, m/sec

The values of A , B , and n are determined empirically to give the best fit to the experimental data within the desired velocity range. This formula is known as King's Law. The value of $n = 0.5$ fits the hot-wire case well when the probe is operated in atmospheric air and the velocities lie between 1 and 100 m/sec. For a hot-film probe in the same velocity range, a value of $n = 0.33$ gives a better fit to the experimental data⁷.

The anemometers can be instrumented such that the current through the element is held constant, then the voltage across the element is related to fluid velocity; or the current is varied such that the element always remains at a fixed temperature, thus heater

current is related to flow velocity. For a thorough discussion of the instrumentation employed with anemometers, consult Ref. 7.

23-7.3 PRESSURE METERS

No problem exists in the measurement of steady-state or static pressure because many gages are commercially available. These measurements can be made on extremely small devices such as those typifying flueric elements. It is in the area of measuring fluctuating pressures within small orifices and channels that problems arise, primarily because the gage must be physically small with low inertia. Since flueric devices have frequency characteristics that could extend to 1000 Hz or more, an adequate gage must have a frequency response to at least several thousand hertz. The gage should not have an acoustical resonant point within the range of interest, and its mechanical resonance frequency should be high.

Excellent piezoelectric gages with the required frequency response are available for transient pressure measurements. They are available in very small size and often can be mounted directly in a flueric element, flush with some internal wall. These gages however are high-impedance devices, and are vibration sensitive. Furthermore, they have a low frequency cut-off, and cannot be used to measure either a steady-state or a slowly changing pressure. Since the gage is a high-impedance device, it requires a preamplifier reasonably close to the gage.

In applications where a preamplifier is prohibited, an electrical pressure gage with low internal impedance is desirable. Such a gage, using a stretched metal diaphragm as the pressure-sensing element, has been developed, as shown in Fig. 23-29⁷. This gage is small and can be mounted in a very small volume. However, it must be connected by a tube to the region in which the pressure is to be sensed. In high-frequency measurements, correction must be made for capacitive effects of the tube. A typical calibration curve is

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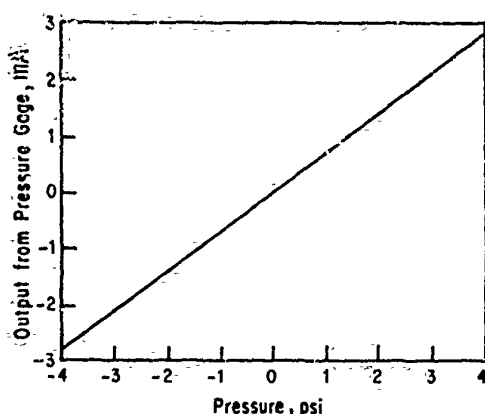


Figure 23-30. Calibration Curve of a Typical Pressure Gage⁷

shown in Fig. 23-30⁷. This plot shows that the linearity over the indicated pressure range is very good.

A recently developed pressure meter uses a heated filament mounted inside a very small ceramic tube. One end of the tube is attached to a reference pressure while the other end is connected to the pressure to be monitored. The ceramic tube is sized so that the flow velocity through it is a direct function of the difference between the pressure being monitored and the reference pressure. The hot filament measures the velocity, which in turn, gives a measure of the pressure difference.

The reference pressure is set slightly lower or slightly higher than the extreme of pressure fluctuation expected in the monitored source. One advantage of holding the reference pressure higher than the pressure being measured is that gas is bled into the system being monitored rather than out of it. Since the reference pressure can be filtered, dirt is kept out of the pickup tube. Flow from the reference also can be kept at a constant temperature. If gas is bled into the system being measured, pressure measurements will not be affected by fluctuations in the temperature of the measured source.

A typical inside diameter for the ceramic tube is 0.002 in. This diameter is so small that very little disturbance is introduced into the region where pressure is being measured. In applications where this small amount is important, another tube and a valve can be installed adjacent to the pressure-measuring tube, and adjusted so that as much fluid is bled off by the second as is introduced by the first. Frequency response of this type pressure gage, which is comparable with that of the hot-wire anemometer, extends into the kilohertz range.

23-7.4 FLOW VISUALIZATION

In device development, knowledge of the actual flow paths of the fluid through the devices is often useful. These paths can be determined by water-flow tables, smoke utilization, and optical techniques.

23-7.4.1 Water Table

In this technique, the device to be studied is built to a scale, usually many times its actual size, and water is pumped through it. The flow paths of the water give an indication of the flow paths through the actual device. Dye usually is added to the water supply, and the flow paths may be photographed for permanent record as the dyed water proceeds through the element under test. Since the fluid behavior of the free surface of water and air are similar, a knowledge of the behavior of the typical fluidic device in the water table may be used as the basis for the scaled-down design of a device in another fluid. Water tables are useful in new element design because the geometry of the element can be changed readily. For example, the shape of the channel walls can be changed easily since they usually are made from a soft malleable material such as lead.

Water tables are expensive to construct. A less expensive method is to pass smoke through a transparent plastic model of the device under study.

23-7.4.2 Smoke

When smoke is introduced in the input nozzles of a transparent model, the flow patterns of the smoke, and hence the flow pattern of the fluid within the device, readily are seen. Smoke can be made by vaporizing kerosene in a smoke generator producing a smoke white in color. With time, however, the kerosene droplets condense and collect on the sides of the device under test. In most instances, this collection is not enough to disturb the experiment. Commercially available smoke-generating machines produce a pure white smoke. In some of these, the smoke is generated by oxidizing mineral oil and mixing it with carbon dioxide.

23-7.4.3 Optical Techniques

One of the most common optical techniques is the shadowgraph. It is the simplest and cheapest to employ for flow visualization. With this method, light is passed through a transparent model normal to the fluid flow impinging on a photographic plate on the opposite side. The resultant pictures represent the rate of change of the density gradient in space normal to the transmitted light. Since this method represents the second derivative of density, it is insensitive to uniform density gradients. Consequently, its usefulness for visualization is restricted to suddenly changing conditions (such as in turbulence or shock fronts in supersonic flow); therefore, quantitative analysis seldom is made with this technique.

Another optical technique, the Schlieren method (based on Toepler's theory), requires more costly and precise equipment than the shadowgraph. With this method, the resultant picture represents the density gradient and furnishes detail in more "gentle" flow than the shadowgraph. It generally is considered the most sensitive of all optical methods, and thereby offers much use for visualization. Care must be taken, however, in interpreting the flow characteristics, in that a single

picture of a density gradient can be misleading unless proper analysis be made. Quantitative analysis becomes more practical for Schlieren methods than the shadowgraph, especially if the flow is two dimensional.

Another optical technique, the interferometer (Mach-Zehnder type), is the most expensive, most precise, and most difficult to adjust. This method is considered favorably because of its ability to record density directly; therefore, quantitative analysis becomes relatively simple for two-dimensional problems.

In consideration of all factors involved, the Schlieren method has received the greatest application. A relatively simple design of this system can be constructed, capable of permitting (1) wide-range sensitivity, (2) the use of color to enhance contrast, and (3) simple adaptation to a shadowgraph or an interferometer of the polarizing or diffraction grating type. In addition, the Schlieren system is more compatible for the restrictions imposed upon the field of coverage and the mechanical requirements of the test section than the interferometer. Also, a preliminary system can be set up using readily available optics such as photographic lenses. A thorough description of these methods is given in Refs. 8 and 9.

23-7.5 FREQUENCY METERS

Measurement of fluid oscillations can be accomplished with a hot-wire anemometer or a sensitive pressure transducer. The hot-wire anemometer has the advantages of very small size, and thus minimum obstruction to flow, and has excellent response. Unfortunately, considerable care must be used in handling these anemometers. Calibration is time-consuming, and the output is a fourth power function.

23-7.6 SIGNAL GENERATORS

A low-frequency signal generator can be

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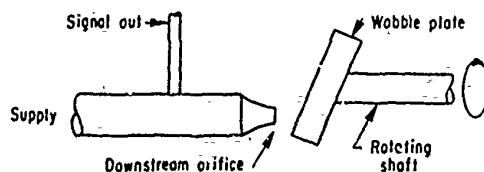


Figure 23-31. Wobble-plate Type Signal Generator⁷

obtained from a variation of the flapper valve; a wobble-plate attached to a rotating shaft, as shown in Fig. 23-31⁷. Shaft rotation varies the distance between the surface of the flapper, or wobble-plate, and the downstream orifice. This changes the resistance of the orifice and the pressure within the volume.

The lower frequency limit of this type of signal generator is zero, or a steady-state pressure. The upper limit depends on wobble-plate speed and the frequency characteristics of the flapper valve itself. Response of the flapper valve drops off with frequency due to the reactive capacitance of the volume and the resistances of the upstream and downstream orifices.

Since the simple wobble plate is dynamically unbalanced, it produces undesirable mechanical vibrations. This fact limits the upper frequency available from this type signal generator. This limitation can be overcome partially by use of a circular cam Fig. 23-32⁷. Since the cam can be balanced

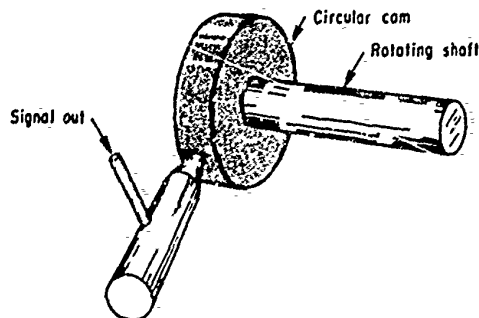


Figure 23-32. Circular Cam Signal Generator⁷

dynamically, higher speeds can be obtained. A variety of output waveforms can be obtained by varying the cam shape.

An electrically-driven flapper provides for easily changeable output wave shapes and higher frequencies. The flapper part of the valve is attached to the voice cone of a loudspeaker, Fig. 23-33⁷. Since the speaker cone can be driven from an electrical-signal generator, a wide variety of output-wave shapes can be obtained by varying the shape of the electrical-input signal. This type of signal generator is very versatile and useful in laboratory development work.

Pressure oscillations can also be provided by piezoelectric elements. In this type of signal generator, the elements are mounted in a cavity. When excited electrically, the elements distort and create a pumping action. This pumping action excites the chamber, and a tube connected to the chamber produces a varying pressure output. These generators can produce pressure oscillations from 20 Hz to between 5,000 and 10,000 Hz. The upper end of this spectrum is well beyond the requirements of most flueric work. The pressure variations available from piezoelectric generators are small, at least in the pressure ranges of interest in flueric work. The variation in output is a function of the electrical power applied, the bias-pressure level (the supply pressure applied to the load), and the volume of the attached load.

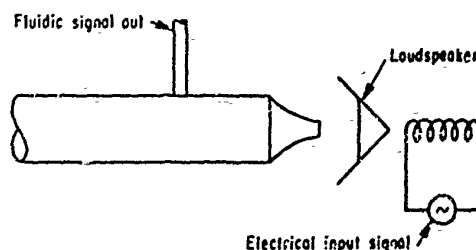


Figure 23-33. Loudspeaker-actuated Signal Generator⁷

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CHAPTER 24

COMPONENT DESIGN

The timer package is composed of a number of individual elements connected together in a modular fashion to fit within a specified volume. For example, present fluoric timers have as components a power source, a stable oscillator, a counter circuit, and an output transducer. The operation of each of these as an entity must be thoroughly understood as well as their operation when integrated in the timer assembly. The paragraphs that follow discuss some of these elements with the emphasis on their use in a military timers or timing circuits. Standard terminology and symbols are used¹.

24-1 POWER SUPPLIES

All fluoric elements require a continuous flow of fluid through them during the period of time that they are functional. Thus the source of power for a fluoric timer becomes a most basic component and should be considered carefully before a supply source is decided upon. Also present devices operate mainly on "flow" rather than "pressure". To achieve isolation between elements, "venting" or "bleeding" is employed. These conditions necessitate an excess of supply fluid.

It is completely feasible to use almost any type fluid as a source supply for a fluoric device. Some examples of tested fluids are air, gases, water, oil, and process fluids. At present, air is used more widely than any of the others.

There are primarily three distinct ways of obtaining a power source:

(1) Use of environmental fluids (ram air, water, etc.)

(2) Packaged supplies

(3) Evaporation of liquids, sublimation of solids, and gas liberated from chemical reactions.

Ram supply appears to be a logical choice for timer circuits for missiles and projectiles, and for objects which have a relative motion with respect to their environment. In military projectile applications, the utilization of ram air has certain advantages and disadvantages, namely:

(1) Advantages:

(a) Inherent safety because the system cannot be activated until the projectile is airborne.

(b) No internal power supplies needed; therefore, a savings in weight, volume, and cost.

(c) Unlimited supply of source fluid.

(2) Disadvantages:

(a) Contaminants in ram air (dirt, water, ice) can make the system inoperative.

(b) Filtering to eliminate contaminants causes an increase of weight, volume, and cost.

Packaged supplies, on the other hand, offer several desirable features, and are being used in missile timers, primarily because the timer can now be a complete package, independent of environment and motion with environment. One serious drawback is its limited

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supply. If we consider bottled supply fluids, we can cite the following disadvantages:

- (1) Additional weight, volume, and cost
- (2) Limited fluid supply
- (3) Pressure variation
- (4) Supply leakage intolerable.

A summary of the advantages and disadvantages of environmental and bottled gas types of power supply is shown in Table 24-1.

Power supplies in the third category — evaporation of liquids, etc. — are primarily potential ways of generating a fluid but at present have not been employed in any military timer application.

24-1.1 RAM AIR POWER

The fluid streaming past a missile, projectile, or vehicle which moves through the atmosphere or water provides a direct source of power without transduction for flueric systems. The movement must be fast enough so that there is sufficient ram pressure to

operate a flueric system. The stagnation pressure is obtained from Fig. 24-1 from altitude, air speed, and air temperature data as follows:

(1) Read the stagnation pressure in standard atmospheres from the graph for a certain air speed and air temperature (use the standard temperature from the table above 35,000 ft).

(2) Multiply the stagnation pressure in standard atmospheres by the standard atmospheric pressure in pounds per square inch corresponding to the proper altitude from the table.

Effective velocities can be quite low for specifically designed systems. US Army Harry Diamond Laboratories in cooperation with Army Aviation Laboratories has designed a flueric flow separation indicator which is a stall sensor for a wing. The device indicates flow separation down to 35 kt, with effective pressures at the instrument as low as 2 in. of water.

Ram air power supplies have many advantages for fluerics:

TABLE 24-1

COMPARISON OF FLUID POWER SUPPLIES

<u>Environmental Supply</u>		<u>Bottled Gas Supply</u>	
<u>Advantages</u>	<u>Disadvantages</u>	<u>Advantages</u>	<u>Disadvantages</u>
Less weight, size, and cost	Contaminants from environment can clog system	Pure source fluid	Additional weight, volume, and cost
Inherent fail safe	Pump required for stationary systems	Operate in any environment	Limited fluid supply
Unlimited supply	Filters required	Tailored for precision circuits	Supply leakage intolerable
Any fluid, liquid or gas			Pressure regulation required
			Limited to gases

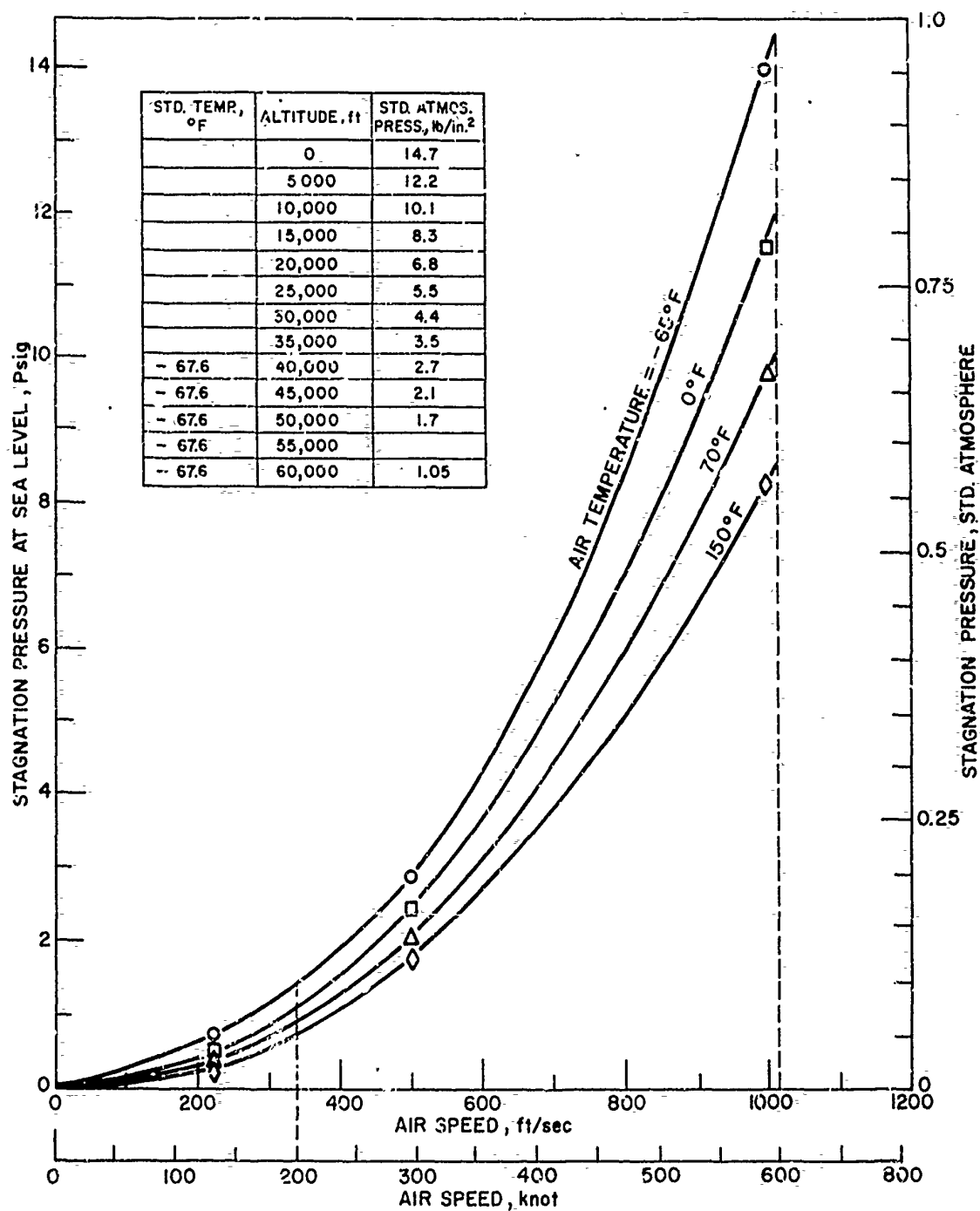


Figure 24-1. Relation of Altitude and Air Speed to Pressure

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(1) Safety. There is no power until the projectile achieves a predetermined velocity. It is completely inert during storage.

(2) Reliability. For example, the power supply unit can be sealed until it is fired in a projectile. When the projectile is fired, the seal is automatically opened. Before ram air is used, rain drops and particles can be removed by a centrifugal separator.

(3) Less weight and space. No fuel supply or high-pressure tanks are needed.

(4) Less pressure regulation. At high velocities, the flow can be choked to limit pressure recovery.

(5) Long term storage. Completely inert in storage.

Electrical power also can be supplied by a fluoric generator which is driven by ram air. The generator has no rotating parts. However, it does have a diaphragm which flexes at a very low stress level. Ram air also can be used to drive a pump².

24-1.2 PACKAGED PNEUMATIC POWER SUPPLIES

Packaged supplies are usually metallic containers with auxiliary equipment—such as relief valves, filters, and regulators—from which a gas emerges to operate downstream fluoric elements. The gas within the package may be generated from the combustion of solid or liquid propellants, or a bottle may have been charged with an inert gas such as air, nitrogen, or argon at a high pressure.

The types using the combustion of propellants usually are classified as steady-state supplies. With these, ideally, one wishes to supply a quantity of gas at a fixed pressure (no change with time) and temperature. By virtue of a chemical reaction, the gas temperatures of steady-state supplies are high.

This fact necessitates flame resistant containers, and heat and corrosion resistant downstream hardware.

Containers that are charged initially with an inert gas under pressure are classified as transient supplies. With these a fall-off of pressure with time occurs. However, with transient supplies the designer can almost guarantee a particle-free fluid at ambient temperature, and filtering may be unnecessary.

24-1.3 STEADY-STATE SUPPLIES

24-1.3.1 General

The steady-state supplies (gas generators) are devices producing gas in a controlled manner³. The supply may be considered as either a constant-rate or constant-pressure source.

The prime advantage of this type of gas generator lies in its ability to deliver a maximum of power for a given weight and volume. The gas in most cases is generated by the reaction of a pyrotechnic mixture. Efficiency is maximized when the gases can be used at high temperatures. This advantage in the gas generator may be a disadvantage so far as the fluoric timer is concerned because it makes it more expensive.

In some applications lower temperature gas is available because the fluoric circuits can be operated by waste gas from other systems such as a servo control system.

Of prime importance in the design of gas generators is provision for furnishing the gas at the time, rate, and pressure required for operation of the fluoric system. This provision is met in most cases by control of the shape, size, and weight of the propellant grain used to supply the gas.

24-1.3.2 Solid-propellant Gas Generators

Solid-propellant gas generators occupy little volume, are light in weight, can be controlled easily for quick initiation or termination of the generating action, and can supply gas at steady-state conditions. The properties of the propellant to be considered are:

- (1) Burning rate of the propellant
- (2) Equilibrium combustion pressure
- (3) Temperature dependency of burning rate and equilibrium combustion pressures
- (4) Density
- (5) Characteristic flame temperature.

The most commonly used types of propellants are double-base or composite. Nitrocellulose and nitroglycerin are components of the double-base propellants. The composite types contain an oxidizer and a reducing agent or fuel. Ammonium nitrate in a butyl or acetate binder is an example of a composite propellant.

Both double-base and composite propellants are presently used as gas generators, but are not considered ideal materials. Composite type propellants provide the lowest burning rates and are cooler burning. As disadvantages, composite propellants require pressure regulation, burning rates are dependent on temperature, ignition is difficult at low pressure, and gases may contain solid material.

Nitrocellulose and nitroglycerin have higher burning rates, and also higher burning temperatures. Unlike the composite materials, the burning rates of double-base propellants are less dependent upon grain temperature.

Fig. 24-2⁴ shows a gas generator in its simplest form. It consists of a section of

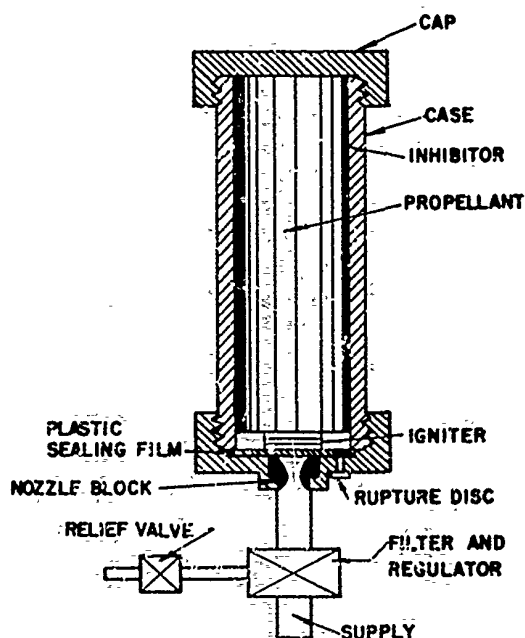


Figure 24-2. Basic Gas Generator

cylindrical casing, capped at both ends, and contains a single grain of propellant which completely fills the case. Gas is allowed to emerge through a nozzle in one end after the grain is initiated by an igniter. Various auxiliary equipment such as a filter, regulator, and relief valve are needed to operate the unit successfully.

With restricted, end-burning grains the supply time is a direct function of grain length and burning rate. The amount of gas generated is directly proportional to burning rate, burning surface area, and density of the propellant. The mass flow rate of the unit is a function of the exit orifice, chamber pressure, and characteristic flame temperature. In addition, the chamber pressure is a function of the ratio of burning area to exit area. In designing a gas generator, the interdependence of these variables should be considered to provide a satisfactory unit.

The volume for steady-state supplies can be expressed in terms of the mass flow rate, propellant density, and operating time as

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$$V = \frac{w_t t}{\rho_p}, \text{ in.}^3 \quad (24-1)$$

where

V = supply container volume, in.³

w_t = propellant gas flow rate, lb/sec

t = burning time, sec

ρ_p = propellant density, lb/in.³

The container volume in cubic feet is plotted in Fig. 24-3⁴, using a ρ_p of 0.053 lb/in.³, against required flow $w_t t$ in pounds. From this figure it is seen that the steady-state supplies occupy smaller volumes than do the transient or bottled gas supplies when the flow rate is equal.

24-1.3.3 Chemical Gas Generators

Gases may be produced from chemical reactions or chemical decomposition of liquid oxidizers and reductants. The gaseous products may be complex mixtures of CO, H₂O, N₂, CO₂, and many other gases. Some examples of combination fuels are nitromethane, nitric acid-aniline, and hydrazine hydrate-hydrogen peroxide. Nitromethane and other monopropellants can be decomposed into hot gases by increasing the temperature and pressure of the reaction. Nitric acid-aniline and hydrazine hydrate-hydrogen peroxide are self-igniting (hypergolic). Other generators depend upon chemical decomposition of compounds through the use of catalysts, such as sodium permanganate, calcium permanganate, and potassium chromate to produce hot gases.

Gas generation by chemical decomposition presents several problems. Fuels and oxidizers usually are highly reactive and extreme care must be taken in storage, transfer, and

reaction initiation. The chemical compounds have rather short shelf lives and therefore will not conform to the usual military requirements.

24-1.4 TRANSIENT SUPPLIES (PRESSURIZED BOTTLES)

Bottled supplies are the most reliable and simplest of packaged power supplies. Some of the factors affecting the selection of a gas for these supplies are:

- (1) Safety in handling
- (2) Toxicity
- (3) Critical temperatures and pressures
- (4) Purity
- (5) Corrosive properties
- (6) Noncondensable content
- (7) Dew point
- (8) Availability of the gas.

The most common gases selected are air, argon, and nitrogen. Because of leakage problems, compressed gas bottles should be charged shortly before use. Leakage rates of bottles produced to commercial tolerances may be too high for long-term storage. For a given minimum mass flow it is known that compressed gas systems require greater volume and weight for the tanks, as compared with other packaged systems. Both mass flow rates and storage-tank pressures decrease with time after initial use. Therefore, the bottle must carry a greater supply than is necessary to provide the minimum mass flow.

With transient supplies, the volume required to supply gas for a given time, pressure ratio, and flow rate is given as⁵:

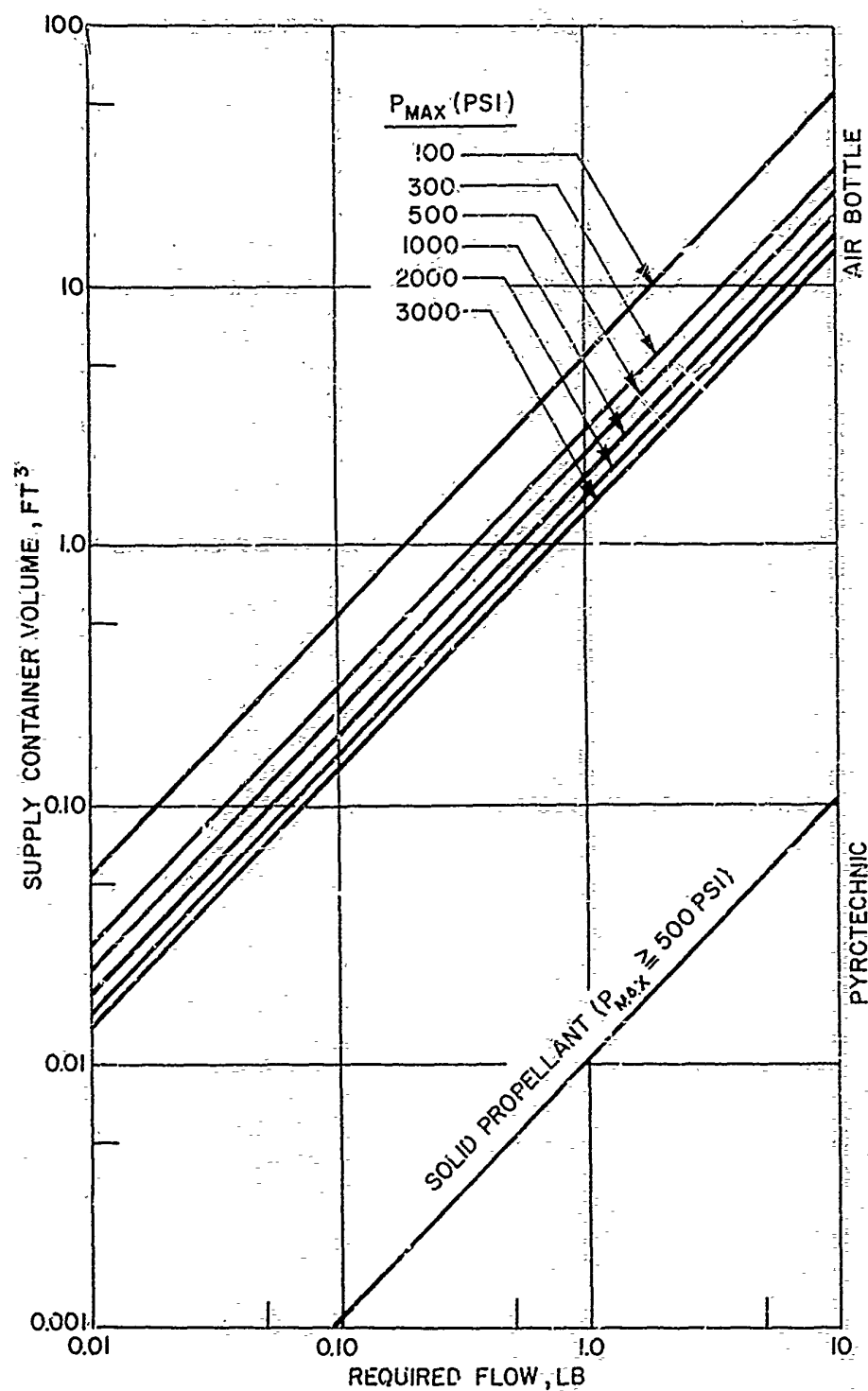


Figure 24-3. Container Volume vs Required Flow for Air Bottle and Gas Generator¹⁶

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$$V = \frac{12 RT_o w_t t}{P_t \ln \left(\frac{P_{max}}{P_t} \right)}, \text{ in.}^3 \quad (24-2)$$

where

V = supply container volume, in.³

R = universal gas constant, ft-lb/lb-°R

T_o = gas temperature, °R

t = time required to supply the gas, sec

w_t = required flow rate, lb/sec

P_t = minimum pressure to supply a flow of w_t , psi

P_{max} = initial tank pressure, psi

Maximum flow will occur when the velocity at the throat is Mach 1. This will take place when the pressure ratio is equal to or less than critical.

If air at 70°F is the fluid considered and P_t is taken as 30 psi (to guarantee supersonic flow since vent is to the atmosphere), the container volumes for various P_{max} versus required flow $w_t t$ is plotted in Fig. 24-3.

Usually the minimum mass flow rate w_t is specified along with the time duration t to supply this flow. Since space is at a premium, the smallest practical volume should be considered. This will necessitate using tanks charged to high pressures, and usually supersonic rather than subsonic flow will occur in the supply nozzle.

24-1.5 STORAGE CONTAINER DESIGN

In the interest of safety, foremost in a designer's mind should be the ability of the container to withstand the maximum pressure without rupture and the incorporation of a

relief valve in case the pressure inadvertently is exceeded. Safety factors between 1.5 and 4 usually are incorporated, and a minimum wall thickness of 0.1 in. is specified. Steady-state supply containers should be fabricated from a good grade of stainless steel that is flame resistant, but transient containers have been made successfully from mild carbon steel. Typical design shapes for containers are shown in Fig. 24-4¹. This container is somewhat idealized to aid analysis, and is composed of a cylindrical section with two end caps of hemispherical shape. The ratio l/d (length-to-diameter) is a useful quantity and is denoted by S . When S equals 1 the container reduces to a sphere. The container may be analyzed in terms of a uniform maximum principal stress (tension in hoop or hemisphere) or on the basis of a uniform wall thickness. If the uniform stress is used, theory shows that the cylindrical section thickness always should be twice as great as the spherical section thickness. Junction stresses are neglected, assuming smooth transition from one thickness to the other.

The container external volume, thickness, and weight as a function of S for each design type can be expressed as shown on Table 24-2⁴. If a wall thickness less than 0.1 in. is calculated, the designer should use a thickness of 0.1 in.

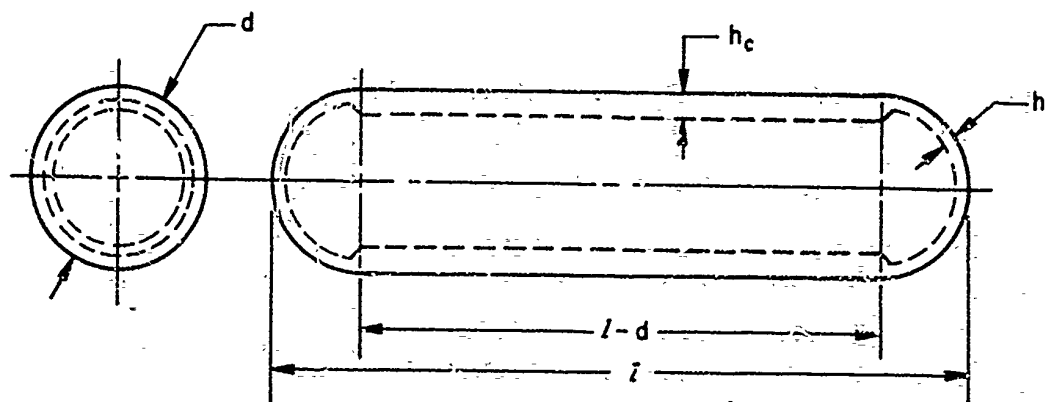
For the uniform stress condition, by combining and rearranging the volume and weight equations, a weight to volume ratio as a function of S can be expressed as

$$\frac{W_c}{V} = k \left(\frac{6S - 3}{3S - 1} \right) \quad (24-3)$$

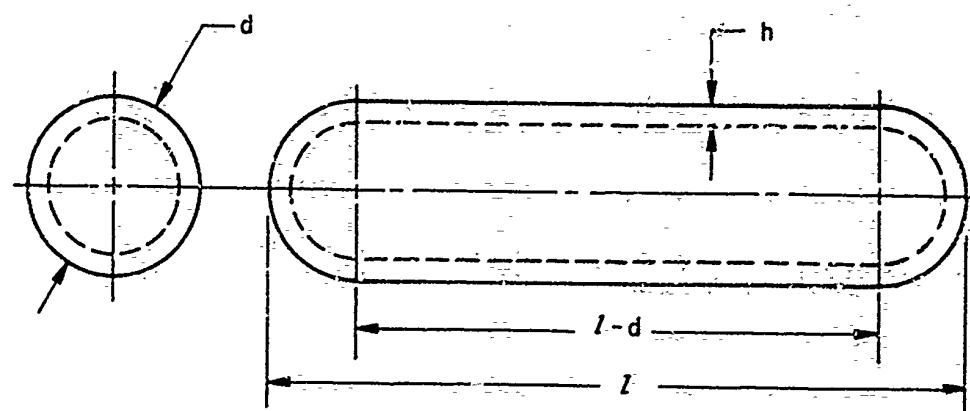
where

$$k = \frac{P_{max} \rho_c}{\sigma}$$

and other terms are defined in Table 24-2.



(A) UNIFORM STRESS DESIGN



(B) UNIFORM THICKNESS DESIGN

Figure 24-4. Two Examples of Idealized Container Designs^{1 6}

Eq. 24-3 shows that the best shape is a sphere for which $S = 1$ (since S can never be less than 1), and $W_c/V = 1.5k$. This gives the minimum weight to volume ratio. As S is increased from 1 to ∞ , W_c/V increases from $1.5k$ to a maximum of $2.0k$.

For the uniform thickness design

$$\frac{W_c}{V} = k \left(\frac{6S}{3S-1} \right) \quad (24-4)$$

It is seen that this expression approaches $2k$ as S approaches infinity, but remains greater than $2k$ for practical values of S . Since the container thickness h_c was used in the development of the uniform stress design, Eq. 24-3 is not valid for $S = 1$. At $S = 1$, W_c/V should equal $1.5k$ as was true for the uniform stress design. Eqs. 24-3 and 24-4 are plotted in Fig. 24-5⁴. The dotted curve for the uniform thickness design should be used for S between about 1.5 and 1. For values of S

TABLE 24-2
EQUATIONS FOR CONTAINER DESIGN

Uniform Stress ($h_c = 2h_s$)	Uniform Thickness ($h_c = h_s$)
$V = \frac{\pi d^3}{12} (3S - 1)$	$V = \frac{\pi d^3}{12} (3S - 1)$
$h_c = \frac{P_{max} d}{2\sigma}$	$h = \frac{P_{max} d}{2\sigma}$
$h_s = \frac{P_{max} d}{4\sigma}$	
$W_c = \frac{P_{max} \rho_c \pi d^3}{4\sigma} (2S - 1)$	$W_c = \frac{P_{max} \rho_c \pi d^3 S}{2\sigma}$

where

V = external container volume, in.³

d = external container diameter, in.

S = l/d ratio

l = total length, in.

W_c = container weight, lb

P_{max} = maximum expected internal pressure, psi

ρ_c = material density, lb/in.³

σ = maximum allowable stress in tension, psi (includes any design safety factors)

h_c = cylindrical section thickness, in.

h_s = hemispherical section thickness, in.

h = thickness of uniform design, in.

Note: If h_c or h_s is < .01 in., use $h = 0.1$ for minimum design.

greater than 5, the difference in the weight to volume ratio for the two curves does not exceed 10 percent of their mean value.

24-2 OSCILLATORS

The base oscillator in a fluoric timer is of utmost importance since it determines the precision of the overall timer. Ideally the oscillator frequency must not be sensitive to the variations in temperature or supply pressure and it must function in the following environments:

- (1) -65° to $+160^{\circ}\text{F}$ (225 deg F spread)
- (2) Spin up to 30,000 rpm

Oscillators have been constructed using four different sources of oscillations: (1) feedback, (2) torsion bar, (3) sonic, and

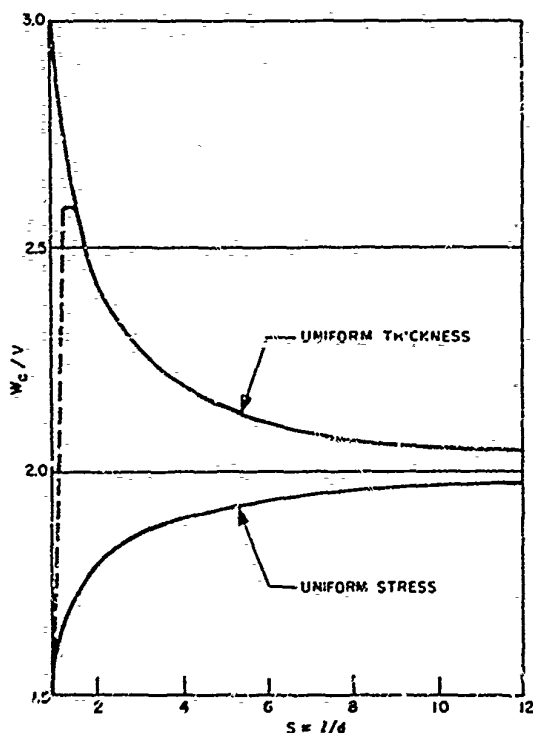


Figure 24-5. Weight-to-Volume Ratio vs Length-to-Diameter Ratio for Cylindrical Tanks With Hemispherical End Caps¹⁶

(4) half-adders. Each of these oscillators is discussed. See also Ref. 6.

24-2.1 FEEDBACK OR RELAXATION OSCILLATORS

The feedback type of oscillator is advantageous since its frequency can be controlled by adjustments and modifications of the feedback path configuration in addition to design changes in the oscillator amplifier; i.e., setback, splitter location, nozzle width, etc.

Ref. 7 gives detailed results on three relaxation oscillators (designed to be insensitive to both temperature and supply pressure variations) using R-C-R feedback loops. One specially tailored oscillator achieved a ± 1 percent frequency change over a pressure range of 6 to 30 psig. and a frequency variation of less than 1 percent over a temperature range from 77° to 175°F at 10 psig. A similar oscillator at a pressure input of 10 psig did not exceed $\pm 1\%$ for a temperature range from -55° to 175°F .

A typical relaxation oscillator is shown in Fig. 24-6. This model used a fixed

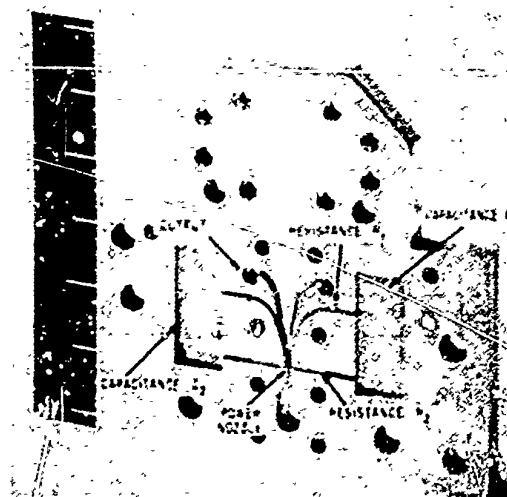


Figure 24-6. Relaxation Oscillator¹⁶

capacitance volume of 0.366 in.³ with the restriction at R_2 being variable. Best results were obtained when R_2 was 0.01 in. wide with the addition of two small adjusting screws placed in the R_1 line to control flow into the feedback loop. Adjusting screws were set to obtain best temperature and pressure insensitivity. Experiments illustrated that a fair degree of temperature and pressure insensitivity could be obtained by a critical choice of the R_1 - C - R_2 parameters. Of the two, temperature insensitivity was considered most important, and it should be noted that above models worked over a temperature range of approximately 100 deg F. Ref. 7 gives a mathematical treatise on the conditions for pressure and temperature insensitivity.

24-2.2 TORSION BAR OSCILLATOR

Ref. 8 discusses an oscillator that deviates somewhat from a true fluoric device in that a mechanical vibrating element is employed. A torsion bar oscillator is shown in schematic form in Fig. 24-7⁷. It consists of a circular torsion bar fixed at one end with the other end free to rotate. A flat plate attached to the free end of the bar not only provides the inertia for the system but is the element driven by the air flow across it, thus furnishing the pressure pulses necessary to drive a counter. The air flow between this plate and the upper stationary plate produces

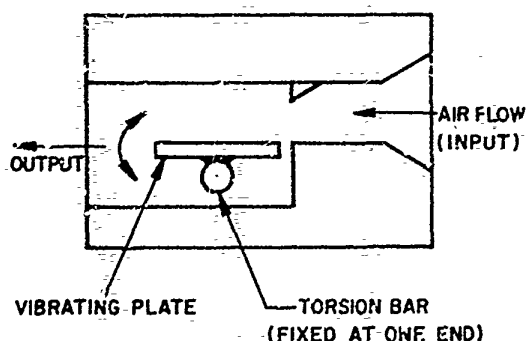


Figure 24-7. Torsion Bar Oscillator¹⁶

a lift on the plate due to Bernoulli's effect. This rotates the leading edge of the plate toward the upper plate until the lift is spoiled due to the loss of air flow. The restoring torque of the torsion bar then rotates the pressure plate back toward and beyond its neutral position. The cycle then is repeated at the natural frequency of the spring-mass system. The oscillations of the vibrating plate produce significant pressure fluctuations in the throat of the device. These are picked up via tubing and fed to a fluid counter circuit.

Since the physical dimensions of the oscillator elements are affected only slightly by temperature variations, the natural frequency of the vibrating plate remains relatively constant over a wide temperature range. It is for this reason that good frequency control can be expected using such a hybrid system.

24-2.3 SONIC OSCILLATORS

The sonic oscillator, as seen in Fig. 24-8⁹, also depends upon feedback for its operation. However, in this case there is an unrestricted tube replacing the circuit elements. Pressure waves propagate through this tube at sonic velocity, controlling the frequency of oscillation. Since the sonic velocity varies directly as the square root of the absolute temperature, the frequency of the sonic oscillator will vary in the same manner—increasing at higher temperatures and decreasing at lower temperatures.

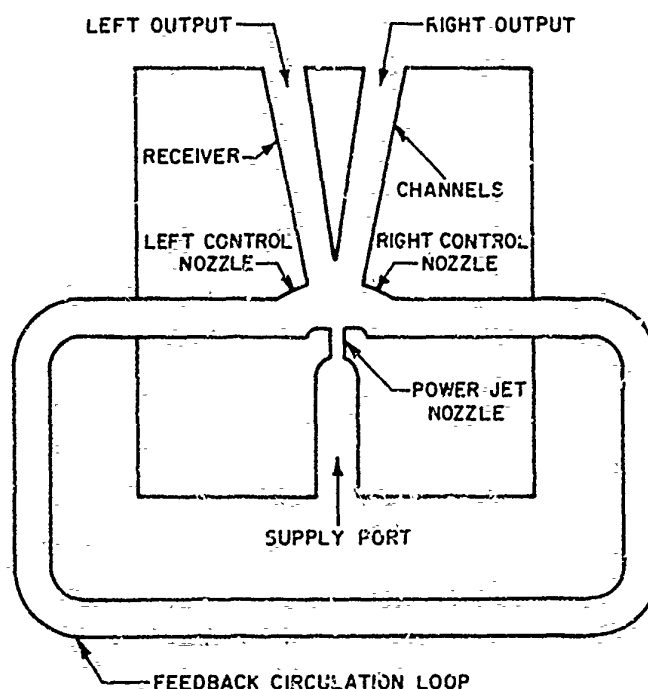
The frequency of oscillation f of the sonic oscillator is⁹

$$f = \frac{a}{2\ell} + \frac{1}{T_s}, \text{ Hz} \quad (24-5)$$

where

a = sonic velocity in the operating fluid, ft/sec

ℓ = length of the feedback passage, ft

Figure 24-8. Sonic Oscillator¹⁶

T_s = amplifier switching time, sec

One method for providing temperature compensation for the sonic oscillator is the use of a temperature sensitive element (an orifice, slide etc.) to vary the impedance of the sonic delay line as the temperature varies. A sonic oscillator with such mechanical temperature compensation is shown in Fig. 24-9. The position of the slide (the degree of obstruction) in the line is controlled by a temperature sensitive element. Changing the position of the slide in the line varies the impedance of the feedback line which changes the switching time T_s (see Eq. 24-5).

An advantage of the scheme is that relatively large slide movement is required for small frequency changes. Thus large dimensional tolerances are permitted, and the scheme lends itself to miniaturization, and permits close matching of the oscillator

temperature characteristics. The disadvantage is that the temperature can be compensated only over a narrow range.

24-2.4 HALF-ADDER OSCILLATORS

Another type of oscillator uses the half-adder element (exclusive or, and) with the addition of a feedback loop. The element is a two input device shown in Fig. 24-10(A)⁸. If either inputs C_1 or C_2 are present (but not both), the output of the device is at port O_2 . However, if both C_1 and C_2 are present simultaneously, the output is at O_1 . If now, see Fig. 24-20(B), power supply fluid is applied to input C_1 and feedback from output port O_2 is applied to input C_2 , the device will oscillate. The cyclic action continues for as long as fluid is supplied to C_1 .

The frequency-temperature characteristics

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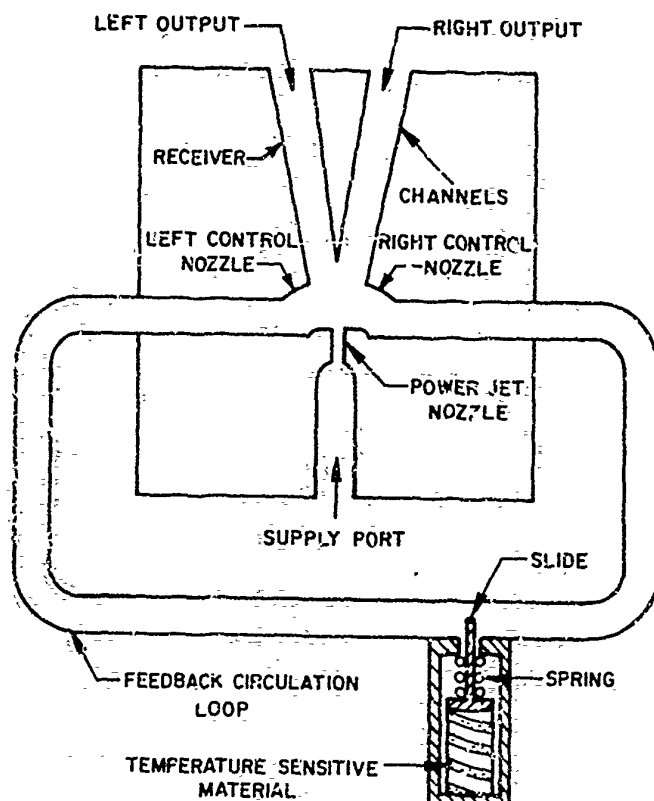


Figure 24-9. Temperature Compensating Scheme for Sonic Oscillator¹⁶

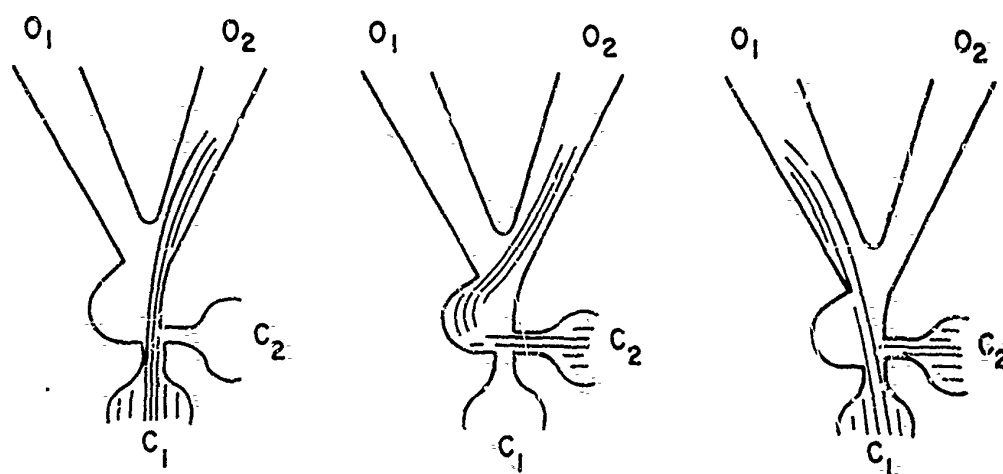
of the half-adder oscillator has frequency reversals as the temperature is increased. Frequency variations occur with changes in supply pressure except at the specific temperature where frequency crossover occurs. At this temperature complete insensitivity to pressure is observed. This suggests that element geometry plays an important role in establishing the frequency-temperature characteristics of fluoric oscillators. In fact, theoretical studies indicate that for any given oscillator there exists a region of temperature insensitivity. By proper selection of feedback-line dimensions and operating pressure, this region can be shifted to one at which operation is desired. Unfortunately, both theory and experiment indicate that temperature insensitivity is obtained at the expense of

pressure sensitivity. Ideally for military applications, a self-compensated (i.e., no moving parts) fluoric oscillator would be most desirable. This is especially true for those systems required to operate in an extreme environment such as high spin.

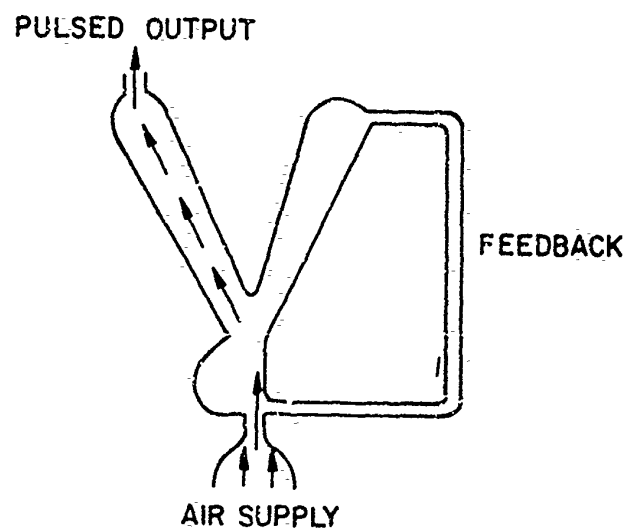
24-2.5 HIGH-PRESSURE, LOW-FLOW OSCILLATORS

A high-pressure, low-flow (HPLF) oscillator is shown in Fig. 24-11¹⁰. All HPLF devices are based on colinear source and receiver nozzles. A jet leaving the source nozzle impinges on the receiver port, causing increase in receiver pressure. When the receiver pressure rises above a critical value, there is a sudden change in flow direction as flow is

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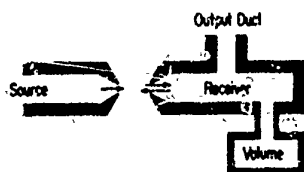
(A) HALF-ADDER (EXCLUSIVE OR, AND) ELEMENT



(B) HALF-ADDER OSCILLATOR ELEMENT

Figure 24-10. Development of an Oscillator from the Half-adder Element

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Figure 24-11. HPLF Oscillator¹⁶

expelled from the receiver. A wave front is produced by the two opposing flows. As the pressure drops in the receiver, the wave front moves toward the receiver nozzle. There is an audible snap and a change of flow direction when the wave front contacts the receiver nozzle. The receiver pressure begins to rise, and the process repeats.

24-2.6 DESIGN OF OSCILLATORS FROM THEORETICAL CONSIDERATIONS

Since the time base oscillator of the fluoric timer must function accurately in a given environment, a great deal of attention should be given to its design. In the design, we should be cognizant of the following requirements for a time base oscillator:

- (1) Temperature and pressure insensitivity within its working limitations
- (2) Small size
- (3) Functional with respect to its downstream components (insensitive to loading)
- (4) Rigid construction.

As discussed earlier, fluoric oscillators can be fabricated with a reasonable degree of temperature and pressure insensitivity, at least over the military operating range. At present, however, an oscillator cannot be designed directly from theoretical considerations, and must undergo a series of experiments to achieve the final model because of the

complexity of the equations to be solved. For example, Ref. 11 discusses a fluid oscillator employing distributed parameters as the feedback loop (ducts of constant cross section). The theoretical frequency vs temperature relationship for a physical model using a feedback line 12 in. long, 0.027 in. in diameter, and operating at 50 psig is as shown in Fig. 24-12¹¹. This curve was generated using the equations presented in Ref. 11. The theoretical T_{max} (point around which maximum temperature insensitivity is to be expected) is approximately -196°F for this model. However, when an experimental model was fabricated and tested at 50 psig the curve of Fig. 24-13¹¹ was obtained with T_{max} in the range 125° to 225°F . The dissimilarity was explained as follows:

"The temperature region at which the frequency peaks is shifted appreciably from the theoretical curve; however, error is to be expected because of the many variables not taken into account; these include the variations of Mach number with position, the capacitance of the amplifier itself, the switching time of the amplifier, and the nonlinear effects due to the waves being of large amplitude."

Apparently, complete use of all variables in their proper manner was too complex to be investigated at the time. The large disagreement between theoretical and experimental results indicate that the variables not considered are extremely important, and apparently additional study is required before it is possible to precisely design oscillators solely from theoretical considerations.

24-2 FLIP-FLOPS

24-3.1 GENERAL

The simplest fluid device is the binary flip-flop shown in Fig. 24-14. This is a digital device that has two stable modes; one with

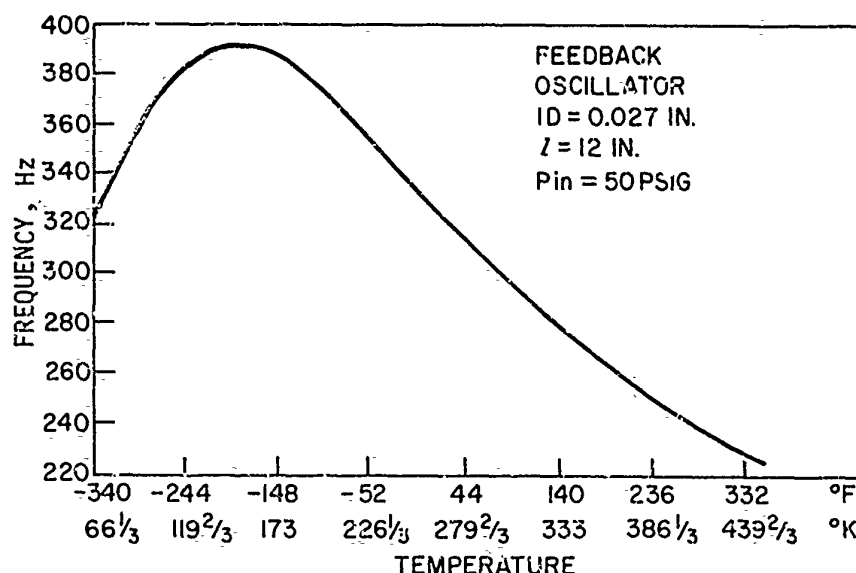


Figure 24-12. Theoretical Performance Curve for Feedback Oscillator Employing Distributed Parameter Ducts

the stream attached to the right wall with output at O_1 and one with the stream attached to the left wall with output at O_2^* . Flipping is accomplished by introducing a control pressure at C_1 or C_2 of sufficient magnitude to satisfy the entrainment characteristics of the stream. The stream then moves to the opposite wall at which time control flow can be removed and action is stable in the new position. Load vents are provided for stability and isolation. Thus, the device can be looked at as having an "on" and "off" position. Elements can be "stacked" or "staged" to produce binary counters similar to electronic logic circuits and many of the control elements that are possible with present-day electronic circuits.

*Stream attachment is a fundamental principle sometimes referred to as the COANDA effect. It is well covered in many references^{12,13} and will not be discussed here.

A more refined configuration of a flip-flop element is shown in Fig. 24-15. This figure portrays the fluid flow in a schematic manner while the unit is in operation. Also in this figure, relative sizes of the physical features of the device are indicated as multiples of the nozzle width. Use of the nozzle width as a scale factor permits scaling up or down of the element at will. At the present time nozzle widths of 0.010 in. are in common use. Smaller sizes to 0.004 in. or smaller may be used but the problems with particle entrapment are increased.

Fig. 24-15(A) shows the flow pattern with the outputs unobstructed, and Fig. 24-15(B) shows the flow pattern with one output partially blocked. The outputs are almost completely decoupled; blocking one output has only a small effect on the opposite output and keeps full pressure on the load. Because there is ample gain, devices designed in this manner easily may be staged and such a unit has been found capable of switching as many as 16 others with a pressure recovery as high

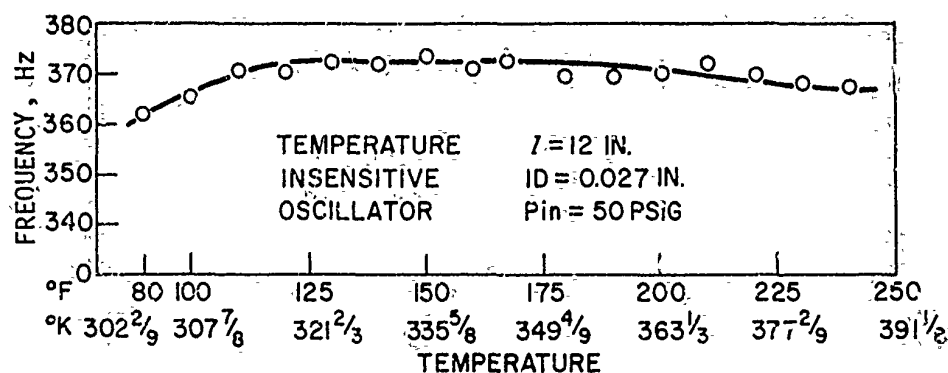


Figure 24-13. Performance of Experimental Oscillator

as 50 percent. Similar designs provide for even higher rates of pressure recovery, but with somewhat lower gain.

To maximize the effect of the side walls, it is desirable to have the nozzle of the power jet deep with relation to its width giving a high aspect ratio. It is also desirable to bring the sidewalls in close to the stream to maximize their effect, thus giving a high gain. If a wide range of operation is desired, it can be achieved at the sacrifice of some gain by moving the sidewalls back from the stream. The minimum aspect ratio for operation of a wall interaction amplifier is about 1. The optimum aspect ratio for minimum flow is about 1.75.

24.3.2 TYPICAL PERFORMANCE CHARACTERISTICS OF A BISTABLE FLIP-FLOP

The element of Fig. 24-16 is a schematic representation of a 5-port flip-flop, for which performance characteristics may be developed. In the following discussion assume that these conditions can be met:

- (1) Supply pressure at port 1 (P_1) can be varied over some given finite range.
- (2) Control pressures P_2 and P_5 can be

opened to the atmosphere or by orifice restrictions, and auxiliary supply can also be controlled independently.

- (3) Port pressures P_1 to P_5 can be measured.

- (4) Flows Q_1 to Q_5 can be measured.

- (5) Elements can be loaded by orifice restrictions in their output legs.

The real element will have some finite output restriction diameter (of orifice) we will call d_o and the nozzle will in general be of rectangular cross section lb . We can define an equivalent circular area of diameter d_n such that

$$\frac{\pi}{4} (d_n)^2 = lb; d_n = \left(\frac{4lb}{\pi} \right)^{1/2} \quad (24-6)$$

is a constant for a given nozzle size.

We can now define a loading parameter d_o/d_n where an increase in this ratio is synonymous with less restriction in the output legs. We will consider stable output to port 4, with control ports open fully. If we take measurements of flow and pressure at ports 1 to 5 for various size output orifices, we will generate typical curves as shown in

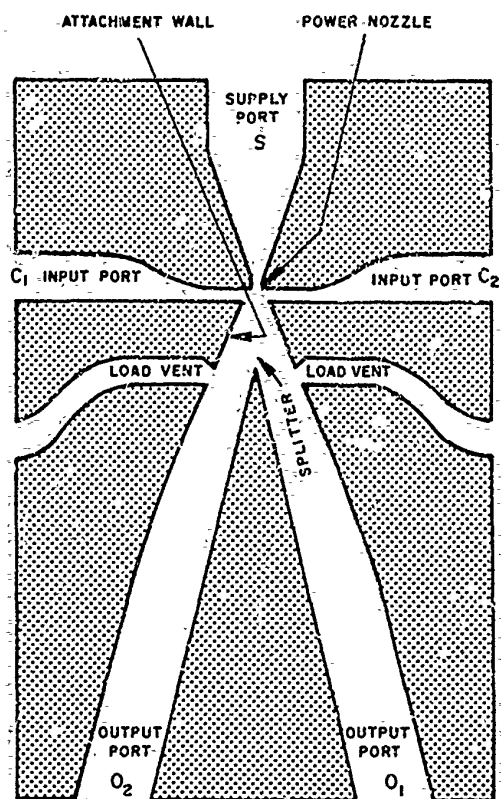
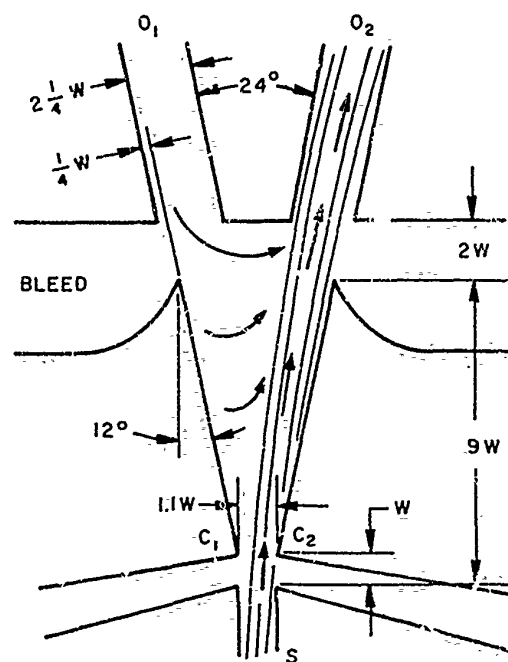
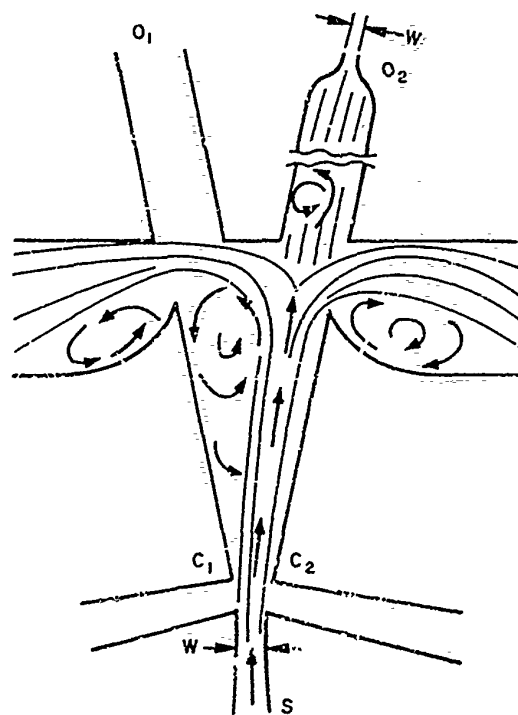


Figure 24-14. Bistable Flip-flop

Fig. 24-17¹⁴. These curves will be identical over a rather large input supply pressure range, thus it is valid to use normalized flow and pressure values. There will be two distinct orifice sizes (or output loads) d_{o1} and d_{o2} between which useful operation and gain will be realized. Diameter d_{o1} is found at the intersection of the P_5/P_1 and P_4/P_1 curves while d_{o2} is at the intersection of the P_5/P_1 and P_3/P_1 curves. Note that since P_3 is open to atmosphere or zero gage pressure, the P_3/P_1 ratio is zero. Due to symmetry, if we were to flip the flow (by increasing (P_5) so that output is at P_3 , and repeat the above, identical curves would be obtained, and all we need do is reverse the roles of P_3 and P_4 in Fig. 24-17 and substitute P_2 for P_5 . For this device the following may be defined when output is at P_4 :



(A) UNOBSTRUCTED OUTPUT



(B) PARTIALLY RESTRICTED OUTPUT

Figure 24-15. Wall Interaction Fluid Flip-flop

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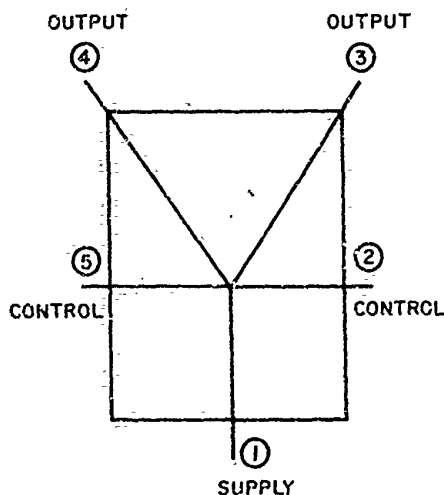


Figure 24-16. Five Port Flip-flop Schematic

$$\text{Pressure Recovery } R_p = P_4/P_1$$

$$\text{Flow Recovery } R_Q = Q_4/Q_1$$

$$\text{Efficiency } N = (R_p)(R_Q)$$

$$\text{Pressure gain } G_P = \frac{P_4 - P_3}{P_5 \text{ (to switch)} - P_5}$$

$$\text{Flow gain } G_Q = \frac{Q_4 - Q_3}{Q_5 \text{ (to switch)} - Q_5}$$

$$\text{Power gain } G_T = (G_P)(G_Q)$$

The gain as a function of loading will decrease in loading typically as shown in Fig. 24-18¹⁴. The best operating point is where N is a maximum.

Ref. 14 gives detailed test results on a large bistable element constructed at US Army Harry Diamond Laboratories. In this example the nozzle dimensions were 0.12 X 0.36 in. (thus d_n was 0.234 in.). The element was tested over a pressure range of 5 to 45 in. of

water (0.18 to 0.62 psi) and the output channels measured 0.36 X 0.36 in. without orifices. The ratio (d_o/d_n) , was observed at a point where $d_o = 0.3725$ in. and (d_o/d_n) was found at a d_o of 0.338 (average values). These values were obtained with zero control port flow (open to atmosphere). At a d_o of 0.348 in. best results were obtained where:

$$\text{Pressure gain} = 3.0$$

$$\text{Pressure recovery} = 31.5\%$$

$$\text{Efficiency} = 43\%$$

The preceding example indicates the manner in which the performance characteristics of a typical bistable flip-flop may be determined. This type of performance measurement and analysis also presents another technique that may be useful in the development of flip-flop elements. Using the empirical design approach, the designer can build a large scale model, test it to obtain the response curves as described in this paragraph, then using a linear design reduction factor scale it down to the desired miniature size.

24.3.3 ADDITIONAL REFINEMENTS

The addition of a concave cusp in the splitter region can result in a high-pressure, high recovery, high stability, flip-flop as shown in Fig. 24-19¹⁰. A vortex is established in the cusp region. When output is at O_1 the vortex rotates clockwise, helping to maintain flow to O_1 . When output is at O_2 a vortex is established on the opposite direction, thus supporting output to O_2 . The vortex increases the stability of attachment of the supply jet, giving high-pressure recovery. However, flow gain and switching time are degraded. With this amplifier, if one output (i.e., O_1) is completely blocked off, flow will commence at the opposite output. If the block is removed, output is again obtained at O_1 since the direction of the vortex (which has not been altered) returns the supply flow to its original path.

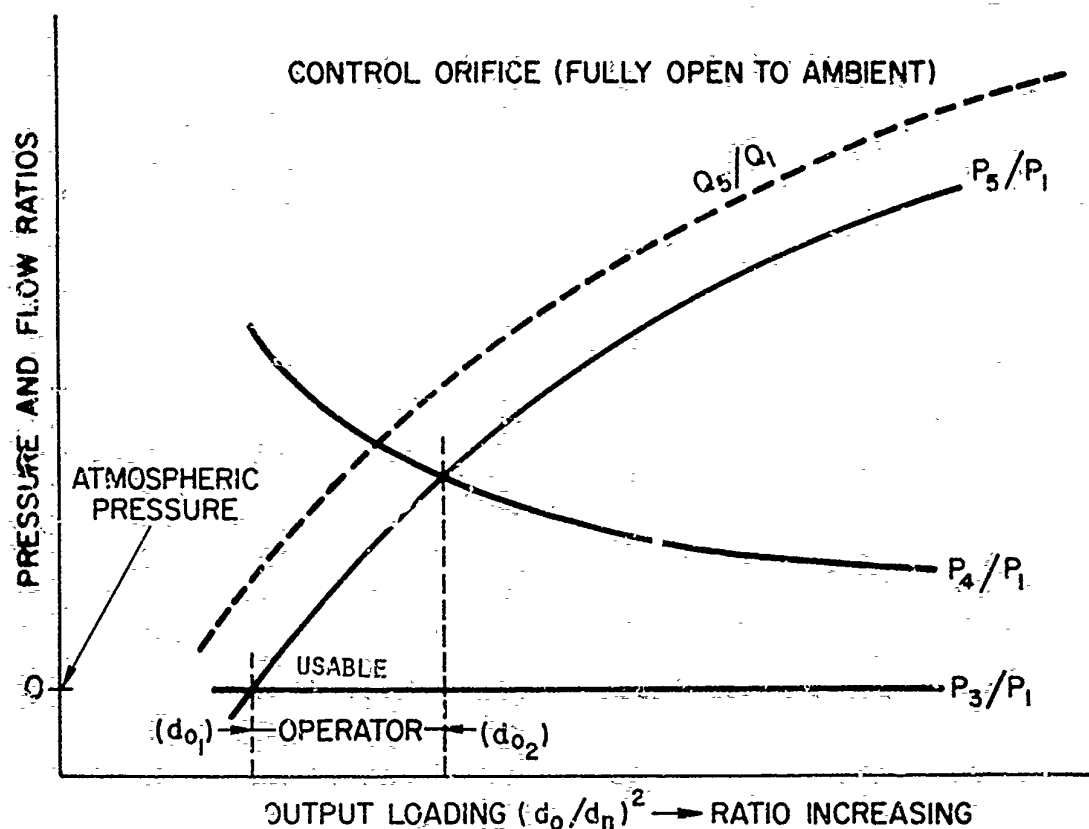


Figure 24-17. Typical Operating Curves

Switching in a high speed flip-flop capable of 0.1 msec or less is illustrated in Fig. 24-20¹⁰. This component uses a fluid-dynamic phenomenon known as the edgetone effect. Under proper supply conditions, oscillation will occur between the cusp of one output port and the splitter wedge. These oscillations remain in a dynamically stable condition until a small control flow shifts this action to the other side, at which time oscillation occurs between the cusp on the opposite port and the splitter wedge.

24-4 COUNTERS

Par. 24-2 on oscillators discusses various methods in which a stable series of pulses can

be produced with some degree of temperature and pressure insensitivity. This paragraph covers the function of counters which, coupled with a stable oscillator and an output sensing device, forms the heart of the fluoric timer system. If stable oscillators could be constructed such that their period between pulses was the time interval desired, there would be no need for a counter system. However, since timer application may be concerned with time durations in the interval of 0.001 to 200 sec, only the very shortest period timer could be obtained by coupling directly to an oscillator. If we consider that a useful pressure disturbance is obtained in a positive as well as negative pressure wave, then to obtain a period of 0.1 sec we would

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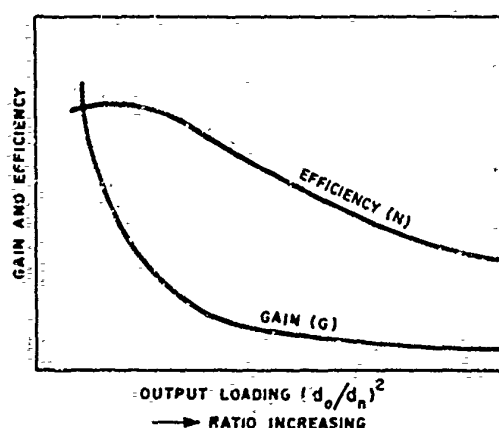


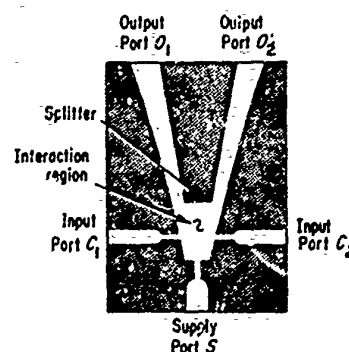
Figure 24-18. Typical Performance Curves

need an oscillator working at 5 Hz; considered a low, unstable, and uncontrollable frequency. Also, since we would like to trigger our timer at time zero, and/or charge time intervals, an intermediate counting system is mandatory.

Therefore, any digitally sequenced and controlled system will employ some form of counter network. The complexity of these counter networks varies, depending upon the needs of the controlled system. Types of counters include binary counters, binary-coded-decimal counters, gray code counters, nonsequential counters, etc. Normally in a timer the counter design will be matched to the application; the result generally will be a unique counting and sequencing network which uses fewer components and performs the prescribed task more adequately than the pure binary form.

24.4.1 BINARY COUNTING

The binary counter is the most widely used counter type in both electronics and fluierics. Table 24-3¹⁶ is a truth table for a three-stage binary counter. The table shows that the condition of each stage in the counter at time "n plus one" is dependent only upon the condition of that stage at time "n" and

Figure 24-19. High-stability, High-pressure-recovery, Wall-attachment Amplifier¹⁰

whether or not the adjacent stage of lesser significance (the stage to the right in the truth table) switches from a "one" time to a "zero" during the transition from time "n" to time "n plus one". This logic can be mechanized in many ways.

A signal passing through a single bistable flip-flop will have its frequency halved, and time period doubled.

Example: An oscillator working at 1000 Hz coupled to a 3-stage binary counter A, B, C, provides the following time periods:

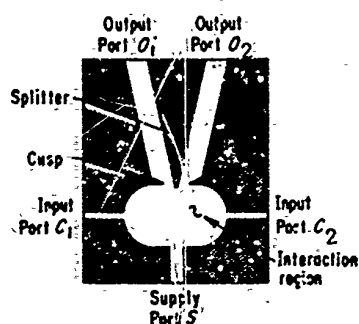
$$\text{From A} \quad 2 \times \left(\frac{1}{1000} \right) = 2 \text{ msec}$$

$$\text{From B} \quad 4 \times \left(\frac{1}{1000} \right) = 4 \text{ msec}$$

$$\text{From C} \quad 8 \times \left(\frac{1}{1000} \right) = 8 \text{ msec}$$

$$\text{From } n \text{ stages} \quad 2^n \times \left(\frac{1}{1000} \right) = 2^n \text{ msec}$$

A more general example of binary counting is shown in Fig. 24-21. This figure shows how N stages can be interconnected and the available outputs of each stage. Note that all

Figure 24-20. Edgetone Amplifier¹⁰

stages are coupled to a common supply S delivering manifold pressure and the O₁ output feeds the input of the next stage. All O₂ outputs are available (or simply vent) at slightly less than S due to pressure loss within the element.

The fluid counter operates due to the same pressure differential that holds the stream of a bistable amplifier against the wall¹⁵. The entrainment of the stream lowers the pressure between the stream and the wall. This low pressure induces a small flow from the higher ambient pressure on the O₁ side of the stream, around the loop to the low pressure adjacent to the wall on the O₂ side (see Fig. 24-22). This flow is too small to switch the stream. When a fluid pulse to be counted is inserted at the bottom of the loop, it joins the small induced flow and provides sufficient flow to satisfy the entrainment and switches the stream to the O₁ output. When the pulse flow ceases, the low pressure is now adjacent to the wall on the O₁ side of the counter. A small flow is now induced from the higher ambient pressure on the O₂ side of the counter to the lower pressure adjacent to the wall on the O₁ side of the counter. The next pulse inserted at the bottom of the loop joins the induced flow and switches the stream back to the O₂ side of the counter where the pattern repeats.

TABLE 24-3
TRUTH TABLE FOR A THREE STAGE
BINARY COUNTER

Count	State Time n			State Time $n + 1$		
	C	B	A	C	B	A
0	0	0	0	0	0	1
1	0	0	1	0	1	0
2	0	1	0	0	1	1
3	0	1	1	0	0	0
4	1	0	0	1	0	1
5	1	0	1	1	1	0
6	1	1	0	1	1	1
7	1	1	1	0	0	0

One also should realize that in the final timer design, a means of resetting the counter to zero, as well as a means of varying the time set over a period of perhaps 0.1 to 200 sec in 0.1-sec intervals may be desired. Some of these problems are discussed in par. 24-10.

24-4.2 BINARY COUNTERS IN SLOW-RESPONDING SYSTEMS

In a very slow responding system, the state of the counter may be simply decoded and used directly to generate the appropriate function. For example, if it is desired to close a contactor at count five of the counter state shown in tabular form in Table 24-3, a set of AND/NAND or OR/NOR gates (see pars. 24-5.1 and 24-5.2) may be used to decode the existence of five (101 ABC) in the counter. The decoding circuits then may be used to close the contactor. With the gating so arranged, each time the counter reaches five, the contactor would close.

24-4.3 BINARY COUNTERS IN FAST-RESPONDING SYSTEMS

When the counter is being used to control systems or circuits which respond almost as

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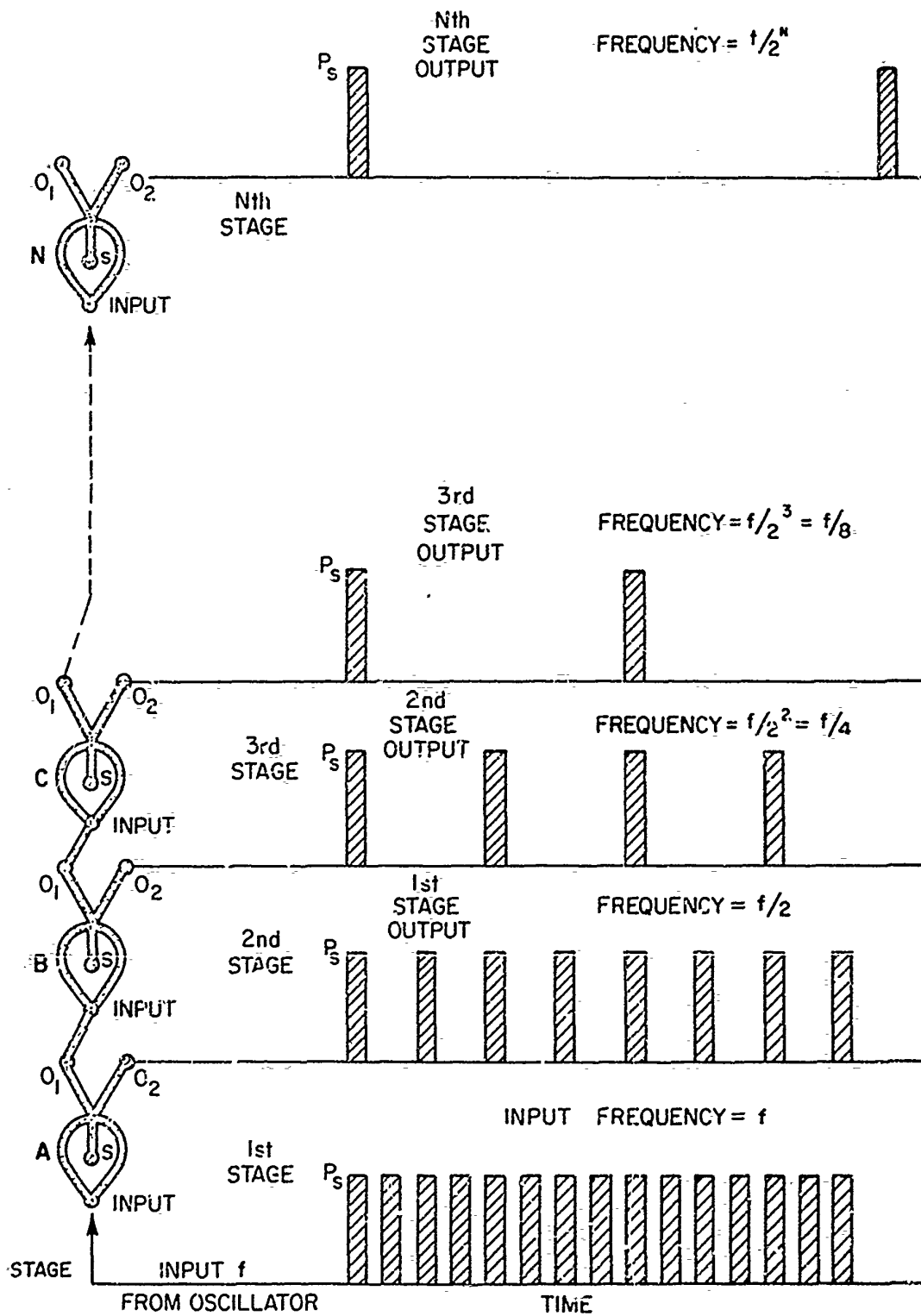


Figure 24-21. Stages of Binary Counter

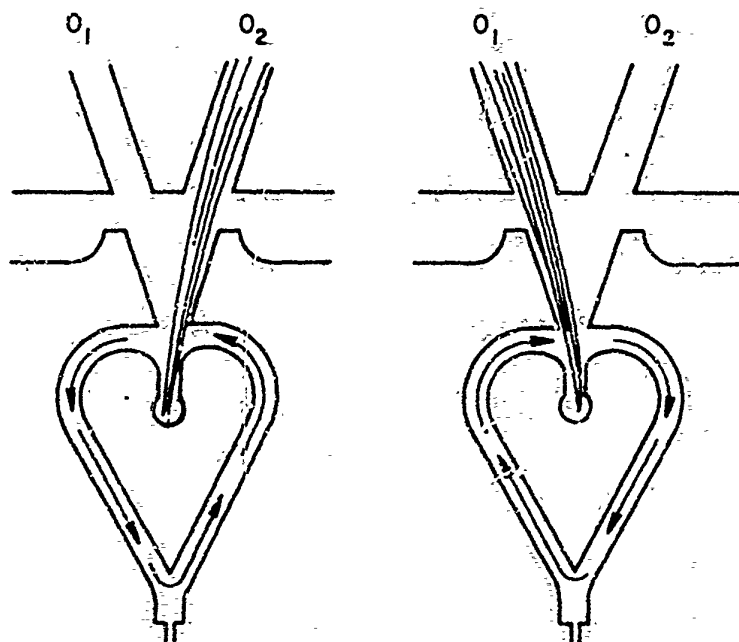


Figure 24-22. Details of Fluid Flow in a Counter

fast, or even faster, than the counter itself, other characteristics of the counter operation must be taken into account—such as the transient condition generated by the “flutter” of the counter. During these periods of transiency it is highly probable that false states might be decoded, thus imposing a new condition on the design of the counter. These problems can be eliminated by dividing the period between state changes into at least two phases: a counter change phase and a system control phase. Complexities added to the circuit by these new conditions include the necessity for developing two-phase clocking systems, usually accomplished by higher speed counters or the use of one-shots operating directly off the oscillator.

24-4.4 DECIMAL COUNTERS

A simple counter, one step more complex than the binary counter, is the counter that returns to zero prior to reaching the

maximum possible count. An example of this type of counter is the binary-coded decimal counter. It is designed to count to nine, then return to zero, and is used widely to provide output control for decimal display systems. Table 24-4¹⁶ is a truth table for the binary-coded-decimal BCD counter. Note that

TABLE 24-4
BCD TRUTH TABLE

Count	State Time n				State State $n+1$			
	D	C	B	A	D	C	B	A
0	0	0	0	0	0	0	0	1
1	0	0	0	1	0	0	1	0
2	0	0	1	0	0	0	1	1
3	0	0	1	1	0	1	0	0
4	0	1	0	0	0	1	0	1
5	0	1	0	1	0	1	1	0
6	0	1	1	0	0	1	1	1
7	0	1	1	1	1	0	0	0
8	1	0	0	0	1	0	0	1
9	1	0	0	1	0	0	0	0

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this is not the only possible design for a base ten counter. Tables 24-5¹⁶ and 24-6¹⁶ are other possible combinations of sequential counters which can serve the same purpose as the counter of Table 24-4 with the simple exception that different decoding matrices would be used to decode the appropriate states.

24-4.5 NONSEQUENTIAL COUNTERS

One interesting variety of nonsequential counters is the Gray code counter discussed in Ref. 16, which changes only a single bit when changing to an "n plus one" state. Because each change of state experiences only the change of a single bit, all of the transient change problems mentioned earlier as inherent in other counter designs are eliminated. Therefore, the number of phases can be reduced to one. Table 24-7¹⁶ shows a Gray code sequence for a counter designed to generate the control sequence for the flow diagram of Fig. 24-23¹⁶.

The simplicity of such a Gray code design is demonstrated by the set-reset equations for the counter. They are:

$$\text{Set A: (clock pulse)} \cdot (\bar{C} \cdot \bar{B} \cdot \text{Start} + CB)$$

$$\text{Reset A: (clock pulse)} \cdot (\text{delay complete}) \cdot (\bar{C} \cdot B + C \cdot \bar{B})$$

$$\text{Set B: (CA)} \cdot (\text{clock pulse})$$

$$\text{Reset B: (AC)} \cdot (\text{clock pulse}) + \text{Malfunction}$$

$$\text{Set C: (B} \cdot \bar{A}) \cdot (\text{clock pulse})$$

$$\text{Reset C: (Failure)} \cdot (\text{Monitoring}) + \text{off}$$

$$\text{Set Monitor: (C} \cdot \bar{B})$$

$$\text{Reset Monitor: } \bar{C}$$

For the convention of bars over the letters, see par. 24-5.1.

24-5 LOGIC CIRCUITS

Logic circuits are made up of a combination of elements such as flip-flops connected so that a meaningful output can be obtained. It was already stated (par. 24-3.1) that the flip-flop element can have two stable modes, either "on" or "off". These can be so chosen

TABLE 24-5

EXCESS THREE BCD TRUTH TABLE

Count	State Time n				State Time n + 1			
	D	C	B	A	D	C	B	A
0	0	0	1	1	0	1	0	0
1	0	1	0	0	0	1	0	1
2	0	1	0	1	0	1	1	0
3	0	1	1	0	0	1	1	1
4	0	1	1	1	1	0	0	0
5	1	0	0	0	1	0	0	1
6	1	0	0	1	1	0	1	0
7	1	0	1	0	1	0	1	1
8	1	0	1	1	1	1	0	0
9	1	1	0	0	0	0	1	1

TABLE 24-6

EXCESS FOUR BCD TRUTH TABLE

Count	State Time n				State Time n + 1			
	D	C	B	A	D	C	B	A
0	0	1	0	0	0	1	0	1
1	0	1	0	1	0	1	1	0
2	0	1	1	0	0	1	1	1
3	0	1	1	1	1	0	0	0
4	1	0	0	0	1	0	0	1
5	1	0	0	1	1	0	1	0
6	1	0	1	0	1	0	1	1
7	1	0	1	1	1	1	0	0
8	1	1	0	0	1	1	0	1
9	1	1	0	1	0	1	0	0

TABLE 24-7

TRUTH TABLE FOR GRAY CODE COUNTER
FOR MECHANIZING FLOW DIAGRAM FOR
THE TYPICAL SEQUENTIAL CONTROL
SYSTEM OF FIG. 24-23

Control Condition	Counter State Time n			Counter State Time $n + 1$			
	C	B	A	C	B	A	
State A	0	0	0	0	0	1	un- conditional when start button depressed
State B	0	0	1	0	1	1	un- conditional upon next clock pulse energize starter
State C	0	1	1	0	1	0	un- conditional upon next clock pulse after de- lay test for malfunc- tion
State D	0	1	0	0	0	0	un- conditional upon mal- function
State E	1	1	0	1	1	1	un- conditional upon next clock pulse ignition on
State F	1	1	1	1	0	1	un- conditional upon next clock pulse Fuel on
State G	1	0	1	1	0	0	un- conditional upon next clock pulse after delay- Initiate system moni- toring
State H	1	0	0	0	0	0	conditional upon fail- ure or off signal

to represent a "true" or "false" statement dependent on whether "positive" or "negative" logic is chosen, respectively. By virtue of the bistable action, an element will remain in one state until acted upon by some external control pressure, thus the concept of "memory" is inherent in each bistable element. The paragraphs that follow discuss

the action of some logic elements that are refinements of the simple flip-flop element from which logic circuits are constructed. A familiarity with Boolean algebra will aid in understanding the notations used. Appendix A lists the more important identities associated with Boolean algebra.

24-5.1 OR/NOR ELEMENTS

The OR/NOR element is a bistable flip-flop

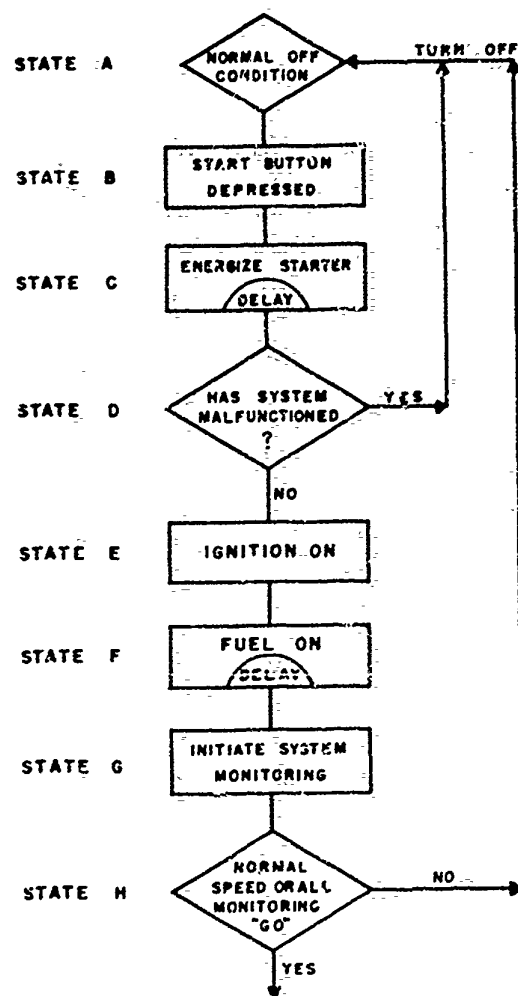


Figure 24-23. Flow Diagram for a Typical Sequential Control System¹⁶

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that will solve the following Boolean equation, $A + B = C$ which is to be interpreted as C equals A or B; i.e., C is true if either A or B is true. Obviously, if both A and B are not true, then C is false. This is portrayed most easily by means of "truth table" shown in Table 24-8¹⁶. Here, the 1's represent true values and the 0's false values. This relationship is called an "OR" relationship. When it is used in a system using fleuric components, it is called an "OR" element, circuit, or gate. Then $\bar{C}$, being the complement of C, functions as the NOR element.

The OR element can contain more than two inputs, thus we could write $A + B + C = D$ for a 3 input device.

Applied to a two-input fluidic device we may interpret the preceding logic as follows (see Fig. 24-24(A))¹⁶:

(1) Used as an OR element. An output is obtained at C if a control input is present at either A or B, or both. No output is obtained at C if no control flow exists at A and B.

(2) Used as a NOR element. No output is obtained at C if control flow exists at A or B. Flow out of C only is present if A and B are simultaneously absent (off). OR/NOR ele-

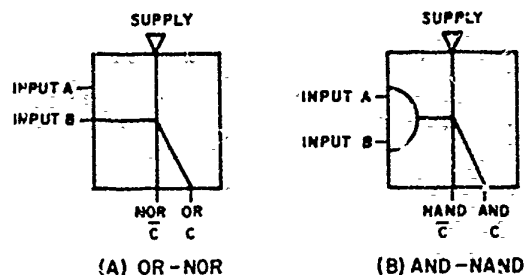


Figure 24-24. Symbolic Logic Representation¹⁶

ments may be staged to form working logic circuits, but usually are combined with other logic elements such as AND/NAND and will be discussed. (NAND means "not and".)

24-5.2 AND/NAND ELEMENTS

The normal AND/NAND element is likewise a bistable flip-flop with two output ports, a supply port and two input ports. It will solve the following relationship:

$$A \cdot B = C$$

which means that C equals A and B. That is, C is true only when both A and B are true. The truth table for the AND/NAND element is shown on Table 24-9¹⁶. $\bar{C}$ is the NAND function of the element.

TABLE 24-8

TRUTH TABLE FOR A SINGLE OR/NOR ELEMENT

<u>A</u>	<u>B</u>	<u>C</u>	<u>$\bar{C}$</u>
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

OR NOR*

*NOR = not OR

TABLE 24-9

TRUTH TABLE FOR A SINGLE AND/NAND ELEMENT

<u>A</u>	<u>B</u>	<u>C</u>	<u>$\bar{C}$</u>
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

AND NAND*

*NAND = not AND

Applied to a fluoric device we may interpret Table 24-9 as follows (see Fig. 24-24(B)):

(1) Used as an AND element. An output is obtained at C only if control flow exists at A and B simultaneously. No output is obtained at C if only A or B are present or neither is present.

(2) Used as a NAND element. Output is obtained at C at all times, except when inputs at A and B are present simultaneously.

24-5.3 COMBINED LOGIC ELEMENTS

As an example of a digital system using logic elements, consider the following (assume that we have two sets of three variables with their complements):

Call them (A, B, C) and (D, E, F). The first set is varying in some manner. We would like to arrange the second set manually to a fixed combination. When the first set is exactly equal to the second set; i.e., when A and D are the same, B and E are the same and C and F are the same, there will be an output. With this given information, the following truth table is made:

A	D	out-put	B	E	out-put	C	F	out-put
0	0	1	0	0	1	0	0	1
0	1	0	0	1	0	0	1	0
1	0	0	1	0	0	1	0	0
1	1	1	1	1	1	1	1	1

The overall output is true only when each combination is true. We may write (including the implements)

$$\text{Overall output} = (AD + \overline{AD}) \cdot (BE + \overline{BE}) \cdot (CF + \overline{CF})$$

See Fig. 24-25¹⁶ for a circuit arrangement to provide this operation and Fig. 24-26¹⁶ for the fluoric equivalent of this circuit.

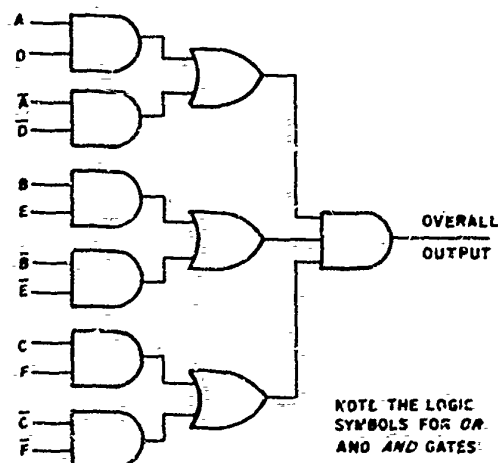


Figure 24-25. Circuit Arrangement for Comparison Circuit¹⁶

The problem could have been solved by using only OR/NOR gates and making use of DeMorgan's laws. This solution is presented in detail in Ref. 16 (pp. 7-8).

In using combined logic elements, there is an easily defined relationship between the OR/NOR elements and the AND/NAND elements. In order to construct a system using logic components, logic levels must be defined. It makes little difference which level is chosen as the "true" level. In digital control systems, however, a name is assigned for either choice. If the higher level is chosen as the true level, the entire system is called "positive logic" system. If the higher level is chosen as the false level, then the system is called a "negative logic" system. By higher and lower levels we mean the following: for a fluoric system we may choose the two outputs of a bistable switching element as A and $\overline{A}$. These outputs are, alternately, flowing at some rate, or not flowing. If we decide to use the positive logic scheme, we may call the flow condition the greater level and define it as the true condition; then, the nonflowing level is the false condition. It may be just as

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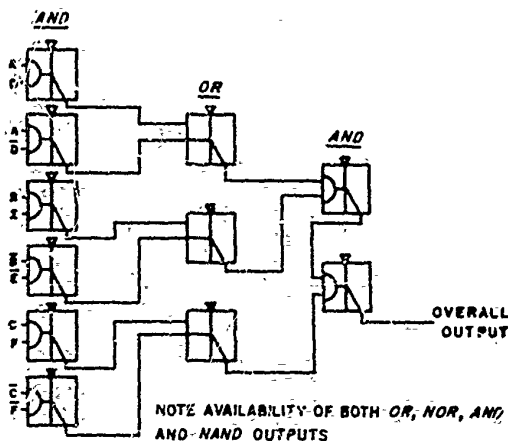


Figure 24-26. Fluoric Equivalent of Fig. 24-25¹⁶

convenient, if not more so in some situations, to reverse these roles. Note from the truth tables for the AND and OR circuits that if the logic levels are reversed, the OR circuit becomes the AND circuit and the AND circuit becomes the OR circuit.

24-6 RESISTANCE ELEMENTS

There are several different types of resistance elements which may be used in the fluoric system:

(1) Tube resistors are small lengths of appropriate cross section having a length several times their width. These elements are sometimes called capillaries.

(2) Orifice resistors are essentially thin disks having a restricting hole placed normal to the fluid flow in the passage.

(3) Porous metal resistors are slugs of a sintered porous metal placed in the passage to resist fluid flow.

(4) Variable resistors may be a series of tapped resistors of the types described or they may be continuously variable as, for example, a needle valve. A special category of variable resistor is the settable resistor which may have its restriction varied by tools, but once having been set becomes a fixed resistor.

24-6:1 TUBE RESISTORS

Tube resistors can be fabricated from glass, metal, ceramics, epoxy, and like materials. Typical resistors have the characteristics indicated by the solid lines in Fig. 24-27¹⁷, obtained with air at a fixed discharge pressure. A straightline with a slope of 45 deg on this log-log plot indicates linearity. Tube resistors have the advantage of linearity, but the disadvantage of being easily clogged.

Tube resistors can be flattened to alter their cross-sectional area (and shape) and their resistance. (Fig. 24-33 shows a crimping tool

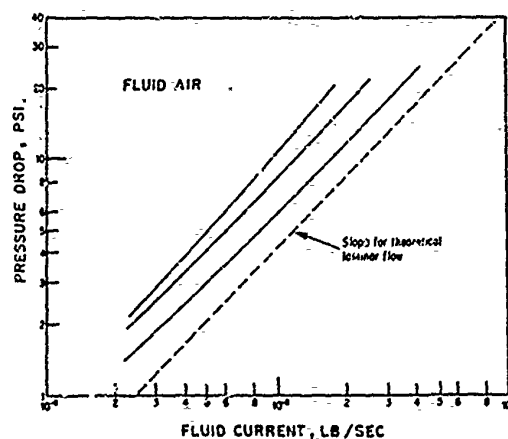


Figure 24-27. Pressure vs Flow for Etched-glass Resistors¹⁷

to be used for this purpose.) Typical linearity curves for flattened tube resistors are shown in Fig. 24-28¹⁷ for air discharge at fixed output pressure. Flattening tends to decrease the slope below 45 deg. Tubes or capillaries are chosen for the resistors because of their more nearly linear characteristics in comparison to an orifice resistor. The resistance of a capillary tube of rectangular cross-section can be approximated by the expression

$$R = \frac{\Delta P}{Q} = \frac{8\pi\mu\ell}{(bh)^2} + \frac{1\rho Q}{6(bh)^2} \quad (24-7)$$

where

R = resistance of capillary channel, lb-sec/in.⁵

ΔP = pressure differential across capillary, psi

Q = flow rate, in.³/sec

μ = viscosity, lb-sec/m²

ℓ = length of channel, in.

b = width of channel, in.

h = depth of channel, in.

ρ = fluid density, slug/m³

Each parameter in the equation will be affected by temperature changes. Thus, one expects the resistance of the capillary to vary with temperature. Theoretical analysis and experimental results indicate that the resistance of a capillary tube fabricated from high temperature epoxy resin *increases with an increase in temperature.*^{*}

^{*}The viscosity of ideal gases increases directly with the square root of the absolute temperature. For real gases, the viscosity usually changes at a rate somewhat greater than this because of the effects of molecular attraction which are assumed zero for ideal gases.

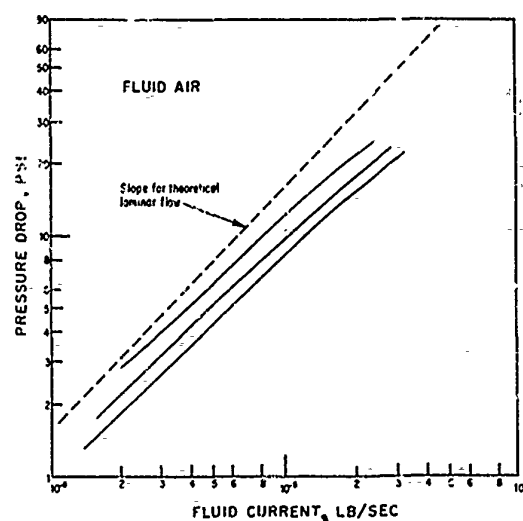


Figure 24-28. Pressure vs Flow for Flattened-tube Resistors¹⁷

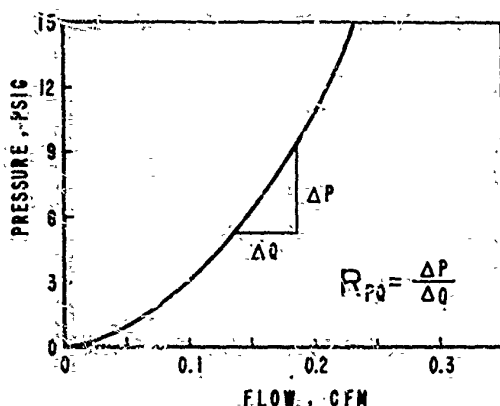
24-6.2 ORIFICE RESISTORS

An orifice resistor is simply a thin disk with a restricting hole placed normal to fluid flow. Usually a coupling or adapter is provided so that different size resistors can be substituted at a given place in the flow line. Drill jig bushings available in a variety of sizes also can be used. These bushings are usually short tubes, available with a collar on one end. Since the bushings are precision drilled, reproducible resistances easily can be obtained. Fluid orifice resistors are available commercially. Dirt and contamination are cleaned more easily from orifice resistors than from tube or porous metal types. Orifice resistors are cheaper to fabricate than tube types but are nonlinear as shown in Fig. 24-29¹⁶ where R_{PQ} is the effective resistance.

24-6.3 POROUS-METAL RESISTORS

Although normally used as filters, sintered porous metal parts can serve as fluid resistors.

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Figure 24-29. Resistance of an Orifice¹⁶

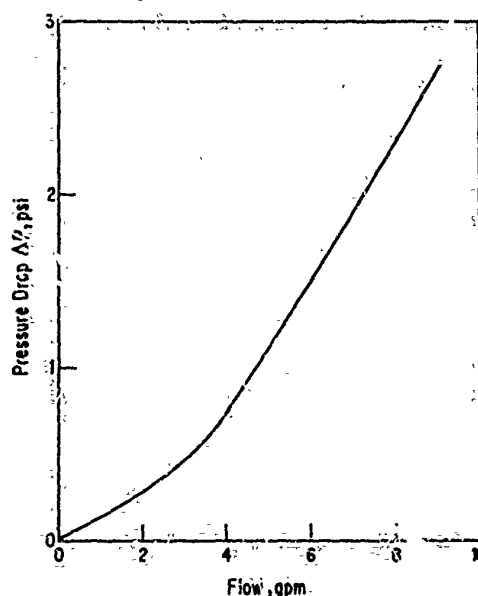
Metals that can be powdered and sintered include monel, bronze, stainless steel, gold, and silver. A wide variety of shapes—such as cones, plates, and cylinders—can be produced where required by the application.

Porous-metal resistors are nonlinear, but the pressure vs flow curves have long straight-line sections. Typical plots for water and hydraulic fluid are shown in Figs. 24-30¹⁷ and 24-31¹⁷.

Porous-metal resistors are not cleaned as easily as orifice or tube resistors. However, they can be cleaned by scrubbing, back-flushing, or chemical cleaning. One excellent method is to backflush while the element is immersed in an ultrasonic bath. Surfaces of porous-metal resistors must be handled with care and protected from dirt and mechanical injury. Porous-metal resistors cannot be plugged by a single dirt particle as can orifice or tube types. Instead, the dirt settles on the porous metal surface and does not change the resistance appreciably. An accumulation of dirt is required to plug a porous-metal resistor.

24-6.4 VARIABLE RESISTORS

All resistors discussed thus far have fixed

Figure 24-30. Flow of Water Through a Porous-metal Resistor¹⁷

resistances. In circuit development, variable resistors also are needed. Tapped resistors easily are fabricated by interconnecting either orifice or tube resistors, and supplying taps at the points of interconnection. Care must be exercised when using such resistors to ensure that unwanted capacitances are not introduced. One disadvantage of tapped resistors is that their resistance is not continuously variable.

The traditional variable fluid resistor is simply a valve. The needle valve is the most widely used type in fluid-circuit development. It offers the convenience of fine adjustment in flow over wide ranges. Needle valves have been constructed with only one degree of taper, producing extremely fine control of flow through the valve (see Figure 24-32¹⁶). If only steady-state conditions are considered, an entire circuit can be developed with needle valves as the only resistors. However, since these valves are nonlinear, it may be necessary to replace many, if not all,

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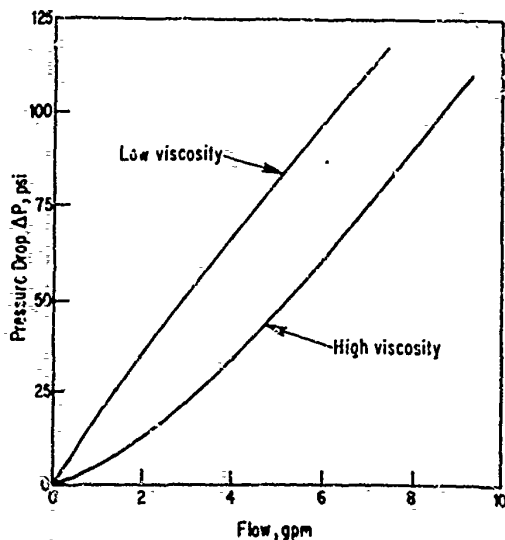


Figure 24-31. Flow of Hydraulic Fluid Through a Porous-metal Resistor¹⁷

of the valves with fixed linear resistors before the small-signal behavior of the circuit can be studied.

A commonly used laboratory technique for this substitution is to adjust the needle valve until the proper values of pressure and flow are obtained. The valve is then removed and its resistance measured. Next, a piece of copper tubing is substituted for the valve in the resistance-measuring circuit and the tubing flattened with a small hand vise until its resistance equals that of the valve. The flattened-tubing fixed resistor is then installed in the circuit in place of the valve. With compressible fluids, it may first be necessary to measure the resistance of the valve and then fabricate the flattened-tube resistor while maintaining the same values of upstream and downstream pressure as in the circuit under development.

A valuable device has been developed for solution of the circuit balancing problem: the



Figure 24-32. Needle Valve With 1-deg Taper Angle¹⁶

settable resistor. A crimpable resistor is installed in the circuit in the nonrestrictive (uncrimped) condition. A terminal-crimping tool (Fig. 24-33¹⁸) is used to reduce the resistor cross-sectional area until the desired downstream flow or pressure readings are attained.

24-7 CAPACITANCES

A fluid capacitance is simply a tank of any geometry into which the fluid may flow and be stored for a time, then discharged. Any tank or container which is safe at the maximum pressure used is suitable for a capacitor. Since the pressures are usually low, the problem can be solved easily. In American Engineering units, capacitance can be defined as volume per unit pressure, and the units are ft^3/lb . As in electrical circuits, fluid capacitance will effect a phase shift such that flow will lead pressure by 90 deg. In a circuit, the fluid capacitor corresponds to the electrical capacitor to ground. It cannot duplicate the action of an electrical in-line capacitor since it

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Figure 24-33. Crimping Tool Placed Over Resistor Tube¹⁶

favors direct current flow. Since pressure is a function of fluid density and temperature for a fixed volume, capacitance C can be expressed more basically as

$$C = \frac{V}{\rho a^2}, \text{ ft}^4\text{-sec}^2/\text{lb} \quad (24-8)$$

V = volume, ft^3

ρ = fluid density, lb/ft^3

a = local speed of sound in fluid stream, ft/sec

Eq. 24-8 is particularly applicable in RC fluid oscillators where it has been substantiated that the oscillator frequency is normally both temperature and pressure dependent. Although it is difficult to determine either analytically or experimentally the variation of capacitance with temperature, there are indications that the effective capacitance *increases with rising temperature*. In any case, it does not appear that effective capacitance decreases with rising temperature. Thus if an oscillator can be designed such that its frequency is approximated by

$$f = \frac{k}{RC} \quad (24-9)$$

where k = proportionality constant

then its frequency of oscillation should decrease as the temperature increases. This is in direct contrast to the usual assumption of increasing frequency proportional to the square root of the absolute temperature.

24-8 TURBULENCE AMPLIFIERS

24-8.1 GENERAL

Turbulence amplifiers make use of the fact that an interacting control jet can vary the degree of turbulence in the main jet, and thus vary output flow or pressure¹⁸. Consider a stream of fluid exiting from an input nozzle as shown in Fig. 24-34(A). At low velocities flow is laminar and, if properly designed, output pressure may be only slightly below input pressure. As the supply pressure is increased, output pressure is increased. Continuing the pressure increase (and stream velocity) a point then is reached where the flow is turbulent ahead of the output receiver (Fig. 24-34(B)) and the output pressure is reduced. Once total turbulent flow has been attained, further input pressure increases output pressure. These stages are shown on Fig. 24-35. A-B represents laminar flow; B-C is transitional region from partial turbulence to complete turbulence; and C-D represents total turbulent flow.

A control flow jet—introduced at right angles and close to the input nozzle, Fig. 24-34(C)—can increase the degree of turbulence and the shape of Fig. 24-35. Since we desire small changes in control jet pressure to effect large changes in output pressure (high gain), initial design parameter should be operational around point B, Fig. 24-35—i.e., natural turbulence should just start near output receiver with zero control pressure. The addition of a small control pressure then will increase greatly turbulence and output pressure, see Fig. 25-36¹⁸.

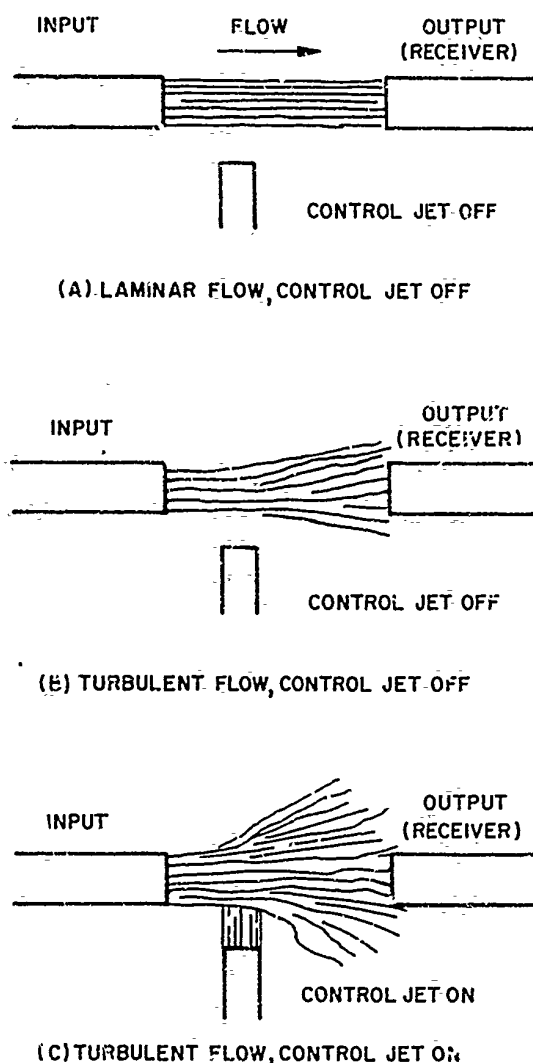


Figure 24-34. Stages of Operation—Turbulence Amplifier

24-8.2 DISTURBING THE MAIN JET

Small disturbances cause the point at which the stream goes turbulent to shift toward the input tube. Disturbances can be introduced into the laminar stream by other fluid streams impinging on the main jet, intrusion of a mechanical agent, or by acoustic waves.

The greater the distance between the input

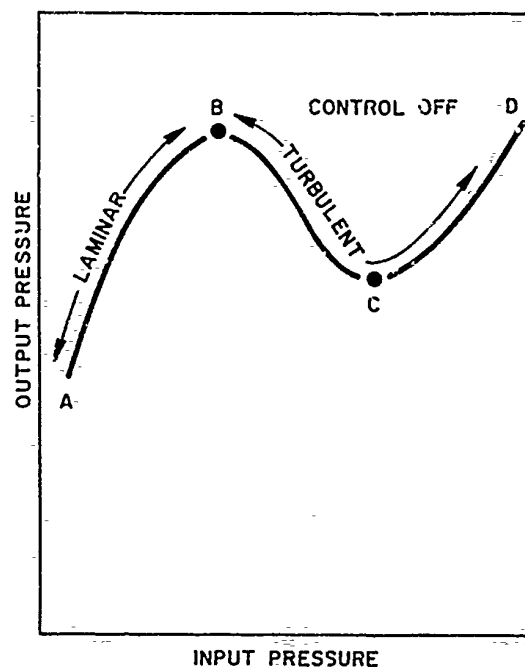


Figure 24-35. Input-Output Pressure Relationship for Turbulence Amplifier With Control Flow Off

tube and output tube, the greater the sensitivity of the device; i.e., the greater the effect of jet disturbances. However, the maximum allowable velocity of the laminar stream decreases with increasing distance between the tubes. On the other hand, the lower the jet velocity, the lower the output pressure. The selection of a supply pressure and a distance between the tubes represents a compromise between sensitivity and useful output.

Theoretically, turbulence amplifiers can be any size, but in practice, there are upper limits. Commercially available devices are used for control rather than power purposes, and they have jet diameters of about 0.030 in. Distance between supply and output tubes ranges from 0.375 to 1.5 in. In a turbulence amplifier of this size, high sensitivity to sonic disturbances begins at about 1 3-in. separation

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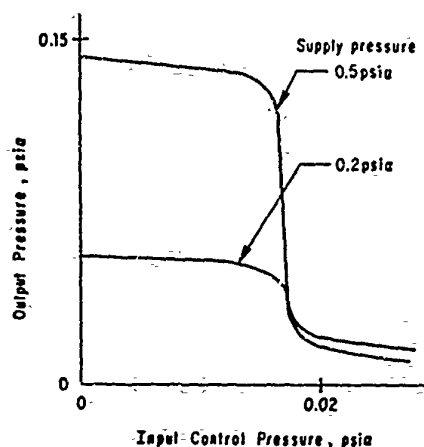


Figure 24-36. Typical Output Pressure vs Control Input Pressure for a Turbulence Amplifier^{1 8}

between supply jet and output tubes. When the device is operated in the acoustic mode, frequency sensitivity varies with the separation. Acoustic sensitivity of these devices is so high that they can be triggered by a mouth whistle at a distance of 300 ft.

The most commonly used turbulence amplifiers are designed to be disturbed by a jet of air projected perpendicularly to the main jet. In practice, several jet inputs can be used. The number of possible inputs is limited only by available space.

An input signal also can be introduced mechanically by moving a small object, such as a wire, into the jet stream preferably near the input jet orifice. This arrangement can be used as a basis of a mechanical-flueric transducer. A small, pressure-actuated diaphragm also can be deflected into the jet stream to produce turbulence. Another manner in which the main supply can be made turbulent is through the electrophoresis effect. A pair of high voltage electrodes positioned across the main supply as shown in Fig. 24-37¹⁰ can develop an "electric wind" that can disturb the main jet.

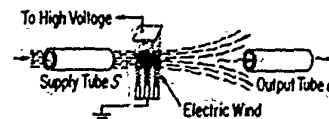


Figure 24-37. Turbulence Created by Electrophoresis Effect¹⁰

24-8.3 INHERENT ACOUSTIC RESPONSE

Acoustic waves are difficult to shield and, in fact, are generated by flueric devices themselves. If acoustic amplification is not wanted, the acoustic sensitivity of the turbulence amplifier should be low so that only flueric amplification is obtained. This can be achieved readily in any given amplifier design because the distances between input and output ports at which sound sensitivity become significant is usually much greater than the distances required when fluid jets are used as the disturbing input. Most turbulence amplifiers used for control purposes are operated in the range where they are not acoustically sensitive. These amplifiers usually are used to sense or respond to a control flow that is directed at approximately right angles to the main laminar input jet, and the distances between input and output elements are held to a minimum.

24-8.4 CASCADING

Since the output of a turbulence amplifier is a pressure, this output can be used to drive the control jet of a second stage. Thus, turbulence amplifiers can be cascaded. Some care is necessary, however, since the output of the amplifier never drops completely to zero over the practical operating range. Thus, if the output of one unit is directly coupled to a second, the second stage must be unresponsive to small signals from the first.

From Fig. 24-35 the required characteristic can be obtained by operating the first stage so

that its output lies somewhat to the left of the peak B. Actually, the amplifier can be designed to operate considerably to the left of B, and a large range of relative unresponsive action can be obtained.

Another approach is to provide a jet stream with sufficient stability that it is undisturbed by the range of the input and can be ignored.

24-8.5 OVERDRIVING

When turbulence amplifiers are used in high-speed circuits, care must be taken to avoid overdriving since the resumption of laminar flow after very strong turbulence is somewhat delayed. When a control signal is turned off, the fluid stream has to become laminar again before full output pressure is regained at the output port. This effect can be observed readily in the output of oscillators. The effect on pulse circuitry is shown in Fig. 24-38¹⁸. Note that the recovery time is much greater than the initial reaction time.

In digital circuitry, this behavior is particularly important where a given device is turned off, and thus has a low output pressure. When a negative signal is applied to the turbulent amplifier in an attempt to turn

it on, it is ineffective if the input signal pulse is too short, because the amplifier does not have time to build up a laminar stream. This effect is shown in Fig. 24-39¹⁸.

24-8.6 PRIMARY USES AND TYPICAL SIZES OF TURBULENCE AMPLIFIERS

Although the turbulence amplifier can be used in proportional applications, its primary use is in logic circuitry. It is particularly useful in this case because a turbulence amplifier can drive up to ten or more secondary units. Furthermore, the turbulence amplifiers are isolated completely, and a single amplifier can have a large number of inputs. Again, the limitation is one of physical room in which to place the multiple inputs rather than any theoretical limitation.

The turbulence amplifier performs a logical NOR function. A NOR function can be used as the basis for all other logic functions such as AND, OR, and counting circuits.

Amplifiers have been constructed with power gains of 40 to 80. If some acoustic sensitivity can be tolerated, pressure gains of 1000 can be obtained in a single stage. With

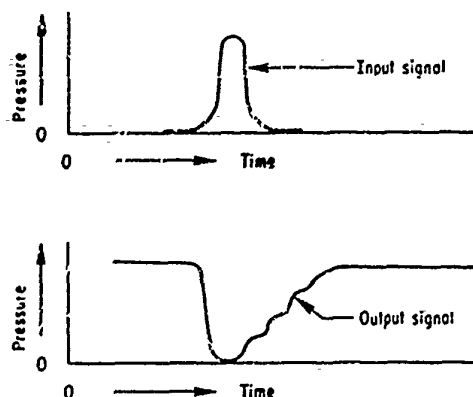


Figure 24-38. Output Pulse for a Positive Input Pulse¹⁸

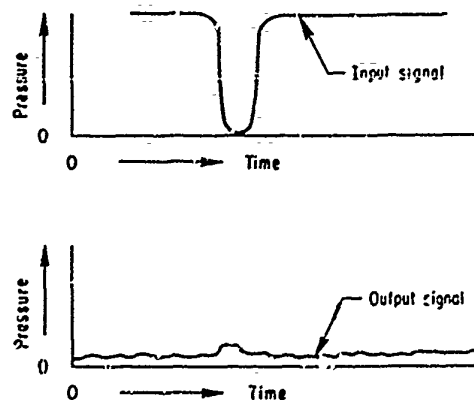


Figure 24-39. Output Pulse for a Negative Input Pulse¹⁸

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this sensitivity, the air currents produced by even small blowers can be detected by open amplifiers many feet from their source.

In digital applications jet sizes can vary over a wide range, with typical supply tube diameters ranging from 0.010 to 0.70 in. For diameters larger than this, the length of straight supply tube required to obtain laminar flow becomes so long as to be impractical.

By use of a typical supply tube diameter of 0.030 in. an amplifier can operate with supply pressure of approximately 0.15 psi and produce an output of 0.075 psi with a no load flow of 1.2×10^{-5} lb/sec. If a control pressure of 0.01 psi is used, the control flow would be about 5×10^{-6} lb/sec.

24-9 OUTPUTS

It is obvious that in order for the fluoric timer to serve a useful purpose, some way must be found to use the energy output from the low-pressure fluid signal at the end of the set time. In designing a military timing system, the difficulty of the design problem stems from the conflicting requirements of the pneumatic signal sensitivity that must be combined with sufficient ruggedness to avoid premature operation. A convenient example of the design problems that must be solved is found in the case of a fluoric fuze for artillery ammunition.

The usual output function of a mechanical time fuze is the release of a spring loaded firing pin. Since spring preloads of 5 to 7 lb are common, a significant output force is required to trip the pin. It appears that the signal or actuation pressure from an end-item sized fluoric timer will be something less than 1 psi. Several investigators have constructed functional, low pressure transducers; however, in most cases these devices require more volume than that necessary for the entire fluoric circuitry package.

24-9.1 BALANCED PISTON OUTPUT DEVICE

One type of output device uses the balanced piston principle. Applying this principle to an output mechanism results in the device shown in Fig. 24-40². Since there is clearance between the spool lands and the cylinder walls, pressure supplied to port 1 enables the spool to float in a centered position. A bleed passage through the spool prevents pressure from building up behind the right-hand land thus eliminating premature operation due to pressure unbalance. Upon the elapse of the set time, an output signal of 1 psi is delivered to port 2. This signal, although small, upsets the equilibrium and causes the spool to move to the left. As soon as the trailing edge of the right-hand land passes port 1, the full supply pressure acts on the exposed piston area and results in a significant output force sufficient to perform work of fairly high magnitudes.

Compared to passive type devices, this device requires a continuous air supply throughout the timing cycle. Power consumption can be reduced by keeping the spool and cylinder clearance to an absolute minimum. Also the balanced spool is sensitive to external shock and vibration. Sensitivity to external loading along a given axis is reduced by addition of the counterweight. Any loading in the horizontal direction, such as projectile acceleration or deceleration, would act equally on the spool and the counterweight. Hence, the net torque about the balance arm pivot remains zero, i.e., the system is still in equilibrium.

For ammunition end-item use, a separate gas bottle capable of providing 20 psi for 180 sec might serve as a power source. A more desirable approach would have the ram-air driven pump supply the device. In any event, although this balanced-piston scheme may not prove to be entirely satisfactory from a power consumption standpoint, it does satisfy the

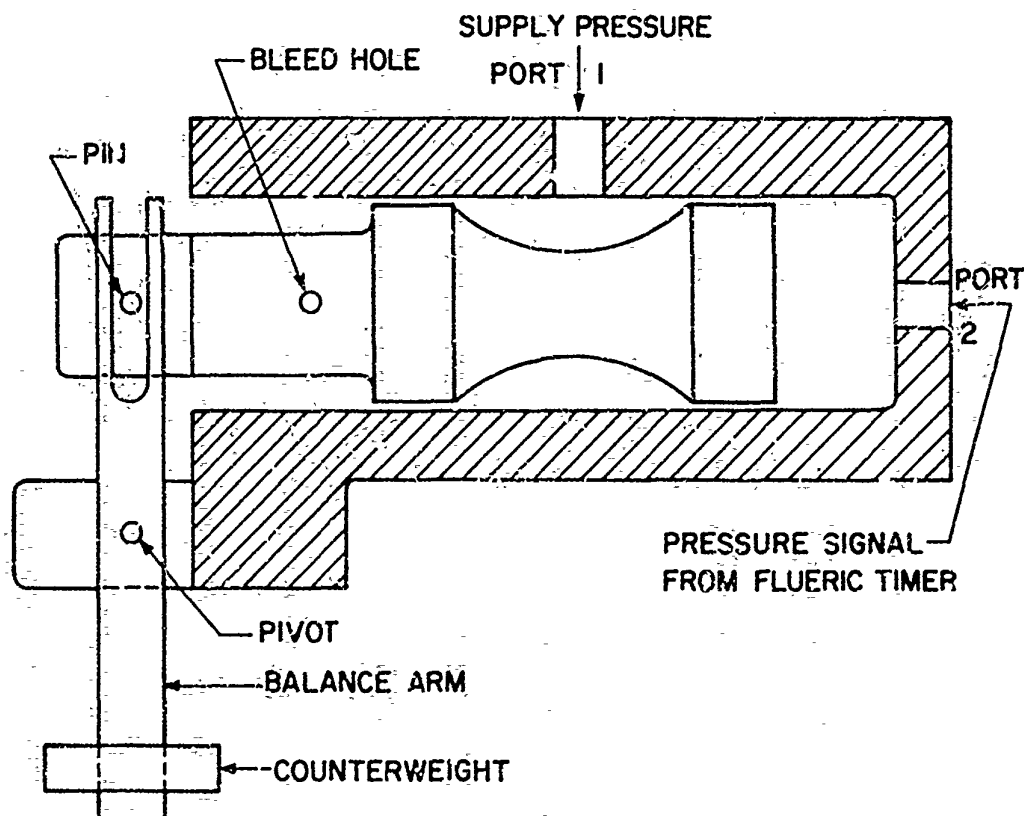


Figure 24-40. Output Mechanism—Balanced Piston Type

requirement for extreme sensitivity to a low level fluoric counter output signal.

24.9.2 BELLOWS-ACTUATED OUTPUT TRANSDUCERS

An output transducer used in a study at Picatinny Arsenal is shown in Fig. 24-41¹². It consists of a small ten-convolute bellows, an adjustable contact, and contact leads. The bellows are 0.090 in. in diameter with a wall thickness of 0.0006 in. One end of the bellows receives the output pressure of the timer and the bellows elongate to close electrical contact. The transducer functions satisfactorily up to 100 Hz. The adjustable contact is set to between 0.004 to 0.006 in.

gap to be operable at output pressures near 2 psi. The nominal linear travel of the bellows at 2 psi was determined to be about 0.012 in. The placement of these transducers is shown in Fig. 24-42¹². No change of response was noted when the assembly was spun about an axis through the center of the timer at rotational rates up to 150 rps. The arrangement of the contacts is such that initial setback forces tend to increase the contact gap. Thus, unscheduled contact closure would occur only due to deceleration forces such as those produced by impact.

In another application, the output interface consists of a bellows-actuated rotary switch as shown in Fig. 24-43¹⁹. The bellows switch is

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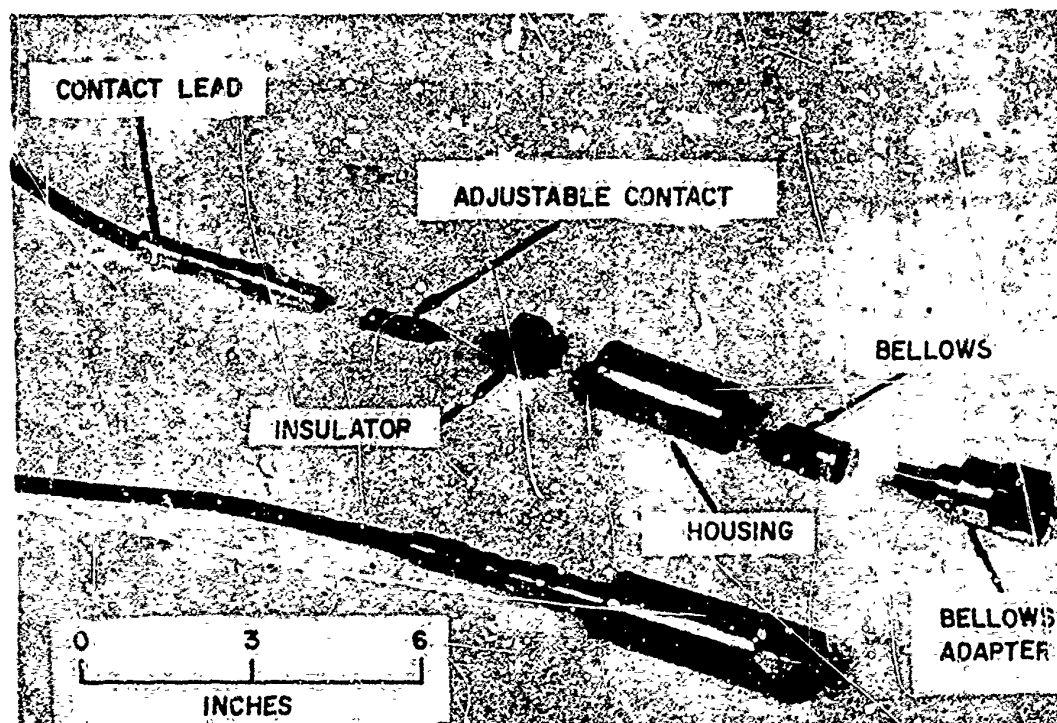


Figure 24-41. Bellows Transducer for Fluid Timer

made symmetrical to promote balancing and to lower the sensitivity to inertia forces, which would tend to operate the switch prematurely. Lateral support and damping are provided by plastic tubes surrounding the bellows. Also the bellows are designed to be stacked solid when not pressurized. This prevents any displacement in one direction and permits elastic preloading to be used to limit any inertia forces that might cause displacement in the other direction.

The present switch requires two output signals from the output logic circuit as shown in Fig. 24-44(A)¹⁹. Here the output circuit is built from three NOR gates; the output signal is on only when A and B are in. In order to obtain fast response of the output interface switch, with its associated volumetric capac-

ity, the third NOR gate used in this circuit has a larger nozzle (0.010 in.). Fig. 24-44(B) shows the output pressure flow characteristics of the third element that drives the bellows rotary switch.

24-9.3 THIN MEMBRANE

In another program, a pressure actuated switch was developed to close contacts with pressures as low as 0.5 in. of water (approximately 0.02 psi)²⁰. The only moving element is a very thin stretched membrane 0.75 in.² in area on which is held one movable contact. The other contact is adjustable to actuate closing over a variation of output pressure. The switch is shown in Fig. 24-45(A)²⁰ along with a view of the overall timer unit in Fig. 24-45(B). After

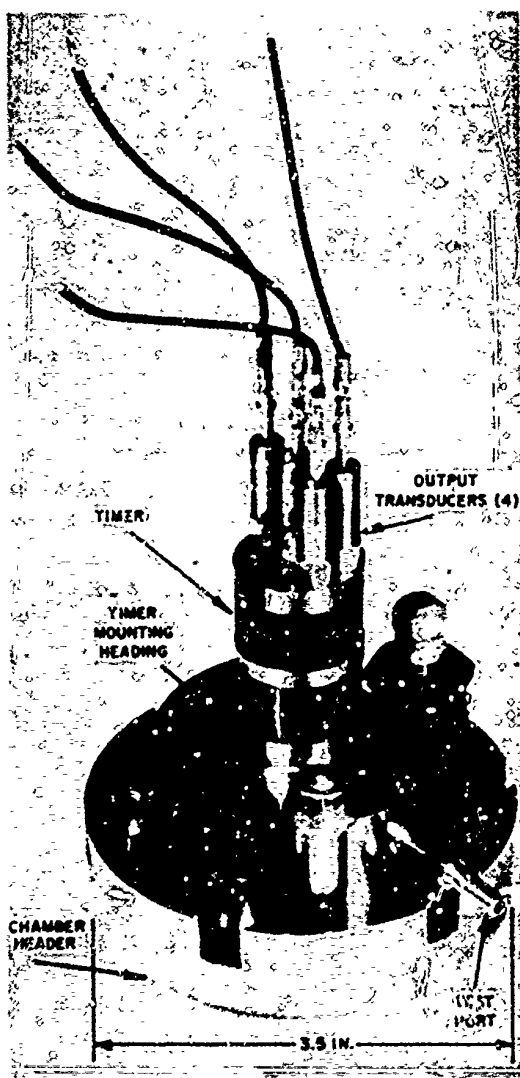


Figure 24-42. Location of Transducers on Timer Body

assembly and test, the switches were encapsulated in epoxy, and no further adjustment was possible or required. These switches were demonstrated to operate for billions of cycles with less than 15% change in the pressure necessary to effect closing. One package of six switches was subjected to the complete

specification test procedure, including temperature (-65° to 165°F), shock, and vibration with a change in pressure of less than 0.5 in. of water required for closing the normally open contacts.

24-10 SETTING METHODS

The requirements for the setting mechanism are: (1) small size, (2) provide a decimal readout, (3) ruggedness, and (4) settable in increments to provide sufficient accuracy. The function of the setter is to program the air flow between the output channels of the binary stages comprising the fluoric counter and the input (i.e., control jets) of the decoder circuit. For timers having binary stage setting ports, the setting mechanism programs the air delivered from the common setting manifold to each stage.

Some proposed setting devices have incorporated punched tape with a geared driving system or entirely geared arrangements. Printed on the tape is the decimal

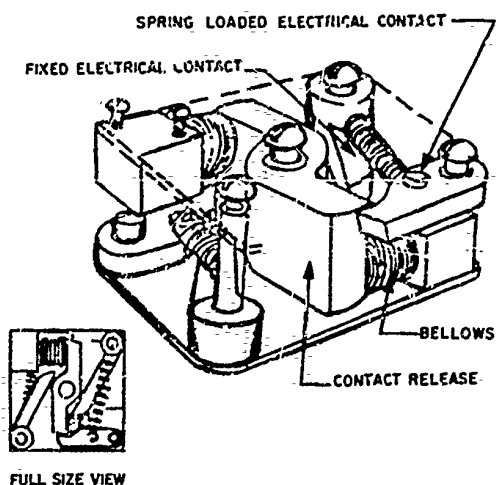
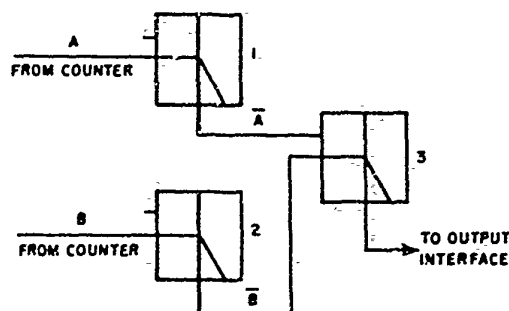
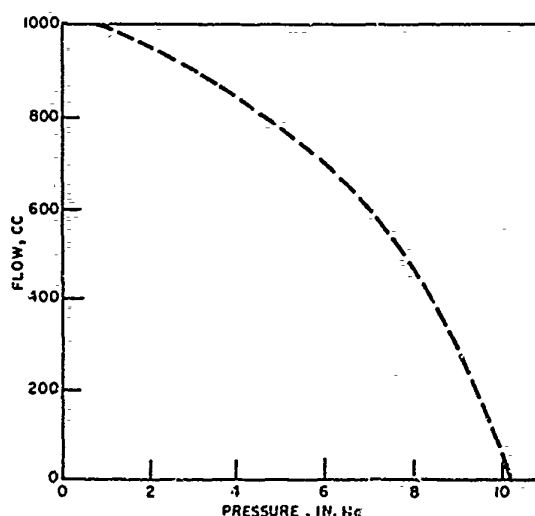


Figure 24-43. Bellows Actuated Rotary Switch

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(A) APPLICATION OF THREE NOR GATES IN OUTPUT CIRCUIT



(B) PRESSURE-FLOW CHARACTERISTICS OF THIRD NOR GATE WHICH ACTIVATES BELLOWS ROTARY SWITCH

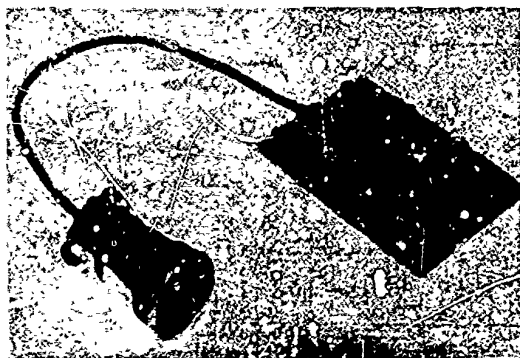
Figure 24-44. Output Interface Circuit for Fluorid Timer

equivalent of the set time corresponding to the binary coded number. Set time is displayed through a window on the timer housing. Although the concept of tape setting is attractive and natural for a binary to digital converter, difficulties may arise when one attempts to package such a device within the available space. For example, the tape length must be sufficient to provide for the maximum time and the tape must be capable of being driven in either direction, i.e., up

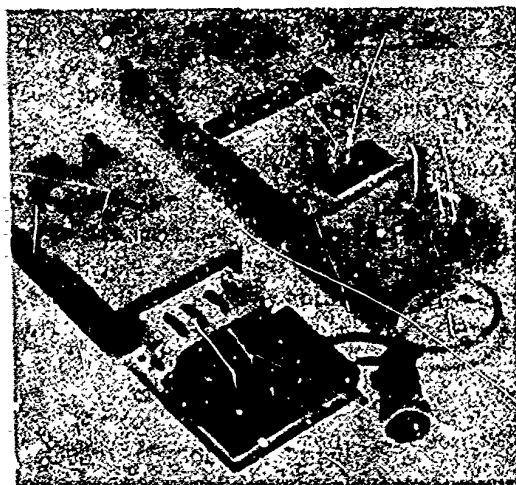
scale or down scale. Also the device must be rugged enough to withstand military operating environments. In an attempt to overcome some of these possible limitations, intermittent gearing should be considered. The apparent advantages of this system are ruggedness, positive two-way drive (no slip clutches, etc.), and compactness.

The feasibility of this scheme was demonstrated at Frankford Arsenal by the bread-

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(A) SIX-PORT DIAPHRAGM PRESSURE SWITCH



(B) SANDIA FLUID TIMER

Figure 24-45. Pressure Sensitive Switch
Used in Fluid Timer

board device shown in Fig. 24-46². The mounting plate is 8 in. square. As shown in Fig. 24-47² each housing contains a stationary cylinder with three equally spaced in-line tubing holes; a thin-walled sleeve with twelve holes arranged in a binary type sequence which is free to rotate about the fixed cylinder; and a spring-loaded shoe carrying three in-line hose connections. When bread-boarded, the sleeves are interconnected by an intermittent gear train. A digital counter is

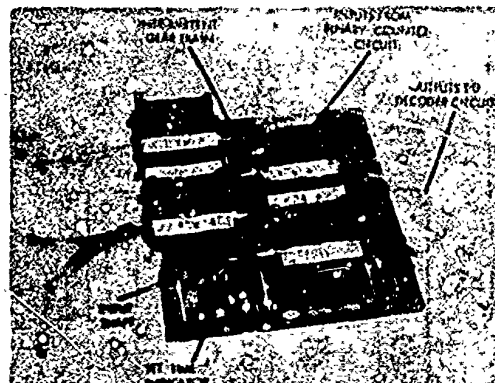


Figure 24-46. Fluoric Timer Setting Device
Using Intermittent Gearing

geared to the input shaft of the first sleeve, providing a decimal readout of the set time.

The sleeve holes are positioned in such a way that each 45 deg of sleeve rotation opens and/or closes the air passageways between the fixed cylinder and the shoe (Fig. 24-48²). The intermittent gear ratio between each sleeve is 8 to 1. Thus 8 revolutions of the first sleeve are required for one complete revolution of the second sleeve. Or one revolution of the first sleeve indexes the adjacent sleeve 45 deg.

To explain the operation of this device, let us take a specific example. Suppose it is desired to set 50.0 sec into the unit. Since a 4 to 5 gear ratio (reduction) exists between the digital counter and the input shaft, for a setting of 50.0 sec, 62.5 turns are required of the input shaft. Referring to Fig. 24-48, 62.5 turns, starting from the all blank position, would program 44.8 sec on the 3rd sleeve, 4.8 sec on the 2nd sleeve and 0.4 sec on the 1st sleeve. The 4th sleeve would not have moved, hence remains blank. The sum of the individual sleeve settings equals the total or desired time of 50.0 sec. If this device now were coupled to an eleven stage counter circuit and an eleven input NOR decoding circuit, upon the first coincidence of zero

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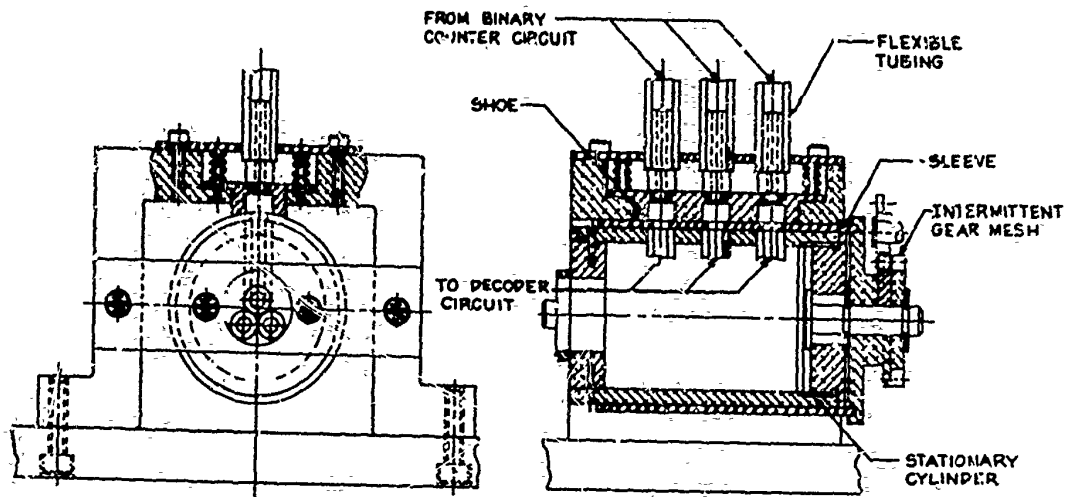


Figure 24-47. Housing Assembly—Flueric Timer Setting Device

signals from binary stages 3, 5, 6, 7, 8 and 9 an output signal from the decoder could occur 50 sec after the initiation of the timing cycle.

To make this setting arrangement suitable

for artillery fuze application, it must be redesigned to fit within the fuze contour²¹. Fig. 24-49² indicates the location and shape of the geared setting mechanism. Notice that the setter is positioned between the binary counter circuit and the decoder circuit. This

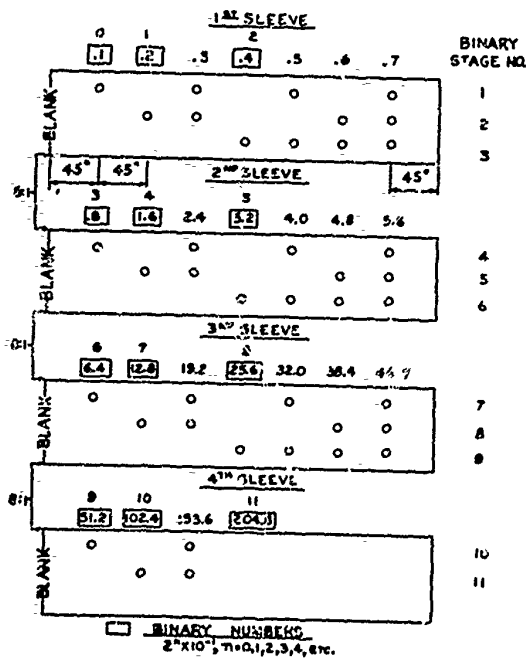


Figure 24-48. Sleeve Hole Locations

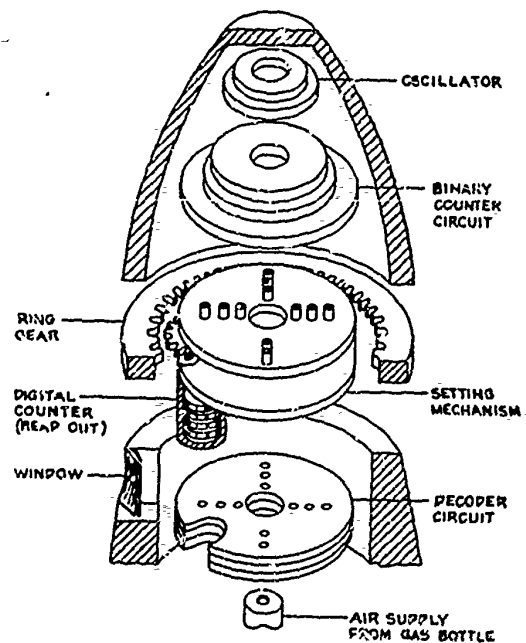


Figure 24-49. Flueric Timer Packaged for Artillery Fuze

is a natural location since the function of the setter is to interrupt the fluid signals between the binary stages and the eleven-input decoder circuit.

This miniaturized setting device consists of four intermittently driven gear wheels of approximately 0.5 in. pitch diameter sandwiched between two parallel metal plates. Each gear wheel hub contains the required twelve through holes and in function replaces the sleeves of the breadboard unit. The plates serve not only to support the gearing, but act as manifolds to permit connecting the fluid circuit to the device. Setting is accomplished by rotating an internal ring gear that drives, via a common idler gear, the first setter wheel and the digital readout counter. The large ring gear would be fixed to the upper portion of the fuze body while a readout window would be located in the lower or stationary portion of the fuze.

An example of a flueric timer developed at Picatinny Arsenal employs punched cards to set time intervals between 2 and 200 sec in increments of 0.1 sec. A sketch of the timer assembly is shown on Fig. 24-50¹². This unit contains five dividing stages, twelve counter stages, and an output stage. With an oscillator working at 640 Hz, the 17th stage would provide a pulse to the output stage (19th) at the rate of $640/2^{17}$, or 0.0048828125 pulse per sec, or approximately 200 sec pulse separation. This is the maximum time delay if the oscillator frequency is not changed. The counter stages are presettable by inserting an encoded card into the timer which, upon receipt of a "preset pulse", initially sets a "0" or a "1" into each stage dependent on the time lapsed desired. Thus if the minimum time delay is desired, which is 1/640 sec, the first 17 stages would preset to "1's" as shown in Fig. 24-51(A)¹², the last stage to a "0". Upon initiation of the first pulse from the

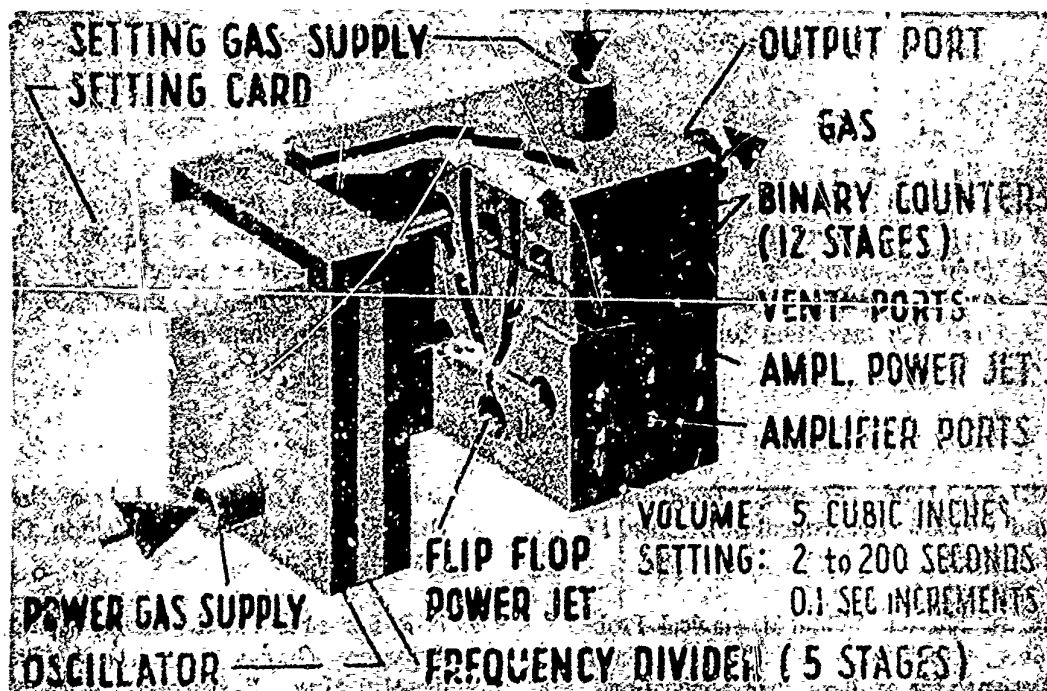
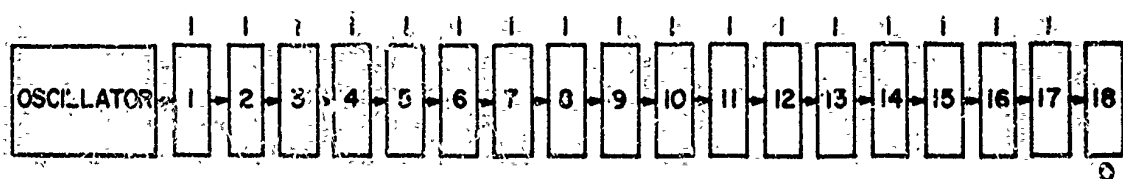
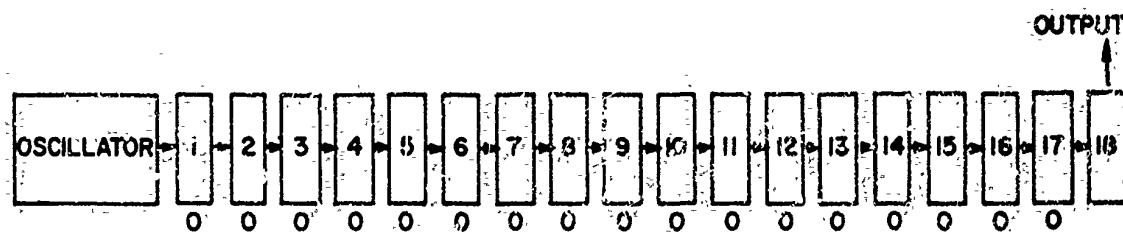
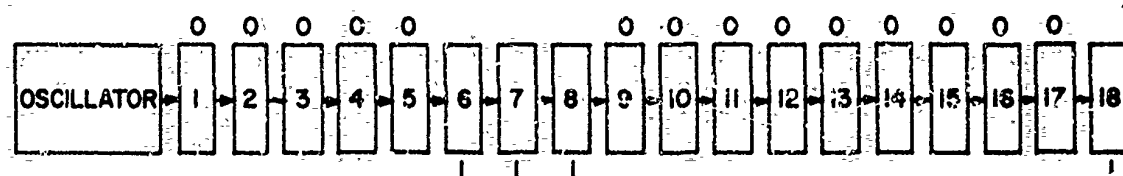


Figure 24-50. Fluid Timer With Card Preset

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(A) SETTING FOR MINIMUM TIME OF $1/640$ SEC(B) TIMER AFTER $1/640$ SEC DELAY

(C) SETTING FOR 17.5 SEC

Figure 24-51. Preset Stage for an 18 Binary Field

oscillator, the first seventeen stages would flip to "0's", the output stage to a "1" which would provide the output pulse in an elapsed time of $1/640$ sec, provided propagation time delay errors are negligible. This is shown in Fig. 24-51(B). For maximum time delay the

coded card initially would preset all "0's" into the 18 binary field. If an elapsed time between these extremes is required, some stages initially would be preset to "0's" and others to "1's". Fig 24-51(C) shows the initial preset for an elapsed time of 17.5 sec.

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CHAPTER 25

PRODUCTION TECHNIQUES

Techniques for fabrication of fluoric devices are not difficult. In fact, the most useful techniques are well-known. However, the fact that the performance and characteristics of a fluoric device are related closely to its geometric shape can lead to problems.

Although models have been constructed which have adjustable parts, in most instances, a change in a geometric shape or in a dimension requires the fabrication of a new device. Then, when a satisfactory design is attained, the problem of reproducing the design in production units arises.

Foremost among the considerations is the choice of material to use in the production units. Fluoric devices are subjected to both structural and hydraulic forces. The material must have sufficient strength to withstand these forces without undue distortion.

Surface hardness of the material also must be considered, particularly if the fluid carries abrasive particles. Wear of the component is especially critical in nozzles and at the splitter in stream-interaction devices. Other factors, such as operating temperature and type of working fluid, also enter into the selection of a material.

The problems of quantity manufacture differ somewhat from those of a development laboratory. In the laboratory, ease of fabrication is desirable to permit rapid change in designs. Long-term properties of the material, such as wear, are often not as important as workability of the material.

Some of the production techniques discussed in this chapter are suitable for mass

production of fluoric devices, while others are useful only in development work. They are mentioned here with the thought that at some time in the future the processes may be feasible on a production basis. For additional guidance on producibility, see Ref. 1.

25-1 MATERIALS

25-1.1 GENERAL REQUIREMENTS

Materials for fluoric devices should be dimensionally stable, capable of being formed with precision (nozzles with dimensions of 0.010 in. or smaller may be required), and suitable for sealing. Due to the critical dimensions of fluid elements and the trend toward miniaturization, a material must be selected that does not drastically change its physical size and shape when exposed to the intended working environment. The environmental conditions may require that the designer consider chemical, thermal, and moisture effects on the device. Also the designer should consider strength, weight, size, cost, and shelf life.

A material must be chosen so that precisely sized and reproducible elements can be fabricated. Also, since present fluid devices are built from laminates, a material must be chosen with its sealability (between layers) in mind. Leaks in a complex fluid timer are difficult to locate and will cause the unit to operate erroneously.

25-1.2 SUITABLE MATERIALS

Fluoric devices are presently fabricated of materials of three general types—plastics, metals, and ceramics. These three provide

TABLE 25-1
SUITABLE MATERIALS FOR FLUORIC DEVICES

PLASTICS		METALS	CERAMICS
Thermoplastics*	Thermosetting**	Suitable	Suitable
a. Most suitable:	a. Most Suitable:	steel	glasses
acetals, nylons, polycarbonates, ABS	melamines phenolics	copper aluminum nickel magnesium (base metals and alloys)	carbides nitrides oxides
b. Usable But Less Desirable:	b. Slightly Less Suitable:		
acrylics polyethers polypropylenes polystyrenes vinyls fluorocarbons	epoxies, polyesters, silicones ureas		
c. Not Suited:	c. Used Mostly for Coatings:		
cellulosics polyethylenes polyurethanes	alkyds		

*Softened or resoftened by heat; then formed; no chemical change.

**Initial molding by heat and/or pressure—after set chemical change occurs and further shape change difficult or impossible.

properties required for each application. Also, any of these may be used in combination with each other to extend their usefulness. Table 25-1 lists materials of each type; Table 25-2² gives the general characteristics of plastics, metals, and ceramics, and consequent application considerations.

25-2 FABRICATION

Various processes have emerged in working with plastics, metals, and ceramics. These are discussed in the paragraphs that follow.

25-2.1 PLASTICS

The processes generally used in fabricating plastics include casting, thermoforming, photoetching, injection molding, compression molding, jet molding, and transfer molding. Typical comparisons with reference to economical quantity of production are shown in Fig. 25-1².

25-2.1.1 Casting

This is a rapidly developing process. Starting from a two-component catalyst system in liquid or paste form, the two components are mixed and immediately poured into a mold. The process can be conducted at room temperature and with low mold pressure, and is suitable for complex precision parts. Types of thermoplastics used include methacrylates, polyesters, nylons, acrylonitrile, and epoxies.

The epoxy casting process produces a one-piece unit quickly and at low cost. With a suitable master unit, the design can be changed quickly and easily. The basic process consists of making plastic duplicates of an item, with the intermediate step of a rubber mold. The item to be duplicated is placed within a suitable form, which may merely consist of blocks of wood or metal arranged on a flat surface to contain the liquid rubber.

TABLE 25-2

GENERAL CHARACTERISTICS OF MATERIALS AND
CONSEQUENT APPLICATION CONSIDERATIONS²

Characteristics:

	Plastics	Metals	Ceramics
Dimensional stability	F	G	E
Precision formability	G	E	E
Seal integrity and durability	G	F	F
Strength	F	E	G
Chemical resistance	G	G	E
Thermal resistance	F	G	E
Moisture resistance	F	F	E
Weight	E	F	G
Processability	E	G	G
Cost per element	E	G	G

E = Excellent G = Good F = Fair

Applications:

Materials	Suitable for Applications Involving or Requiring:	Not Suitable for Applications Involving or Requiring:
Plastics	Mild environmental conditions Low cost Low weight	High mechanical, thermal, and moisture resistance High precision High dimensional stability
Metals	High thermal shock Mechanical shock High precision	Low weight High moisture Very high dimensional stability
Ceramics	High chemical, thermal, and moisture resistance High precision Very high dimensional stability	High thermal shock Mechanical shock

The liquid, a silicone rubber compound (RTV) that vulcanizes at room temperature, then is poured over and around the master. Use of a vacuum chamber at this time is helpful in removing bubbles of entrained air from the rubber. (Another technique for removing entrained bubbles is to work the rubber with a very fine stream of high-velocity air that punctures the bubbles.) The rubber penetrates quite well into the surface

details of the master. Vulcanizing time, depending on mold temperature and the curing agent used, ranges from a few hours to 40 hr. When vulcanized, the mold is sufficiently flexible and elastic to be removed from the master without great difficulty or deformation. The mold is examined after its removal from the master, and "flash" is trimmed off. Modifications may be carved into it at this time. When the mold is fully

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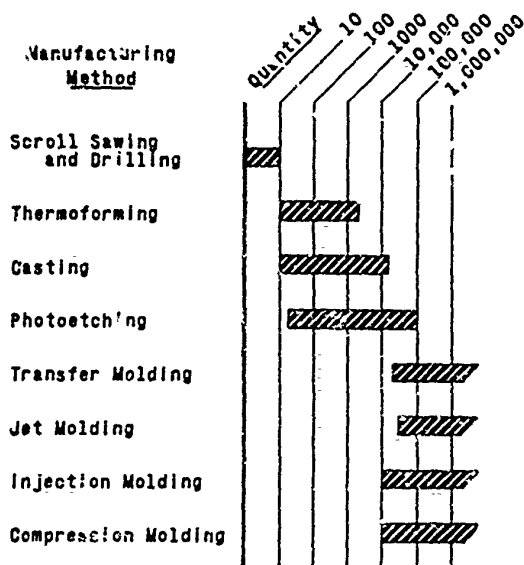


Figure 25-1. Comparison of Plastic Forming Processes for Fabricating Economic Production Quantities²

prepared, the epoxy compound is poured in. Bubbles are removed from the epoxy either mechanically, with a pick or brush, or by means of a vacuum. After the epoxy has cured, the piece is removed from the mold. Here, again, the elasticity and flexibility of the rubber allow pieces to be removed which have no draft. With little or no further work, the resulting piece accurately duplicates the desired features of the original item. Once the optimum geometry is found, the process can be used to duplicate units indefinitely and with considerable uniformity and accuracy from copy to copy. If the mold becomes damaged, second and third generation molds can be made from the epoxy pieces with little or no loss of detail.

As a material for use in fluidic devices, epoxy has several desirable properties. It can be machined if necessary; it can be permanently bonded to other epoxy pieces, such as cover plates, or to itself if a unit should be broken; and it can be made with different degrees of softness and flexibility in each of several layers.

25-2.1.2 Thermoforming

This process uses a thermoplastic material. Heat and pressure, or vacuum are used to force the material to conform to the die contour. The process is suited to large planar fluidic elements where precision and detail requirements are not too high.

25-2.1.3 Photosensitive Plastics

DuPont has developed a photopolymer plastic (TemplexTM) that is being used to form fluidic elements. Because of the speed and simplicity of the process, it is especially useful for breadboard experimental work, where the designer must know quickly the effect of small design changes. For large lots better methods are available. The process centers on the fact that the photosensitive plastic when exposed to ultraviolet light becomes insoluble. The unexposed part remains soluble in dilute aqueous sodium hydroxide spray. The process is shown in Fig. 25-2².

This process offers several advantages:

- (1) Construction Ease. Three-dimensional

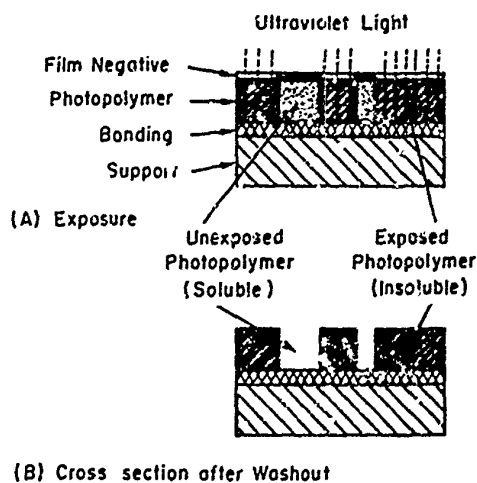


Figure 25-2. Photoetching of Photosensitive Plastic²

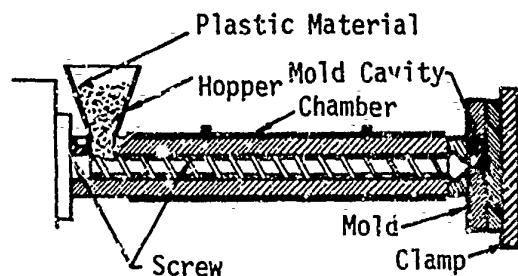


Figure 25-3. The Screw Method of Injection Molding²

plastic configurations can be made from two-dimensional black and white copy.

(2) Speed. Once the negative is prepared, processing requires about 20 min.

(3) Smooth Side Walls. An uneven surface can disrupt laminar flow.

(4) Simplicity. Both material and special-purpose machinery are available and, because no unusual skills are required, in-house manufacture is possible.

(5) Precision. A mean side wall taper of 2 deg can be maintained.

Several limitations also should be noted:

(1) Operating Temperature Range. Presently limited to approximately -100° to $+200^{\circ}$ F.

(2) Aspect Ratio. Cannot exceed 3:1.

(3) Sensitivity to Moisture and Some Chemicals. The results of long-life experiments to test dimensional stability and other critical features are being determined.

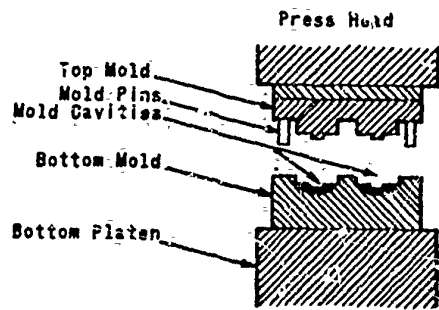
25-2.1.4 Injection Molding

Injection molding is a process for forming a granulated thermoplastic material into a complex, precision-finished part at high

speeds and with little material waste. The process is similar to the die casting of metals in some respects. Injection molding usually is accomplished by the plunger method or the screw method. The screw method, shown in Fig. 25-3², uses a continuous screw to transport the granulated material from the hopper, through a heating chamber, and into the mold. The movement of the screw thoroughly mixes the constituent resins, plastics, and fillers as they are being liquefied at temperatures that range between 250° and 500° F. The choice and control of temperature are important; for, while increasing temperatures facilitate the movement of the plastic into the mold cavities, too high a temperature may degrade the material. The mixture is forced at pressures of 10,000 to 20,000 psi through a system of channels into the mold cavities. Cooling channels keep the mold temperature below the fluid point of the plastic. After the part has solidified, the mold opens to eject the part and then closes as the cycle is repeated. The operation usually is entirely automatic to this stage. Little finishing work is necessary other than "degating" to remove the excess material that solidified in the channels between the nozzle and the mold cavities.

The plunger method uses a ram to force the material into the mold. This technique is not as satisfactory as the screw method because of occasionally incomplete mixing of the material charge, somewhat higher heat required, and the increased complexity of the plunger-type equipment. Roughly 80 percent of new injection molding machines purchased are of the screw type. The use of multicavity dies allows simultaneous production of many identical parts which may weigh only a fraction of an ounce. Since thermoplastics can be remelted, the excess material can be reprocessed. Manufacture of multicavity dies for injection molding is a costly and time-consuming process. Therefore, injection molding should be used for flexible device components only where the design configuration is fixed and large quantities are required.

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Figure 25-4. Compression Molding²

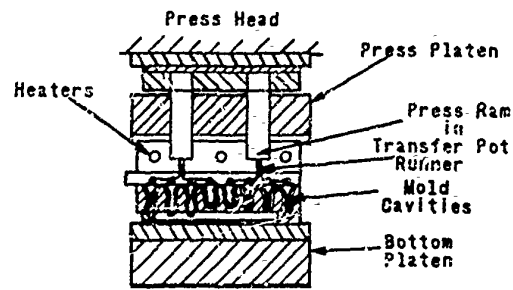
25-2.1.5 Jet Molding

This process is used with thermosetting materials and is an adaptation of the plunger method of injection molding used with thermoplastics. The feature of this method is to use controlled heat so that the granules of the thermosetting material become "soft" but the material does not "set" or polymerize until some time later when the mold is filled completely. These critical controls make the process some ten or twenty times longer than injection molding.

25-2.1.6 Compression Molding

A die for compression molding is shown in Fig. 25-4². A fairly precise "charge" of thermosetting resin is placed in the mold cavity, and the top mold is brought down to induce pressures of 2000 to 4000 psi (or greater) on the mold. The temperature—typically between 250° and 375°F—and pressure are held until polymerization occurs, then the part is removed.

Compression molding is a high-pressure process most advantageous for the forming of identical parts of relatively simple design from thermoset materials. Compression molding is more economical for high volume than small lot production. The operating cycle—a function of the material, part thickness, and size—may be a minute or longer. Tolerances can be held to ± 0.005 in. per linear inch

Figure 25-5. Transfer Molding²

where necessary. Like other molding techniques, close tolerances specified but not actually required increase the cost of the finished part. Excess flash created between the top and bottom molds must be removed from the molded part. The scrap rate, which is sometimes 30%, is higher for compression molding than for injection molding mainly because thermoset rejects and flash cannot be remolded. Compression molding requires more complex machines and more highly skilled operators than the injection process.

25-2.1.7 Transfer Molding

In the transfer process (Fig. 25-5²) the molding material is placed in a chamber called a transfer pot usually located above the closed, heated molds of the machine. Mold heat and plunger pressure cause the thermosetting preform to plasticize enough so that the material flows through the runners into a mold cavity. The total time of pressure application may be as long as one minute. After the material has been cured, the mold is opened and the finished part ejected without cooling.

25-2.2 METALS

Fabrication processes for metals include conventional machining, powder metallurgy, die-casting, chemical machining, electroforming, electrical discharge machining, and electrochemical machining.

25-2.2.1 Conventional Machining

The most commonly used processes include milling and engraving (pantograph). There is a definite lower limit of size to which these processes can be used, and they are not usable for the microminiature elements that have begun to appear. However, these processes are suited for laboratory breadboard construction. By using the pantograph method, a large scale master of the element is generated, then a model is accurately milled in Bakelite, using a pantograph engraver with a lower limit tool diameter of about 0.1 in., which also becomes the channel width limit.

In conventional machining, if a separate unit is made to incorporate each design change, a great many hours of valuable shop time is used. In addition, successive units may vary slightly in those dimensions that should have remained unchanged. While not often serious, such changes add an unknown factor to the analysis of test data. To assure that only the desired dimensions are changed, sometimes only one unit is built. This unit is then tested, disassembled, modified, reassembled, and retested. This process takes less shop time than does the construction of separate units, but only a limited number of variations can be made on one unit. In addition, if the desired configuration is passed, it is usually not practical to "back up" and re-examine it. In any event, the number of combinations possible in such a study makes any process that involves machine work on each unit prohibitive in both time and money.

25-2.2.2 Powder Metallurgy

Powder metallurgy is a technique that produces finished parts of uniform density and high strength, starting from powdered metals. Typical metals are copper, tin, lead, zinc, nickel, and iron. The technique is suitable only for relatively high production quantities (1000 units or more). The process consists of a sequence of powder blending,

pressing, and sintering. Blending produces the desired mixture, then cold pressing between 20 and 30 tons produces a "green state" item, which is still fragile. Sintering is the next stage which is performed in an oven at high temperatures, but below the melting points of the metal powders. Sintering provides a strong chemical bond and "recrystallizes" the powdered particles. The atmosphere of the furnace usually consists of inert gases that prevent the sintered material from oxidizing. Powder metallurgy requires certain special design considerations. First, thin parts and narrow, deep sections should be avoided: the former may break and the latter may prevent complete formation of the part. These limitations may make the process unsuitable for flueric elements with high aspect ratios and for delicate splitters. The tolerances permitted in the direction of pressing should be greater than those at right angles to pressing. Dimensions perpendicular to the pressing direction can be held to about ± 0.0015 in./in. Slots and channels must be tapered to two or three degrees to allow ejection of the part from the die after compacting.

25-2.2.3 Die Casting

Die casting is a process that forces molten metal alloys into metal dies to produce complex parts. This technique is a rapid and relatively inexpensive method of producing large quantities of precision metal parts. There are actually four principal methods of die casting: plunger, air injection, vacuum, and cold chamber methods. The first three are examined in the paragraphs that follow. Selection of the proper method is determined primarily by the kind of alloy to be cast and the production quantity desired.

For all these methods, section thicknesses are also a function of the type of alloy used. A practical minimum is 0.040 in., and maximum sections up to 0.5 in. are possible, although problems with shrinkage are likely. Tolerances attainable vary with the type of

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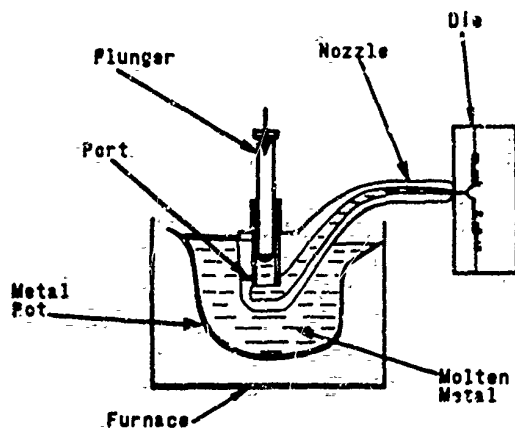


Figure 25-6. The Plunger Method of Die Casting²

alloy, but a figure of ± 0.004 in./in. gives a rough order of magnitude for linear dimensions.

Except for finishing, secondary operations usually are not required for die cast parts. In all instances, however, flash and cores must be separated from the finished part. Mechanical, chemical, electrolytic, or electroplated finishes may be used where they are required for proper performance of the fluoric elements.

A discussion of die casting methods follows:

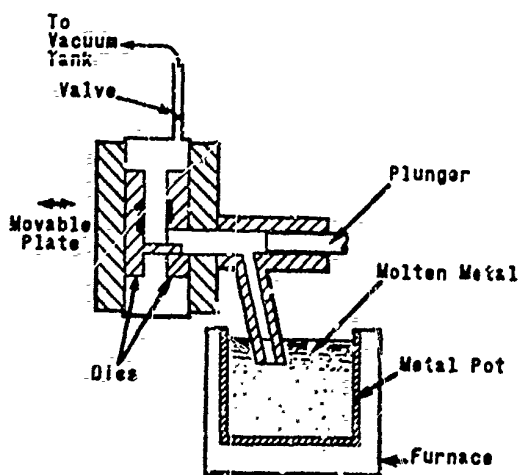


Figure 25-7. The Vacuum Method of Die Casting²

(1) Plunger Method. As its name implies, the plunger method (Fig. 25-6²) uses a plunger to force the molten metal alloy into the open die. The plunger moves vertically in a vessel immersed in a large metal pot containing the molten metal. Molten metal is allowed to flow from the pot into the vessel during the upstroke of the plunger. On the downstroke, the metal in the vessel is forced into the spout through the nozzle, and into the die cavity. When the metal in the die hardens, the plunger repeats the cycle. The die is opened and the casting is ejected during the plunger upstroke.

(2) Air Injection Method. This method differs from the plunger method in that air pressure of 300 to 600 psi, rather than a plunger, is used to force the metal into the die, and the whole vessel, rather than the plunger, moves through an upstroke and a downstroke. The air injection method is well suited to production of aluminum alloys, although low melting point alloys may also be used.

The vacuum process (Fig. 25-7²) offers certain improvements of particular interest to the designer of small fluoric elements and circuits. Thin walls, important for miniaturization, can be achieved with the vacuum process. Wall thicknesses of 0.030 in. are common, and 0.018-in. walls are obtainable. Improved surface finishes reduce the need for additional finishing operations after casting. Lower porosity throughout the casting increases the part tensile strength and hardness.

A partial vacuum is maintained in the injection chamber and die cavity. The plunger then forces the molten metal into the partial vacuum of the die cavity. After solidification, the vacuum is released, the part ejected, and the piston withdrawn for another cycle. The vacuum process can produce parts as rapidly as conventional die casting methods, but at the higher cost of maintaining a partial vacuum.

TABLE 25-3
TYPICAL SURFACE DIMENSIONAL TOLERANCES* IN
PHOTOETCH PROCESS²

Metal	Metal Thickness, in.				
	0.001	0.005	0.010	0.015	0.020
Copper & Alloys	0.0005	0.002	0.003	0.005	0.005
Steels	0.0005	0.002	0.003	0.005	0.005
Aluminum Alloys	0.002	0.005	0.005	0.005	0.005
Molybdenum	0.0005	0.002	0.003	0.005	0.005
Titanium	0.0005	0.002	0.003	0.005	0.005
Nickel	0.001	0.003	0.005	0.005	0.0075

*Tolerances $\pm$ (in.)

25-2.2.4 Chemical Machining

Two general types of process are included under chemical machining: photoetching and chemical milling. Each is discussed:

(1) Photoetch Process. This process is being applied to metal sheets 0.020 in. thick or less and is becoming more and more important in fabricating laminar fluoric elements. It works on the principle of employing chemicals to "etch" away exposed metal areas while a photographic technique "masks" out other areas that are to remain unchanged (Fig. 25-8²). This process has been used with the following metals in order of increasing difficulty: copper, nickel, carbon steel, stainless steel, aluminum, titanium, and molybdenum. Etching rates vary from 0.005 to 0.003 in./min, and dimension tolerances increase with increasing metal thickness (see Table 25-3²).

(2) Chemical Milling. This process is similar to photoetching in that both processes use etchants to remove the metal. However, chemical milling uses tape or paint rather than the photographic method to prepare the metal and is suitable for thicker parts. It can be used for almost any metal (see Fig. 25-9²).

Chemical milling has several advantages

that are important to the manufacture of fluoric units. A specified amount of material may be uniformly removed from the surface of a metal part to leave a complex pattern. Parts, once masked, may be etched simultaneously in numbers that are limited only by the size of the etchant bath. Chemical milling does not change the structure of the metal

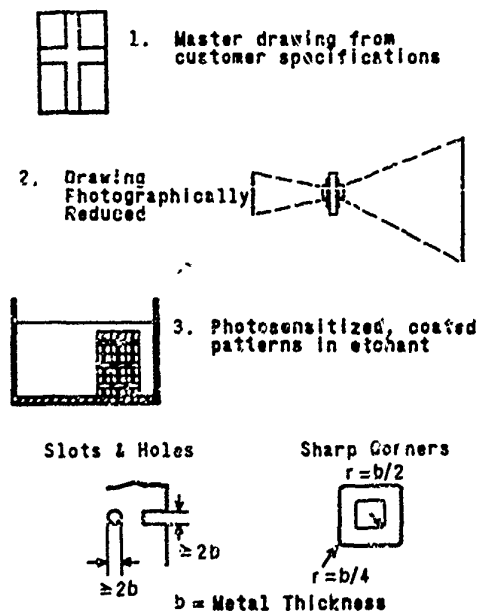


Figure 25-8. Photoetching Process and Design Considerations²

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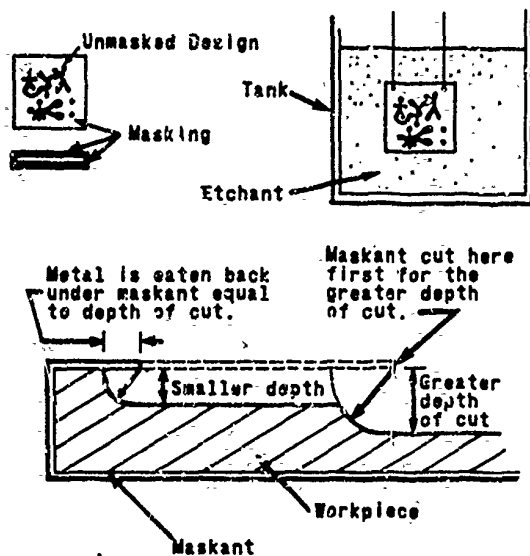


Figure 25-9. Chemical Milling, Showing the Effect Upon the Workpiece²

being etched, nor does the process set up internal stresses. Finally, operating and overhead costs are often lower than those for other metal-removal techniques.

Chemical milling also has limitations. The process is relatively slow: to etch a 1/8-in. slot requires from 40 min to 4 hr, depending upon

the etchant and material. Secondly, improper masking may not be obvious until after the etch has been made. Finally, the process presents some design problems. Undercutting is unavoidable and must be taken into account in design. The resultant rounded corners may have an undesirable effect for fluid flow. There is a limit to miniaturization, imposed by masking techniques, beyond which chemical milling cannot be used.

25-2.2.5 Electrical Discharge Machining (EDM)

This method of metal removal employs a spark discharge between the tool and the workpiece. EDM is particularly useful for complicated designs in hard, brittle metals. A typical EDM system is illustrated in Fig. 25-10². The tool, which is the cathode, is shaped in the form of the desired cavity. The workpiece is the anode and is submerged in a dielectric fluid. Typical equipment operates with high currents and a potential of approximately 80 V across a gap separation of about 0.001 in. An intense spark occurs across the gap. The spark vaporizes a small amount of metal from both the tool and the workpiece. The DC source is pulse-modulated up to 100,000 pulses per sec and the gap is adjusted to maintain a constant voltage drop. Metal is lost from both the tool and workpiece but less is lost from the tool. Ratios of workpiece penetration to tool-wear vary from 3:1 to 7:1.

25-2.2.6 Electrochemical Machining (ECM)

This is a deplating operation in which the cathode tool and anode workpiece are immersed in a flowing electrolyte. A DC current passes through the circuit, and the deplated metal is carried off in the electrolyte. Metal removal rates vary from 0.1 in.³/sec for a 1000-A unit to 1 in.³/sec for a 10,000-A unit. Typical potentials maintained across a gap (0.001 to 0.003 in.) are 4 to 10 V. Typical electrolytes are sodium chloride, or sodium nitrate at flow rates up to 200 ft/sec.

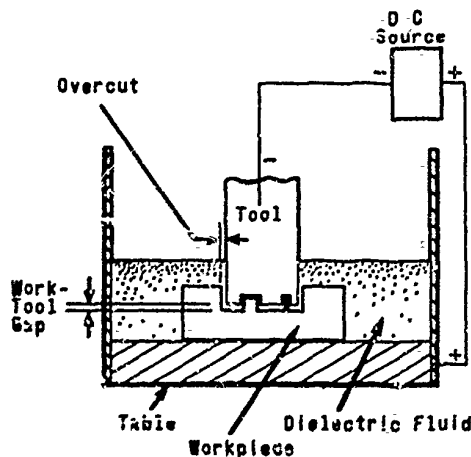


Figure 25-10. Electrical Discharge Machining Arrangement²

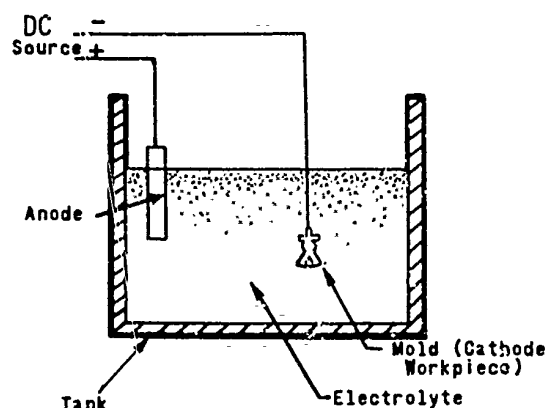


Figure 25-11. Electroforming²

Compared to EDM, the ECM technique is to be preferred when: (1) lot sizes are comparatively large and on a continuing schedule; (2) the volume of metal to be removed is large, (3) a good finish, relative to cutting time is required; (4) the area of engagement between workpiece and electrode is large; (5) three-dimensional contours are required; (6) the contour of a cut is critical; and (7) erosion of the electrode would disturb the form.

25-2.2.7 Electroforming

This is an electrolytic plating technique for manufacturing metal parts. It is similar but not identical to electroplating. Electroforming can be used to produce very complex forms with excellent tolerances, but it is expensive, limited to a few metals, and economically more suitable for small production runs. The electroforming process requires a core that duplicates the cavity or inside dimensions of the part to be produced. The core is placed in an electrolyte bath, and metal is electrolytically deposited over all surfaces of the core at a constant rate. When the required amount of metal has been deposited, the core is removed from the bath and separated from the metal deposited on it. The metal deposit then becomes the finished part having the internal dimensions of the core and a

thickness dependent upon the metal deposited from the bath (see Fig. 25-11²).

Cores for electroforming are made from metals or nonmetals and can either be expendable or reusable, depending upon the design of the part. Plastics, plasters, waxes, stainless steel, and aluminum are possible core materials and can be dissolved by suitable chemicals without damaging the part produced. The electroforming baths are similar to those used in electroplating. Only a few types of metal can be electroformed: copper, silver, iron, nickel, and chromium.

Electroforming techniques with expendable cores offer new design possibilities for the manufacture of complex, planar, and axisymmetric flueric subassemblies and complete units, in one piece and without interconnections or parting planes. The possibilities for making unusual and miniature configurations appear to be limited only by the ability to fabricate cores. Miniature parts from 0.030 to 0.20 in. in diameter, 1/8-in. long, and with a wall thickness of 0.001 ± 0.0001 in. have been produced. Thicknesses may vary from 0.001 in. to about 1 in.

25-2.3 CERAMICS

Three general processes of fabricating ceramics may be used: photoetching, ultrasonic machining, and electron beam machining.

25-2.3.1 Photoetched Ceramics

A process developed by Corning Glass Works in conjunction with the US Army Harry Diamond Laboratories uses a photographic technique with a thin sheet of silicate glass that contains a photosensitive ingredient such as the cesium radical, CE^{+3} . In the presence of ultraviolet light, the exposed glass absorbs the radiation, creating a print constant in depth. Post heating to 1200°F creates colloidal particles in the exposed areas. When dipped in hydrofluoric acid, the

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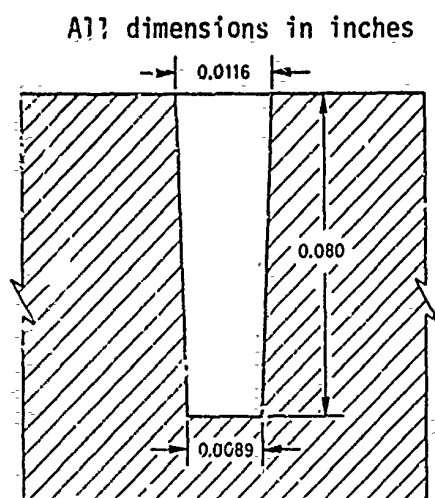


Figure 25-12. Cross Section of Typical Channel Etched in Photosensitive Glass³

exposed areas are etched away 20 to 30 times faster than the unexposed glass. With this process, the sides of a channel have a slope of less than 2.5 deg from the vertical, Fig. 25-12³. The channel is then, for all practical purposes, rectangular.

Typical nozzle dimensions for devices built by this technique are 0.020 by 0.080 in. Nozzles as small as 0.005 by 0.002 in. are accurately reproducible by the method. These nozzle widths are comparable to the diameter of a human hair.

Depth of the etching easily is controlled. With a 0.040-in nominal depth, variation in depths across a plate can be kept within 0.002 in. Across a single element, tolerances can be kept within 0.001 in. Tolerances on holes and channel widths up to 0.25 in. can be kept within 0.001 in. Up to 1 in., widths can be kept within 0.002 in. Up to 5 in., center-to-center distances can be maintained within 0.003 in.

Good surface finishes are attained by etching. A typical finish for a wall is 125 μ in. The bottoms are considerably smoother, 20

μ in. being a typical value. The larger value of 125 μ in. appears to be low enough to assure proper device performance.

Certain precautions are necessary in designing the pattern to be optically reduced. For example, nozzles should be designed at least 0.010 in. longer than the desired finished length because they etch from both ends. To produce a sharp splitter, the wedge must be designed with a radius on the end so that when the etching process is finished, the wedge has just eroded down to a sharp point. Narrow channels and small holes present problems. A fresh supply of acid cannot be maintained at the etching surface and erosion lags behind the expected rate.

When the fluidic circuit is etched, a covered plate must be sealed onto it. Various gaskets have been tried but have been abandoned in favor of sealing with an epoxy cement. For a more permanent seal, a glass cover plate can be fused onto the etched base.

The glass etching method gives excellent reproducibility. The technique has been developed to the point where variations in the etched base plates have a smaller effect on the device or circuit performance than does the effect of assembly variations.

These fluidic elements offer advantages of high dimensional stability, no moisture absorption, good shock resistance, and operating capabilities to temperatures of 1000°F. The process is summarized in Fig. 25-13³.

25-2.3.2 Ultrasonic Machining

Ultrasonic machining is used to work hard brittle materials, including ceramics. The method is based upon the concept of minute particle removal by fine abrasive particles traveling at high velocities. The pattern eroded is identical to the shape of the tool. The tool is held very close to the workpiece and vibrated at 15,000 to 30,000 Hz with an amplitude of 0.001-0.005 in. Between the

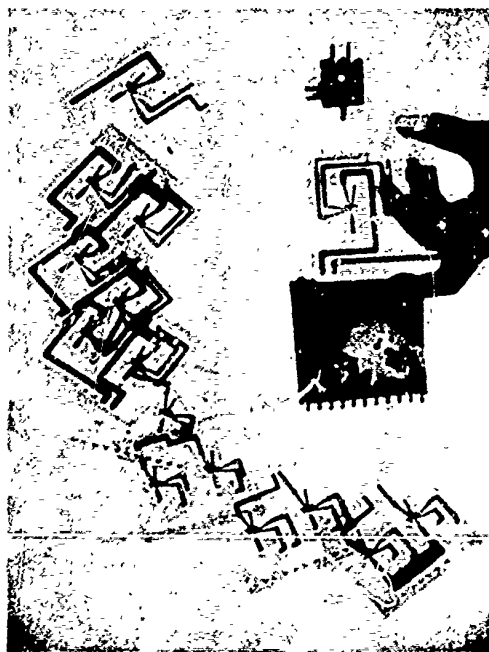
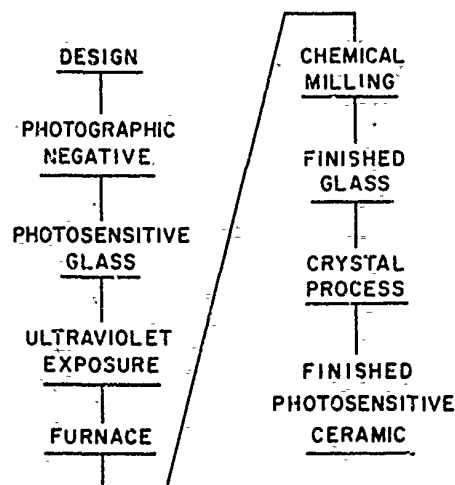


Figure 25-13. The Photoetching Process for Ceramics and Some Examples of Etched Photosensitive Ceramic²

tool and workpiece is a slurry containing the abrasive, such as boron carbide or aluminum oxide. The tool, made from cold-rolled or stainless steel, wears only slightly. No pressure is exerted on the workpiece by the tool. A typical setup is shown in Fig. 25-14².

25-2.3.3 Electron Beam Machining

Electron beam machining focuses a stream of electrons in a bundle about 0.001 in. in diameter with a cross-sectional density of 10^9 W/in.² on the workpiece and vaporizes the material it impinges upon. Removal rates are small (about 0.1 mg/sec) and only relatively small cuts are economically feasible. The process makes possible the production of quite precise and fine cuts of any desired contour in any material. Fig. 25-15² is a typical setup. The two major limitations are that (1) a vacuum of about 10^{-4} mm of mercury must be maintained within the chamber, and (2) X-ray shielding must be used. However, the capability of this process to cut 0.005-in. channels separated by 0.010 in. may be very important for microminiature devices.

25-3 SUMMARY

As indicated, fluoric devices can be formed from a variety of materials that are selected by the designer on the basis of performance properties. When production is considered, the economy of each process also must be weighed against other factors before a decision is made. Looking to the future, it appears that metals and ceramics will be used more often than plastics. Also, since the advent of microminiaturization, the requirements will be for processes that can fabricate

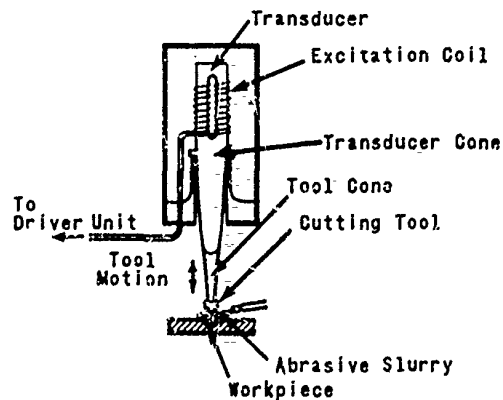


Figure 25-14. Ultrasonic Machining²

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TABLE 25-4

COMPARISONS OF VARIOUS FABRICATION TECHNIQUES FOR FLUIDIC DEVICES²

	Quantity Requirements			Element Design			Relative Economy
	Low	Medium	High	Complexity	Miniaturization	Accuracy	
Plastics							
Casting	E	G	F	G	F	G	F
Thermoforming	E	G	F	F	P	F	F
Photoetching	E	G	G	E	G	G	G
Injection Molding	P	F	E	G	G	G	E
Compression molding	P	F	E	G	G	G	E
Jet Molding	P	F	E	G	G	G	E
Transfer Molding	P	F	E	G	G	G	E
Metals							
Powder Metallurgy	P	G	G	G	F	G	F
Die Casting	P	F	E	G	G	G	G
Chemical Machining	G	E	F	E	E	E	F
Electroforming	G	F	P	E	G	E	F
Electrical Discharge Machining	P	G	G	G	F	G	F
Electrochemical Machining	F	G	G	G	G	G	G
Ceramics							
Photoetching	F	G	G	E	E	G	G
Ultrasonic Machining	P	F	G	G	G	G	P
Electron Beam Machining	P	P	G	E	E	E	P
E = Excellent G = Good F = Fair P = Poor							

complex precision parts of small size. Such processes include the photoetching techniques, chemical machining, and electron beam machining. These processes are also economically sound for mass production. Table 25-4² compares the various techniques

with some indication of the characteristics of each process. This table is by no means absolute but serves as a rough appraisal of the merits and limitations of each process according to present state-of-the-art fluid element fabrication techniques.

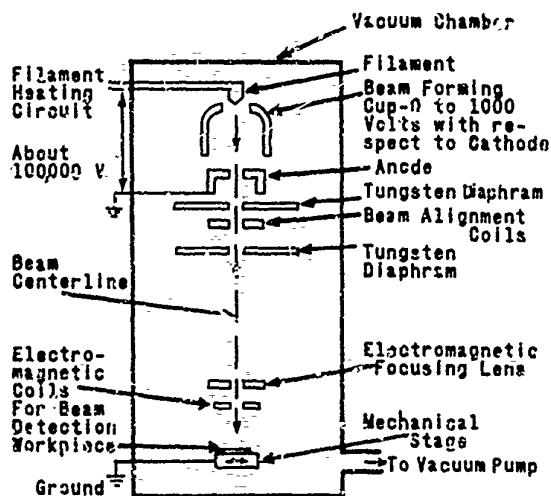


Figure 25-15. Electron Beam Machining²

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PART SIX — MISCELLANEOUS TIMING DEVICES

CHAPTER 26

ELECTROCHEMICAL TIMERS

Electrochemical timing devices are simple, small, low-cost items capable of providing delays from seconds to months.

These timers are somewhat similar to the corrosion delays used in early bomb fuzes. In the corrosion delays, the delay period is controlled by the time required for acid to dissolve a baffle and trigger an output¹. At constant temperature, the chemical action on which the delay depends is quite accurate. The Germans reported an accuracy of $\pm 3\%$ for the thrust cutoff in V-2 rockets. However, the reaction is very temperature sensitive, and there is no opportunity for temperature compensation in these devices. Therefore, the delay times obtained are not accurate in military applications where uniform operation is required over an extended temperature range.

While several electrochemical timers have been investigated for military applications, only the silver electroplating timer is in current use. This timer is convenient and reliable, and is therefore considered at length. Mention is also made of the solion and the mercury timer. For other, less common, and experimental electrochemical systems, see Ref. 2.

Because advantages and disadvantages differ for the various timer types, they are listed separately for each timer in the paragraphs that follow.

26-1 BASIC CONSIDERATIONS

26-1.1 ELECTROPLATING ACTION

The operation of electrochemical timers is based on Faraday's first two laws of electrolysis which state: (1) the amount of electrochemical decomposition is proportional to the quantity of electricity passed, and (2) the amounts of different substances deposited by a fixed quantity of electricity are proportional to their chemical equivalent weights. Mathematically, Faraday's two laws are expressed as³

$$W = \frac{E}{F} \int I dt, g \quad (26-1)$$

where

W = weight of deposit, g

E = equivalent weight of substance deposited, g

F = Faraday's constant = 96,000 C/g equivalent weight

$\int I dt$ = total number of coulombs, A-sec

Hence, when a solution is electrolyzed, the number of electrons received at the anode must equal the number delivered to the cathode. The ions arriving at the cathode are reduced (i.e., they obtain electrons) and those ions arriving at the anode are oxidized (i.e.,

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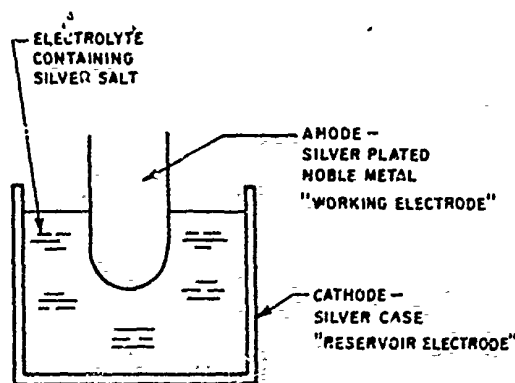


Figure 26-1. Silver Plating Action

they forfeit electrons). Electrochemical systems that obey these laws are called coulometric, and devices that use these principles are called coulometers.

We here are concerned specifically with the silver system, shown diagrammatically in Fig. 26-1. It consists of a silver case forming the cathode, a silver-plated anode of noble metal, and an electrolyte solution of a soluble silver salt. The anode is called the working electrode, the cathode, the reservoir electrode. These terms are needed because cell operation is reversible. As a matter of fact, the reversibility makes the electroplating system attractive as a timer. Operation is as follows: to start, the working electrode is unplated and the timer is set by passing a known time integral of current through it. During the timing cycle, the working electrode, now the anode, is depleted of its silver.

During the timing cycle, current flows through the cell to convert silver metal to silver ions at the anode ($\text{Ag} \rightarrow \text{Ag}^+ + e^-$). The ions then move to the cathode to replace the ions that have been reduced there ($\text{Ag}^+ + e^- \rightarrow \text{Ag}$). This deplating operation is preferred over plating because of its well-defined end point. During timing, while silver is being removed from the anode, cell impedance is low. The cell voltage drop will be about 0.01 to 0.1 V depending on cell temperature and other factors. When all the silver is expended, the

impedance rises rapidly and results in a sharp increase in voltage to about 1 V. This voltage step can be used as a circuit trigger. The electrolyte obeys Ohm's law like metallic conductors, except under abnormal conditions—such as very high voltage, very high frequencies, or strong concentration polarizations.

Since the chemical action is reversible, the timer can be run down, recharged, and rerun. This repeat action is ideal for testing and quality assurance purposes. However, there is a limit to the number of successful repeat cycles for some types of cell. After many cycles the timer becomes inaccurate. This is because of the exhaustion effect common to all electrochemical systems. The reversibility difficulty develops when the electrochemical oxidation-reduction process is disturbed by the "microscopic" early depletion of cations in a localized area. An overvoltage in this area then leads to the generation of hydrogen and other side effects. Although this process occurs for only a very brief time, perhaps only a microsecond in each cycle, the action is sufficient to lead to a general deterioration in the timing interval after a few cycles. On the other hand, a large number of good runs, as well as temperature independence for the timing cycle, is claimed for some of the newer cell types.

The ampere has been defined as that amount of current which, flowing for 1 sec, will deposit 1.118 mg of silver for each coulomb of charge. (This is why electroplating timers are called coulometers.) This same 1.118 mg of silver is deposited at 0.5A for 2 sec or at 310 μA for 1 hr. The general relationship, in customary units, is

$$t = \frac{C}{I}, \text{ hr} \quad (26-2)$$

where

t = time, hr

C = coulomb capacity, $\mu\text{A}\cdot\text{hr}$

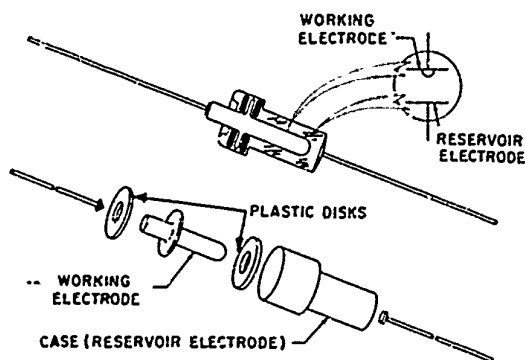


Figure 26-2. Bissett-Berman E-Cell⁵

I = current, μA

26-1.2 THE ELECTROPLATING SYSTEM

The electroplating system consists of three parts:

(1) A battery and its circuit which deliver a constant direct current. Batteries are affected by ambient temperature but variations in their output can be controlled by temperature-compensated electronic circuits. A uniform current is a prerequisite for accurate timer operation.

(2) An electroplating delay cell in which the constant current causes a chemical (silver) to react (be depleted) at a known rate (see par. 26-1.1).

(3) A detector that senses the relative progress of the reaction, usually the depletion of one of the chemicals (silver) from one of the electrodes.

Detection can be accomplished in several ways. In electrical readout the change in output voltage is sensed by means of a suitable detection circuit, in mechanical readout a motion results that can activate a switch or plunger to perform the desired output; visual readout permits the observation of a change in appearance, such as color of electrolyte or position of components. Mil-

tary timers with electrical and mechanical readouts are described in the paragraphs that follow. Visual readout has not been used in military devices but is described in pars. 26-4 and 26-5.

Note that electroplating systems integrate the product of current and time. The current need not be continuous but may be interrupted in which instance the cell still "counts" the cumulative product. Therefore, these devices can be used both as coulometers and as integrating accelerometers in which current is a function of acceleration.

26-2 ELECTROPLATING TIMER WITH ELECTRICAL READOUT

26-2.1 PRINCIPLE OF OPERATION

When a constant current is passed through the electroplating timer (preset coulometer), it deplates silver from the working electrode onto the reservoir electrode. The increase in voltage drop across the cell at the end of deplating is used for electrical readout. The principle is described in detail in par. 26-1.1.

26-2.2 CELL CONSTRUCTION

Coulometers are manufactured commercially by Gibbs⁴ and Bisset-Berman⁵, the latter calling its device an E-Cell. The E-Cell has been used in several military applications, such as providing the delay in the Antipersonnel Mine, BLU-54/B^{6,7}.

Cell construction is illustrated in Fig. 26-2⁵. The cell consists of a silver case (the reservoir electrode), 1/4 in. in diameter and 5/8 in. long. The working electrode of gold over base metal is held in place by two plastic disks that serve both as seals and electric insulators. The case is filled with electrolyte containing a silver salt in a weak acid⁸. Electrical leads complete the cell. Cell weight is about 0.1 oz.

The cell illustrated is a single-anode cell,

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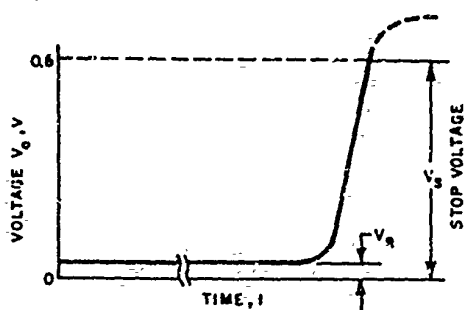


Figure 26-3. Operating Curve of Coulometer at Constant Current⁵

permitting a single time delay. When more than one delay is desired, several anodes of different sizes may be combined in the same unit⁹. The deplating of each anode results in a sharp increase in output voltage. 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 power requirements of E-Cells is low and accuracy of the timing interval is within $\pm 4\%$. One exception to this accuracy is for short-delay setting after long storage.

26-2.3 TIMER DESIGN

The design of an electroplating timing system, like that of all other multicomponent systems, requires repeated consideration of the characteristics of each component until a

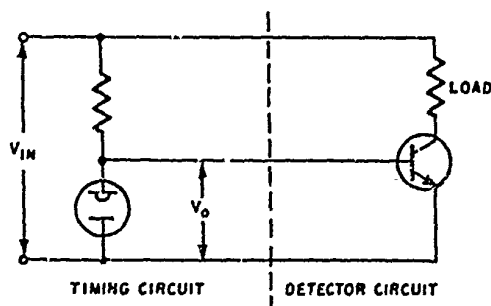


Figure 26-4. Coulometer Detector Circuit⁵

consistent combination is achieved. The first element, a source of constant DC current, is not discussed in this handbook. A special battery may be required if this power is not available from one of the circuits of the main system. Depending on the desired delay, current levels vary from about a microampere to a milliamperere.

The second element is the coulometer itself. Described in par. 26-2.2, it is available in a large variety of models and timing intervals. Before a specific cell can be selected, consideration must be given to the output detection circuit.

The output signal of the coulometer is a change in voltage. During the timing interval, the voltage is low, see Fig. 26-3⁵. Upon completion of anode deplating, the voltage rises rapidly thus indicating the end on the timing interval. One way to detect this voltage rise is by use of the simple detector circuit shown in Fig. 26-4⁵. The performance of this circuit is made clear by considering its three phases of operation:

(1) While the cell deplates, the run voltage V_R is below the activation voltage of the transistor. Since the cell therefore 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) When operating at the stop voltage V_s , the cell draws a very small residual current I_s , which in most cases is negligible compared with that drawn by the transistor. Thus, the equivalent circuit is essentially the original circuit without the coulometer.

Typical voltage-current characteristics at various operating temperatures are shown in Fig. 26-5⁵. Fig. 26-5(A) shows the maximum running (deplating) voltage and current while Fig. 26-5(B) shows the stop voltage and its

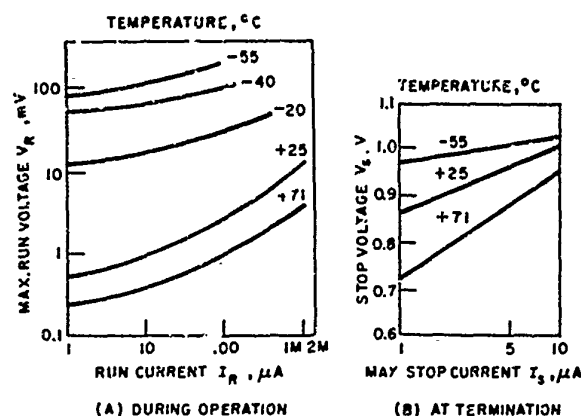


Figure 26-5. Typical Coulometer Voltage-current Characteristics⁵

associated current. The stop voltage V_s is associated with the activation voltage threshold of the transistor in the detection circuit while the stop current I_s is the residual current passing through the cell at that voltage. Since most circuits offer stop voltages of about 0.7 V, stop currents are about 1 μA . More sophisticated detection circuits can be considered to achieve other desired effects.

Given the required time delay and selecting a power source with a constant current in the microampere range, the designer obtains the capacity required from Eq. 26-2. The microampere-hour rating defines a particular coulometer.

Experimental solid-state types of coulometer are currently being developed¹⁰. Both the electrode and the electrolyte in these types are ionic pastes like those used in solid-electrolyte batteries. Operating in the same manner as the liquid-electrolyte device, they are small, rugged, and accurate within $\pm 5\%$.

26-2.4 ADVANTAGES AND DISADVANTAGES

The characteristics of the electroplating timer with electrical readout may be summarized as follows:

(1) Advantages:

- (1) Good accuracy (within $\pm 4\%$)
- (2) Good miniaturization
- (3) Simple and inexpensive
- (4) Wide variety of timing intervals
- (5) Very low power requirements
- (6) Good shock and vibration resistance
- (7) Operation over military temperature range

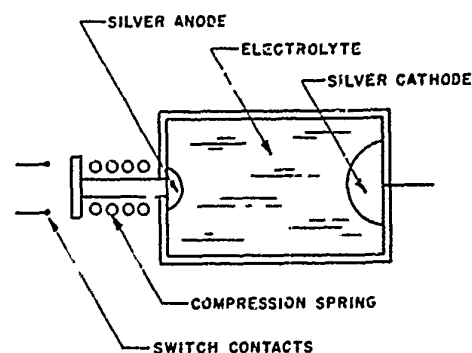


Figure 26-6. Electroplating Timer With Mechanical Readout

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- (8) Reusable several times (by deplating).
- (2) Disadvantages:

- (1) Detection circuit required
- (2) Decreased accuracy for short set times after long storage.

26-3 ELECTROPLATING TIMER WITH MECHANICAL READOUT

26-3.1 PRINCIPLE OF OPERATION

Electrochemically, the mechanical-readout timer operates in the same manner as the electrical-readout timer (see par. 26-1.1). At the end of deplating, however, the action differs. A schematic arrangement of a mechanical-readout timer is shown in Fig. 26-6. The cell consists of a silver anode that may be likened to the head of a pin, a silver cathode, and an electrolytic solution containing silver ions. When a constant current is passed through the electroplating timer, it deplates silver from the anode onto the cathode. At the end of the timing interval, the anode has been reduced in size to the diameter of the pin shaft. At that instant, the spring causes mechanical motion. By pushing against a flange at the other end of the pin, the spring pulls the pin out of the hole in the cell wall.

Because of the displacement of parts, the action of a mechanical-readout timer is not reversible. Whereas the timer in Fig. 26-6 illustrates the output of closing a switch, the output motion obviously can be applied to the opening or closing of several switches or to the operation of a plunger.

26-3.2 CELL CONSTRUCTION

Cell construction is illustrated in Fig. 26-7. This is the Interval Timer, MARK 24 MOD 3, a component of Firing Mechanism, MARK 42. Originally designed for use in a sonobuoy, it currently is incorporated in Destructor, MARK 36¹¹.

The timer cell (based on a patented idea¹²) consists of a molded polychlorotrifluoroethylene (Kel-F) cup that holds the anode assembly. After filling with an electrolyte of a silver fluoroborate solution, the cup is heat sealed with an end plug that holds the silver cathode. The anode assembly consists of a silver plunger to which a contact disk is fastened. 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 (1) closes an SPST (Single Pole, Single Throw) switch and (2) opens the anode switch so as to terminate the deplating action. The contact force at switch closure is 0.8 lb and contact resistance after switch closure is less than 0.3 ohm.

The timer is 5/8 in. in diameter, 1-5/8 in. long, and weighs 9 g. For some applications, the timer is sealed in Thermofit heat-shrink tubing (not shown in the figure). Timer accuracy under water (for which it was designed) at 28° to 90°F is $\pm 5\%$; over the entire military temperature range, accuracy is $\pm 10\%$. Models have withstood shocks as high as 12,000 g, low and high frequency vibrations, cold storage at -80°F, and temperature-humidity cycling.

Dual action, when required, is available from Interval Timer, MARK 25. This timer is essentially a dual MARK 24 timer. It closes two SPST switches by two separate contacts that operate from separate anodes. Construction and size are the same as for the MARK 24.

A commercial timer is shown in Fig. 26-8⁴. Its construction is similar to that of the MARK 24 timer. It also closes an SPST switch with gold-plated contacts. Body size is 5/8 in. by 7/8 in. Accuracy over the military temperature range is $\pm 10\%$.

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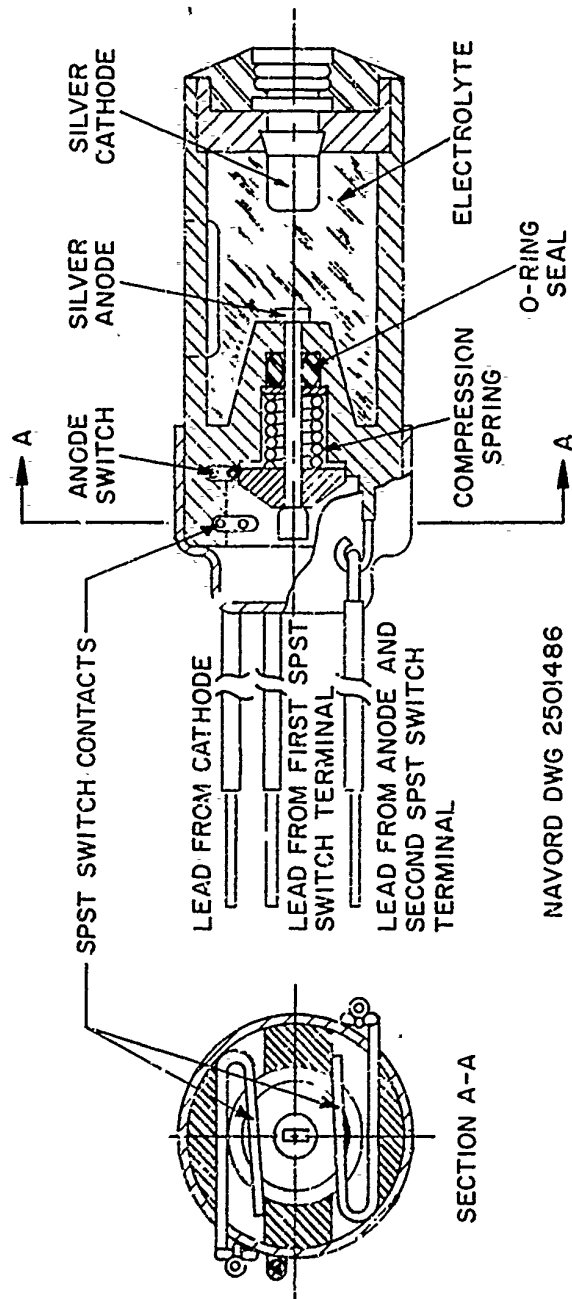


Figure 26-7. Interval Timer, MARK 24 MOD 3

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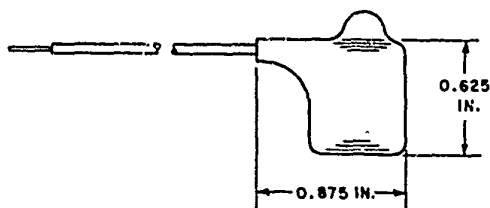


Figure 26-8. Mechanical Readout Timer by Gibbs

26-3.3 TIMER DESIGN

The design of a mechanical-readout timing system is simpler than that of an electrical-readout system. In effect, the mechanical-readout system has only two elements, a source of constant DC current and the coulometer itself. The output of the coulometer is the operation of a switch or plunger, and no separate output circuit is required.

Depending on the delay desired, the battery current level varies from a micro-ampere to a milliamperere. In the MARK 24 and MARK 25 timers current flow is regulated by the voltage applied and a precision resistor connected in series with the cell. Operating time is computed by

$$t = \frac{CR}{V}, \text{ hr} \quad (26-3)$$

where

t = time, hr

C = coulomb capacity, A-hr

R = resistance, ohm

V = voltage, volt

For the MARK 24 timer, $C = 0.005$, and for the MARK 25, $C = 0.01$. By varying voltage, resistance, or both, delays of 5 min to 30 days can be achieved.

26-3.4 ADVANTAGES AND DISADVANTAGES

The characteristics of the electroplating timer with mechanical read-out may be summarized as follows:

(1) Advantages:

- (a) Simple and inexpensive
- (b) Low power requirements
- (c) Good shock and vibration resistance
- (d) Operation over military temperature range
- (e) No detection circuit required.

(2) Disadvantages:

- (a) Not reversible
- (b) Difficult to seal.

26-4 SOLION

26-4.1 PRINCIPLE OF OPERATION

The solion is an electrochemical timer using an oxidation-reduction system that uses ions in solution instead of electrons as the charge carriers. Solions have found application mainly as diodes with both electrical and visual readout. They also have been designed as tetrodes and used as electrical amplifiers and general-purpose integrators. The electrolyte contains a specified amount of iodine and a comparatively large amount of potassium iodide². Hence, the solution contains triiodide I_3^- .

Shown schematically in Fig. 26-9³, the solion timer consists of two identical compartments separated by a semipermeable diffusion barrier. When current is passed

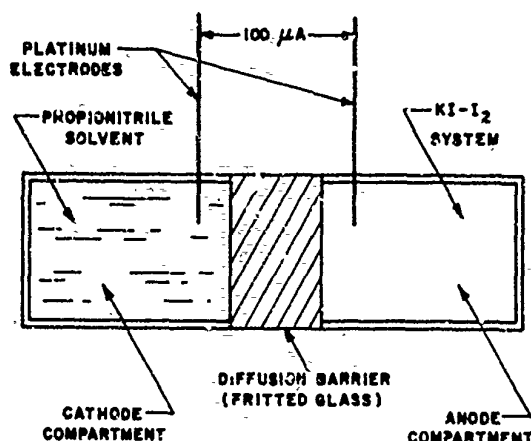


Figure 26-9. Solion Timer

through the cell, iodine is reduced in the cathode compartment ($I_3^- + 2e^- \rightarrow 3I^-$), and the iodide ion is oxidized in the anode compartment ($3I^- \rightarrow I_3^- + 2e^-$). The net result is that iodine is transferred to the anode compartment. The amount of iodine transferred is proportional to the time and current, and the conductivity of the electrolyte is proportional to iodine concentration, permitting an electrical readout. The color of the electrolyte is also a function of iodine concentration, so that visual readout is possible.

The polarization curves for the solion are shown in Fig. 26-10³ for five different

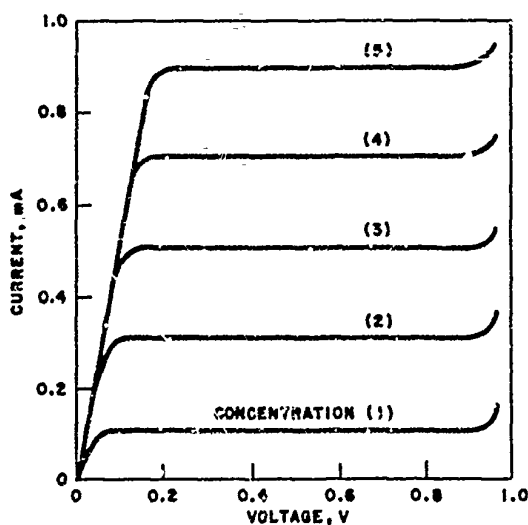


Figure 26-10. Typical Polarization Curves for the Solion

concentrations of the tri-iodide ion. Note that Ohm's law breaks down in the solion; the current and cell resistance maintain a constant value with increasing voltage up to approximately 1 V, where the oxidation-reduction on process terminates and Ohm's law resumes. The resistance of the solion cell varies exponentially.

For timing purposes, the electrical readout is not entirely satisfactory because the step function at the point of exhaustion of iodine ions is uncertain and inaccurate. The end points varied 162 parts per thousand at room temperature, and the device ran even slower at -25° and $65^\circ C^2$. Repeat cycles are limited by the exhaustion effect (see par. 26-1.1).

The solion has been reported to withstand vibration in all three axes, from rest to 50 g at 0 - 2000 Hz, with displacements as large as 0.5 in. Solions have been stored over a year without any detectable deviation in operational ability.

26-4.2 ADVANTAGES AND DISADVANTAGES

The characteristics of the solion may be summarized as follows:

(1) Advantages:

- (a) Good miniaturization
- (b) Good shock and vibration results
- (c) Low power requirements
- (d) Good storage potential
- (e) Current controlled by conditions at the cathode only.

(2) Disadvantages:

- (a) Poor accuracy (about $\pm 20\%$)
- (b) Uncertain time end point
- (c) Exponential resistance characteristics

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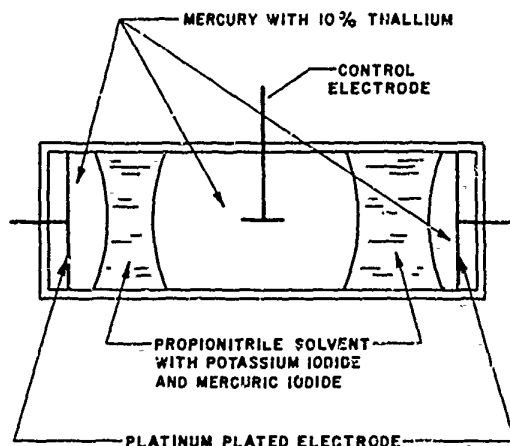


Figure 26-11. Mercury Timer

(d) Low frequency response (lower than that of transistors by a factor of 10^6)

(e) Degeneration of timing interval

(f) Limited temperature range.

In summary, the solion lacks precision and will not function over the military temperature range. While the solion has some commercial applications, it has not been used in a military device.

26-5 MERCURY TIMER

26-5.1 PRINCIPLE OF OPERATION

This device operates by transporting mercuric ions through a solvent that separates two bodies of mercury, eventually exhausting one of the mercury reservoirs. The chemical equations associated with the reaction are $4I^- + Hg \rightarrow HgI_4^{2-} + 2e^-$ for the anode and $HgI_4^{2-} + 2e^- \rightarrow Hg + 4I^-$ for the cathode.

Shown schematically in Fig. 26-11³, the mercury timer consists of a cell, often a glass tube, with anode and cathode at the ends and a control electrode in the center. Three pellets of mercury are shown, separated by two bodies of electrolyte consisting of an iodine solution. Upon current passage through the

cell, mercury is electroplated from the anode through the electrolyte to the cathode. Buildup of mercury at the cathode causes the electrolyte gap to approach and—at the end of the delay—contact it, at which time the voltage drops to permit an electrical readout. Visual readout also is provided by observation of mercury pellet motion.

The mercury timer operates with a current of 50-100 μA . Operation is reversible except that the number of cycles is limited by the exhaustion effect (see par. 26-1.1).

Difficulties appear when an attempt is made to operate the mercury timer over the military temperature range. These include (1) the necessity for lowering of the freezing point for the cell contents because operation when frozen is destructive (mercury freezes at $-38^\circ F$), (2) mercury expansion problems, and (3) electrolyte-mercury interface difficulties experienced with changing temperatures.

The relatively high coefficient of expansion of mercury creates the danger of a cracked housing when the environmental temperature is increased; the same coefficient of expansion will threaten the mercury-solvent interface when lower temperatures are encountered. Also, difficulties have been reported with the deposit of mercury on the end terminals³.

The mercury timer has withstood vibration and shock tests including a 150-g shock, a continuous 16-g acceleration, and 15-g vibration at 5000 Hz on all axes. A sloshing effect is reported due to resonance at 400-600 Hz.

26-5.2 ADVANTAGES AND DISADVANTAGES

The characteristics of the mercury timer may be summarized as follows:

(1) Advantages:

(a) Good accuracy (over narrow temperature range)

- (b) Good miniaturization
- (c) Low power requirements.
- (2) Disadvantages:
 - (1) Limited temperature range
 - (2) Fragile
- (3) Occasional sloshing effect
- (4) Setting required before operation can begin.

In summary, the mercury timer is delicate and cannot operate over the military temperature range. While the timer has some commercial applications, it has not been used in a military device.

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CHAPTER 27

NUCLEAR DECAY TIMERS

A low-frequency, high-accuracy time base may be constructed by making use of the decay of a radioactive substance in conjunction with a particle detector. In addition, electronic circuitry is required to produce a usable timer. Although nuclear decay is randomly distributed in time, accuracy can be obtained by sampling a sufficiently large number of counts. One significant advantage of the nuclear timer is that its time base rate is independent of temperature and other environmental variations. Fig. 27-1 shows the block diagram for a nuclear decay timer.

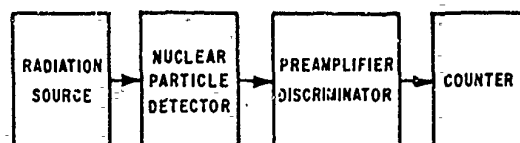


Figure 27-1. Elements of Nuclear Decay Timer

ionization process thus providing signals from the detector of approximately equal pulse heights.

27-1 RADIATION SOURCE

27-1.1 DESIRABLE PROPERTIES

To be useful for a nuclear time base generator, the radiation source should have the following properties:

- (1) Monoenergetic particles
- (2) Highly ionizing particles
- (3) Long half-life
- (4) Decay products producing little radiation
- (5) Capability for permanent mounting
- (6) Ready availability.

The radiation should be nearly monoenergetic to provide for ready discrimination between output pulses produced by the detectors, and the internally generated noise in the detectors and amplifiers. All monoenergetic particles will lose approximately the same proportion of their energy in the

Highly ionizing particles increase the signal-to-noise ratio and minimize the degree of amplification required to reach the input level of electronic scalars. There should be no significant change in the disintegration rate of the radiation source during its predicted use and storage life. Therefore, the source should have a long half-life. Fig. 27-2¹ may be used to estimate the half-life required of the radiation source, once the operation and storage periods and acceptable decrease in activity have been fixed. For example, if the radiation source is to retain 99% of its activity after a period of 10 yr, a source with a half-life greater than 6.3×10^2 or 630 yr should be chosen. A more exact estimate may be made from the following equations¹

$$N = N_0 e^{-\lambda t} \quad (27-1)$$

where

N = radioactivity at time t

N_0 = initial radioactivity

λ = decay constant, yr^{-1}

t = time span, yr

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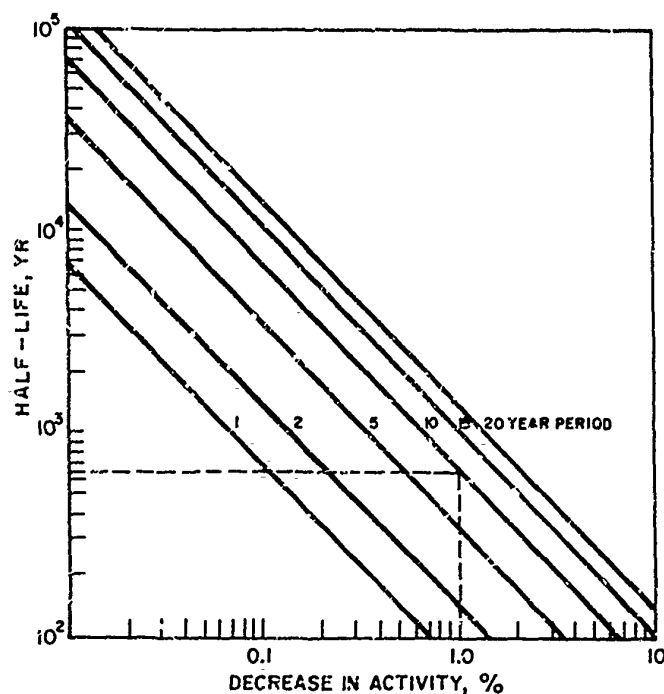


Figure 27-2. Decrease in Radioactivity as a Function of Use and Storage Period

$$T_{1/2} = \frac{0.693}{\lambda} \quad (27-2)$$

where $T_{1/2}$ = half life, yr

27-1.2 TYPES OF RADIATION

Four natural forms of radiation could be considered for this application: X rays, gamma rays, beta particles, and alpha particles.

Gamma rays and X rays are essentially the same radiation form and differ only in the manner in which they are produced. They are a highly penetrating radiation and therefore would be difficult to apply safely in a miniature timer because of the protective shielding required; also timer geometry could not be arranged conveniently to provide shielding.

Beta particles are high velocity electrons. The penetration characteristics of beta particles would require only a minimum of

shielding, a few millimeters of aluminum. However, beta particles are not monoenergetic. The particles emitted from a particular radioisotope would have a continuous distribution of energies and would be difficult to use because of the signal-to-noise ratio problem in detectors.

Alpha particles are identical with the nucleus of a helium atom, consisting of two protons and two neutrons. These particles are emitted from the nucleus of certain of the heavy radioactive elements. Alpha particles have a discrete energy which, depending upon the producing isotope, are in the range 4 to 10 MeV. The shielding required for alpha particles is simple, several sheets of paper providing adequate shielding in nearly all instances. Alpha particles are strongly ionizing.

Considering the characteristics of each type of radiation, it is apparent that alpha particles are most suitable for use in a nuclear timer.

TABLE 27-1

**RADIOISOTOPES APPLICABLE TO NUCLEAR
TIME BASES**

Radioisotope	Half-Life, yr	Specific Activity, curie/g
Uranium 235	7.1×10^8	2.15×10^{-6}
Neptunium 237	2.2×10^6	6.89×10^{-4}
Uranium 238	4.5×10^9	3.34×10^{-7}
Plutonium 239	2.4×10^4	6.17×10^{-2}

27-1.3 RADIOISOTOPES

Selection of the radioisotope for use in the time base can be made based on the requirements discussed:

- (1) A source of alpha particles
- (2) Half life sufficiently long for operational requirements
- (3) Energy level (specific activity) high enough for reliable detector operation.

Table 27-1¹ lists radioisotopes that may be considered for nuclear time base applications.

27-2 NUCLEAR PARTICLE DETECTOR

The radiation detector used in the nuclear timer provides an electrical signal for each radiation event it detects. Radiation detectors presently in use include ionization chambers, proportional counters, Geiger-Mueller counters, scintillation counters, and semiconductor radiation detectors. Ionization chambers, proportional counters, and Geiger-Mueller counters operate on similar principles and are included in the general class of gas tube counters.

27-2.1 GAS TUBE COUNTERS

These counters usually consist of a cylindrical gas filled chamber and a central electrode that is insulated from the chamber.

The chamber wall is made from a high work-function material, such as stainless steel or nickel. In a typical gas tube counter, the central electrode is usually about 0.003 in. in diameter, a compromise between physical strength and a high field strength near the electrode at a relatively low supply voltage.

With the central electrode serving as the anode and the chamber wall as the cathode, a voltage is applied to the tube. When ionizing radiation passes through the gas, the positively charged ions resulting from the ionization are attracted to the cathode where they are neutralized while the negative charges or electrons travel toward the anode.

While gas tube counters could be applied to military timers, each type presents some difficulties that must be recognized:

(1) The output pulse of the *ionization chamber* is independent of the operating voltage, provided the operating voltage is high enough so that recombination is negligible and low enough so that no secondary ionization occurs. The amplification factor is therefore unity. Thus a relatively large chamber (at least 3.5 cm long) is required.

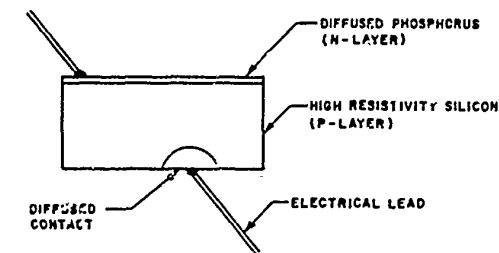
(2) The amplification in a *proportional counter* is a strong function of gas pressure. In the fixed-volume chamber, pressure varies significantly over the military temperature range.

(3) *Geiger-Mueller* counters have an inherent recovery time that makes their response slower than desirable.

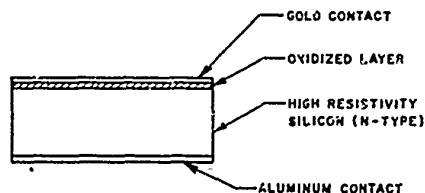
27-2.2 SCINTILLATION COUNTERS

The operation of a scintillation counter is based on the fact that in certain materials the ionization and excitation processes caused by nuclear radiation are accompanied by the emission of light or scintillations. The light photons are absorbed by the cathode of a photomultiplier tube that then emits photoelectrons to produce a current pulse.

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(A) DIFFUSED JUNCTION DETECTOR



(B) SURFACE BARRIER DETECTOR

Figure 27-3. Semiconductor Radiation Detectors

Since photomultiplier tubes are very sensitive to shock, require a well-regulated, high-voltage power supply, and exceed the volume limits of military items, scintillation counters are not suited for the nuclear time base.

27-2.3 SEMICONDUCTOR RADIATION DETECTORS (SRD)

A relatively new detector, the SRD, is described in several recent references^{2,3}. The SRD can be classified as a semiconductor junction detector. Its usefulness results from exploiting the phenomena occurring at the junction of two special types of material when placed together. Very pure, single-crystal silicon is used as one of the materials while the other material varies with the type of detector. Fig. 27-3¹ shows a diffused junction and a surface barrier detector. Details of construction vary with different manufacturers.

A diffused junction detector usually is prepared by diffusing phosphorus onto the surface of a pure wafer of p-type silicon. The diffusion depth is on the order of one micron and constitutes the n-layer of the diode. In the surface barrier detector, surface states are allowed to form by spontaneous oxidation on the surface of a pure wafer of n-type silicon. The formation of the oxide takes place through an evaporated gold layer that is provided for electrical contact. An inversion layer is thus formed having electrical properties similar to those of the diffused layer in a diffused junction detector. In this case the oxide layer acts as the p-type side of the diode junction.

Electrical leads to the associated electronics are attached easily to the front surfaces of both of these detectors because both the diffused and the gold surfaces are highly conductive. For the back contact to the SRD care must be taken to avoid any sharp change in resistivity that would result in the formation of a rectifying barrier. Two solutions to this problem are:

- (1) Doping a portion of the silicon bulk with an impurity to lower surface resistivity.
- (2) Evaporating a thick layer of aluminum onto the back surface.

The inherent energy resolution of SRD's is better by a factor of ten than that of gas tube counters. The counting rate of SRD's is limited only by the external electronics. SRD's can be made much smaller than gas tube counters, and they are more immune to physical damage due to shock. The main difficulty in the SRD approach is obtaining a detector that provides a sufficiently large signal-to-noise ratio over the military temperature range.

27-3 ASSOCIATED ELECTRONICS

Associated electronics must be included in

the time base system because the nuclear particle detector itself cannot provide an output usable by the counting circuits. The detector output must be amplified. The output is on the order of millivolts but a signal on the order of volts is desired by the counter. Since the capacitance of the detector varies with temperature, it is not desirable to have the voltage output of the amplifier depend on detector capacitance. Rather, a charge-sensitive preamplifier should be used that has a negative charge feedback to the input capacitance through a small capacitor (about 5 pF)⁴.

In addition to amplification, a means of discriminating between the pulses to be

counted and the inherent noise levels of the detector and the amplifier must be provided. Nuclear time bases use integral rather than simple discrimination². The function of simple discriminators is to pass only pulses exceeding a preset threshold level, whereas differential discriminators pass pulses having amplitudes with a preset "window" above the threshold.

A serious disadvantage of a nuclear time base is the relatively long calibration time required. For typical values of 1000 Hz and 0.1% accuracy, calibration time is 4000 sec. This compares with 10 sec per reading of electronic, electromechanical, or mechanical time bases.

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1. D. E. Voeller, *A Nuclear Time Base-Feasibility Study*, US Army Harry Diamond Laboratories, Washington, D.C., Report TR-1300, 12 Auguts 1965 (AD-622 629).
2. W. J. Price, *Nuclear Radiation Detection*, Second Edition, McGraw-Hill, Inc., N.Y., 1964.
3. G. Dearnaley and D. C. Northrup, *Semiconductor Counters for Nuclear Radiations*, John Wiley and Sons, N.Y., 1963.
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APPENDIX A

BOOLEAN ALGEBRA APPLIED TO LOGIC CIRCUITS

Boolean algebra is the algebra of propositions that are permitted to be either true or false. Thus it is useful for the combination, manipulation, and simplification of control functions that can be represented by variables whose values are limited to discrete binary digits 0 and 1. These digits represent the two states of many common binary or bistable devices—e.g., nonconductive or conductive, discharged or charged, current on or off.

The basic building block used in the design of the logical elements of fluoric and electronic timing systems is the *gate*. A gate is "a circuit having an output and a multiplicity of inputs so designed that the output is energized when and only when a certain definite set of input conditions are met"¹. Gates can perform various arithmetic operations and control functions. The theory of gating networks is expressed conveniently in Boolean notation. Note that logic circuits for electronic timers are discussed in par. 11-4.2 and those for fluoric timers in par. 24-5.

Fig. A-1² shows the symbol of an AND gate. The gate receives two input signals A and B and generates an output function C only when both A and B are present. Fig. A-1 also shows a switch analogy of the gate; lamp C lights only when A and B are closed. AND functions also are termed logical multiplications; a dot is used as the AND symbol. The

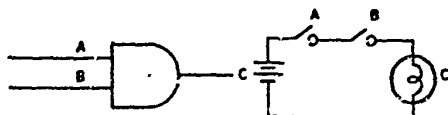


Figure A-1. Symbol and Switch Analogy for AND Gate²

following symbolizes that A and B produce C:

$$A \cdot B = C \quad (\text{A-1})$$

The basic OR gate is shown in Fig. A-2². If either A or B is present (switch closed), there is an output C. OR functions are termed logical addition; the symbol used is a plus sign. The following symbolizes that A or B produces C:

$$A + B = C \quad (\text{A-2})$$

A third basic operation is the inversion or *not* function (Fig. A-3²). The symbol is a bar over the function, viz., $\bar{A}$ means that A is not present (equals 0). The *not* function inverts the state of the bistable function—i.e., it transforms a 1 into a 0 and vice versa.

The logic associated with EXCEPT, NOR, and other logical decisions can be built up from the basic logic functions of AND, OR, and their inversions.

Consider the statement: *not* A AND *not* B. Fig. A-4² shows a possible presentation. Note that both A and B are inverted to get *not* A AND *not* B. The mathematical expression is

$$\bar{A} \cdot \bar{B} = C \quad (\text{A-3})$$

The figure also shows *not* (A AND B)

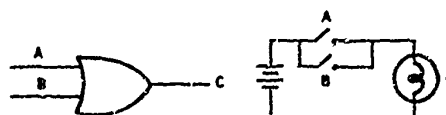
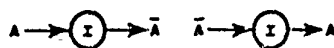
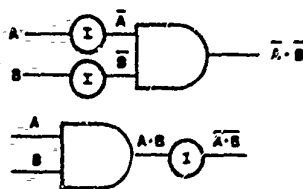


Figure A-2. Symbol and Switch Analogy for OR Gate²

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Figure A-3. not Symbol is Bar Over Letter²

expressed as $(\bar{A} \cdot \bar{B})$ which does not equal $\bar{A} \cdot \bar{B}$. This fact is made clear by the Venn diagram (Fig. A-5²) wherein all areas of true conditions are shaded while false areas are left blank.

Figure A-4. Symbolic Representation of not A AND not B, also not (A AND B)²

A list of Boolean postulates and equations is given in Table A-1³. The analogy between electrical, fluoric, and electromechanical systems for the basic gates in logic is contrasted in Fig. A-6. The recommended symbols for logic diagrams are contained in Ref. 4 while fluoric symbols are contained in Ref. 5.

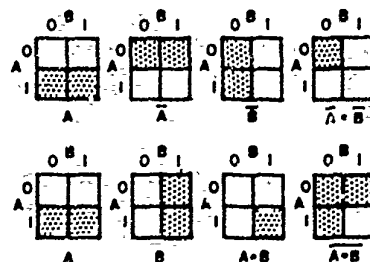
Figure A-5. Venn Diagram for Fig. A-4²

TABLE A-1

BOOLEAN POSTULATES AND EQUATIONS³

- | | |
|---|--------------------------------|
| 1. $A + A = A$ | Absorption rule for + |
| 2. $A \cdot A = A$ | Absorption rule for · |
| 3. $A + B = B + A$ | Commutative rule for + |
| 4. $A \cdot B = B \cdot A$ | Commutative rule for · |
| 5. $(A + B) + C = A + (B + C)$
$= A + B + C$ | Associative rule for + |
| 6. $(A \cdot B) \cdot C = A \cdot (B \cdot C)$
$= A \cdot B \cdot C$ | Associative rule for · |
| 7. $A \cdot (B + C) = A \cdot B + A \cdot C$ | Distributive rule for · over + |
| 8. $\frac{A + B \cdot C}{A + B} = \frac{(A + B) \cdot (A + C)}{A + B}$ | Distributive rule for + |
| 9. $\frac{A \cdot B}{A + B} = \frac{\bar{A} + \bar{B}}{A + B}$ | De Morgan's rule for · |
| 10. $A + B = A \cdot B$ | De Morgan's rule for + |
| 11. $A + \bar{A} = 1$ | |
| 12. $A \cdot \bar{A} = 0$ | |
| 13. $0 + A = A$ | |
| 14. $0 \cdot A = 0$ | |
| 15. $\bar{\bar{A}} = A$ | |
| 16. $A \cdot \bar{A} = 0$ | |
| 17. $A + \bar{A} \cdot B = A + B$ | |
| 18. $A + \bar{A} \cdot B = A + B$ | |
| 19. $A \cdot \bar{B} + B \cdot C + C \cdot A = (A + B) \cdot (B + C) \cdot (C + A)$ | |
| 20. $\bar{\bar{A}} \cdot B + A \cdot C + B \cdot C = A \cdot B + B \cdot C$ | |
| 21. $\bar{\bar{A}} = A$ | |

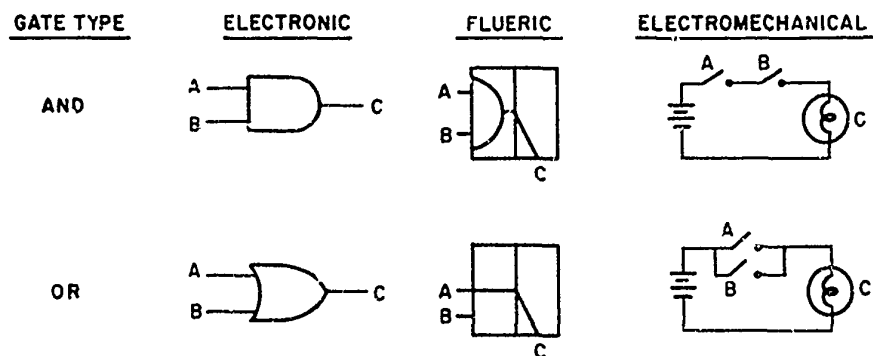


Figure A-6. Symbols for the Basic Gates

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3. *Fluidic Systems Design Guide*, Fluidonics Division of the Imperial-Eastman Corp., Chicago, Ill., 1966.
4. MIL-STD-806B, *Graphic Symbols for Logic Diagrams*, Dept. of Defense.
5. MIL-STD-1306, *Fluerics, Terminology and Symbols*, Dept. of Defense.

GLOSSARY

This glossary is restricted to key terms for timing systems and components. Additional terms may be found in the following references:

MIL-STD-444, *Nomenclature and Definitions in the Ammunition Area*, Department of Defense, Change 2, 9 July 1964.

MIL-STD-1306, *Fluerics, Terminology and Symbols*, Department of Defense, 17 July 1968.

AMCP 706-210, *Engineering Design Handbook, Fuzes*.

IRE Dictionary of Electronic Terms and Symbols, Institute of Radio Engineers, Inc., N.Y. 1961.

Eric Bruton, *Dictionary of Clocks and Watches*, Arco Publications, London, 1962.

Amplifier. An active electric or fluoric component that increases the strength of the signal applied to it.

Arming. The changing from a safe condition to a state of readiness for functioning. Generally a fuze is caused to arm by one or a combination of means as acceleration, rotation, mechanical drive, chemical action, electrical action, or air travel.

Atomic Clock. A timer that employs as its frequency regulator the vibration of the cesium atom. The atomic clock is the most accurately known frequency standard because the radio frequencies emitted by atoms and molecules at low pressures are fixed and unchanging with time and independent of temperature.

Balance Spring. A fine spring, usually spiral, used for oscillating the balance wheel of a

clockwork. Also called hairspring.

Balance Wheel. A balance for clockworks to regulate their beat. It is usually shaped like a wheel.

Bistable Device. A device that has two stable states, such as current on or current off.

Cesium Beam Resonator. A device which utilizes the transition of the cesium atom designated as $Fm(4,0) \leftrightarrow (3,0)$. The frequency of oscillation has been established as 9,192,631,770 cycles per ephemeris second.

Counter. A device capable of changing from one to the next of a sequence of distinguishable states upon each receipt of an input signal.

Delay. An explosive train component that introduces a controlled time delay in the functioning process.

Delay, Arming. (1) The interval expressed in time or distance between the instant an item of ammunition carrying a fuze is launched and the instant the fuze becomes armed. (2) The time interval required for the arming process to be completed in a nonlaunched item of ammunition.

Delay, Functioning. The interval expressed in time or distance between initiation of the fuze and detonation of the main charge.

Ephemeris Time. Time calculated from the orbit of the earth around the sun (as opposed to the rotation of the earth). Ephemeris time has been adopted as the fundamental unit of time.

Escape Wheel. The last wheel in the gear train

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of a clockwork which is controlled by the escapement.

Escapement. The part of a mechanical clockwork which regulates the rate of transmission of energy. *See also:* specific escapements.

Escapement, Self-starting. An escapement that has the ability to start oscillating, without an external force, from any rest position, and to sustain the oscillations as long as energy is supplied.

Escapement, Tuned. An escapement consisting of a pivoted balance mass and a restoring spring, pulsed by an escape wheel.

Escapement, Untuned. An escapement consisting of a pivoted mass driven by an escape wheel. The mass oscillates without a spring.

Explosive Train. A train of combustible and explosive elements arranged in the order of decreasing sensitivity. Its function is to accomplish the controlled augmentation of a small impulse into one of suitable energy to cause the main charge of the ammunition to function. A fuze explosive train may consist of a primer, a detonator, a delay, a relay, a lead, and a booster charge, one or more of which may be either omitted or combined.

Failure Diameter. The minimum diameter of an explosive cylinder which will sustain propagation in the axial direction. Below this diameter, propagation is retarded or extinguished due to radial heat losses.

Feedback. The return to the input of a part of the output of a device, system, or process.

Flip-flop. A bistable device.

Fluidics. The area within the field of fluidics, in which fluid components and systems perform sensing, logic, amplification, and control functions without the use of moving mechanical parts.

Fluidica. The general field of fluid devices

and systems and the associated peripheral equipment used to perform sensing, logic, amplification, and control functions.

Fuze. A device with explosive components which initiates a train of fire or detonation in an item of ammunition by an action such as hydrostatic pressure, electrical energy, chemical action, impact, mechanical time, or a combination of these.

Fuze, Time. A fuze that can be preset to function after the lapse of a specified time.

Gear Train. An arrangement of two or more gears meshing to transmit power from a driving shaft to a driven shaft at a different speed or in a different direction.

Hair Spring. *See:* Balance Spring.

Igniter. (1) Any device, chemical, electrical, or mechanical, used to ignite. (2) A specially arranged charge of a ready-burning composition, usually black powder, used to assist in the initiation of a propelling charge. (3) A device, containing such a composition, used to amplify the initiation of a primer in the functioning of a fuze.

Initiator. A device used as the first element of an explosive train, such as a detonator or squib, that, upon receipt of the proper mechanical or electrical impulse, produces a burning or detonating action. It generally contains a small quantity of a sensitive explosive.

Integrator. A device that sums discrete or variable quantities over some specified range of the selected or independent variable.

Junghans Escapement. A type of tuned, two-center escapement named after its original designer.

Logic Device. One of the general category of devices that perform logic functions; for example, AND, NAND, OR, and NOR. They can permit or inhibit signal transmission with certain combinations of control signals.

Loran. A long-range pulsed radio aid to navigation, the position lines of which are determined by the measurement of the difference in the time of arrival of initially synchronized pulses.

Monostable Device. A device with one stable and one astable state. When triggered, it goes from the stable to the astable state, and later returns to its stable state.

Oscillator, Electronic. A circuit for producing an alternating waveform, the output frequency or repetition rate of which is determined by the internal characteristics of the device.

Oscillator, Fluoric. A fluoric device for producing a periodic change in fluid pressure, velocity, etc. The output frequency or repetition rate is determined by the internal characteristics of the device.

Pallet. The part of an escapement which intercepts the teeth of the escape wheel.

Primer. A relatively small and sensitive initial explosive train component that, on being actuated, initiates functioning of the explosive train but will not reliably initiate high explosive charges.

Pyrotechnic Composition. A physical mixture of finely powdered fuel and oxidant, with or without additives, to produce heat, light, smoke, or special effects when ignited. The mixture is consumed in the process of burning.

Relay. An explosive train component that provides the required explosive energy to initiate reliably the next element in the train. It is especially applied to small charges that are initiated by a delay element and, in turn, cause the functioning of a detonator.

Runaway Escapement. An untuned, two-center escapement in which the escape wheel drives an inertial mass alternately clockwise and counterclockwise. The oscillatory motion of the mass regulates the escape wheel motion. Also called verge escapement.

Safing and Arming Device. A mechanism that prevents or allows an explosive train to operate.

Setback. The relative rearward force of inertia which is created by a forward acceleration of a projectile or missile during its launching phase. Setback is directly proportional to the acceleration and mass of the parts being accelerated.

Sidereal Time. The time of the rotation of the earth as measured from a clock star, instead of from the sun.

Solion. An electrochemical timer based on an oxidation-reduction process that uses ions in solution instead of electrons as the charge carriers.

Spin. The rotation of a projectile or missile about its longitudinal axis to provide stability during flight.

Timer. A programming device that controls the time interval between an input signal and an output event or events. *See also:* specific timers.

Timer, Analog. A timer that obtains its programmed time delay by directly measuring the magnitude of some continuously variable parameter, often the rise in voltage from zero to some predetermined value.

Timer, Digital. A timer (1) having a numeric display of the time, or (2) measuring time by counting the output pulses of an oscillator.

Timer, Electronic. A timer using electronic digital or analog elements.

Timer, Electrochemical. A timer based on the constant rate of a chemical reaction at a constant current.

Timer, Fluoric. A timer using fluoric digital or analog elements.

Timer, Interval. A timer that switches electric circuits on or off for the duration of the preset time interval.

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Timer, Mechanical. A timer based on the constant rate of a clockwork escapement.

Timer, Pyrotechnic. A timer based on the linear burning of a column of pyrotechnic delay material.

Timer, Sequential. A timer in which either each interval is initiated by the completion of the preceding interval or a sequence of timed outputs is produced. The intervals may be adjusted independently.

Transducer. A device that converts signals from one medium to an equivalent signal in a second medium.

Universal Time. The time calculated from the rotation of the earth (i.e., Greenwich Mean Time) but corrected for certain irregularities, including movement of the earth's axis and rotation.

Verge Escapement. See: Runaway Escapement

Wall Attachment. The phenomenon in flueric devices in which a fluid stream flowing close to a surface is deflected to that surface even if the surface is at a considerable angle to the original direction of flow.

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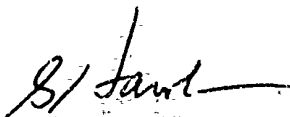
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