ENGINEERING DESIGN HANDBOOK

MILITARY PYROTECHNICS SERIES

PART FOUR

DESIGN OF AMMUNITION FOR PYROTECHNIC EFFECTS

HEADQUARTERS, US ARMY MATERIEL COMMAND MARCH 1974

CORRECTED
COPY

DEPARTMENT OF THE ARMY
HEADQUARTERS UNITED STATES ARMY MATERIEL COMMAND
5001 Eisenhower Ave, Alexandria, VA 22304

AMC PAMPHLET
NO. 706-188

15 March 1974

ENGINEERING DESIGN HANDBOOK
MILITARY PYROTECHNICS SERIES
PART FOUR, DESIGN OF AMMUNITION FOR PYROTECHNIC EFFECTS

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LIST OF SYMBOLS*

A = bore area, in.^{2}

A = surface area, m^2 or in.^{2}

A_o = Beattie-Bridgeman constant

a = acceleration, ft sec^{-2}

a = factor, dimensionless

a_r = radial acceleration, ft sec^{-2}

B = object brightness, c-m^{-2}

B_o = Beattie-Bridgeman constant

BR = burning rate, in. sec^{-1}

BT = burning time, sec

B' = background brightness, c-m^{-2}

b = distance from center of gravity to center of pressure, ft

b = excluded volume of molecules, in.^{3}

b = Wien displacement constant, 2897 μ-°K

C = capacitance, F

C = concentration of smoke, lb ft^{-3}

C_b = brightness contrast, dimensionless

C_c = color contrast, dimensionless

C_o = overall contrast, dimensionless

C_y = vertical smoke dispersion coefficient, dimensionless

CP = candlepower

c = deceleration factor, ft^{-1}

*Symbols that bear units or subscripts other than those shown here are defined in their immediate context.

LIST OF SYMBOLS (Con't.)

c = factor, dimensionless

c = speed of light, 3×10^{10} cm sec^{-1}

d = diameter, in.

d_c = constructed diameter of parachute, ft

d_g = groove diameter, in.

d_o = calculated diameter of parachute, ft

d_p = projected diameter of inflated parachute, ft

E = energy, J

E = energy level of an atom or a molecule, erg

E = illumination, lm m^{-2}

E = Young's modulus, dyn cm^{-2} or psi

E_r = energy fraction lost by reflection, dimensionless

E_t = energy fraction lost by transmission, dimensionless

E_λ = energy distribution, W (sr-mμ)$^{-1}$

e = thermodynamic efficiency, dimensionless

F = factor, dimensionless

F = force, lb

F = luminous flux, lm

F_a = axial force, lb

F_c = crosswind force, lb

F_d = drag force, lb

F_g = gage factor, dimensionless

F_r = centrifugal force, lb

F_s = shear force, lb

LIST OF SYMBOLS (Con't.)

F_t = total force, lb

f' = f-stop number of camera, dimensionless

f = frequency of light emitted, Hz

G = glare scattered and reflected in the same direction as light from the object by particles, lm m^{-2}

g = acceleration due to gravity, ft sec^{-2}

h = constant, dimensionless

h = height, ft

h = Planck constant, 6.63 × 10^{-27} erg-sec

h_t = heat transfer coefficient, cal cm^{-2}-°C^{-1}

I = current, A

I = intensity, c

I = moment of inertia, lb-sec^2-ft

I_a = axial moment of inertia, lb-sec^2-ft

I_o = initial intensity without smoke, c

I_o = intensity normal to the source, c

I_t = transmitted light intensity, c

K = luminous efficiency, dimensionless

K_D = normalized drag, dimensionless

k = Boltzmann constant, 1.38 × 10^{-16} erg °K^{-1}

k = coefficient of thermal conductivity, cal (cm^2-°C-sec-cm)$^{-1}$

k = factor, dimensionless

L = inductance, H

L = length, in

M = Mach number, dimensionless

LIST OF SYMBOLS (Con't.)

M = overturning moment, ft-lb

M = projectile mass, slug

M_p = mass of part, slug

N = rate of spin, rad sec^{-1}

n = factor, dimensionless

n = number of moles of gas

n = number of sources

n = rifling twist, cal rev^{-1}

n = Sutton's stability parameter, dimensionless

OSR = optical slant range

P = pressure, dyn cm^{-2} or psi

P_j = pressure when the projectile is at the muzzle, psi

P_m = peak pressure, psi

Q = quantity of heat, cal

R = resistance, ohm

R = universal gas constant, 1543 ft-lb (°R-lb mole)$^{-1}$

$\overline{R}$ = vector distance from muzzle to projectile, ft

R_c = calibrating resistance, ohm

RF = range factor

r = energy ratio, dimensionless

r = output, dimensionless

r = radius, m or ft

S = stress, psi

S_b = bearing stress, psi

LIST OF SYMBOLS (Con't.)

S_b = buckling stress, psi

S_c = combined stress, psi

S_h = hoop stress, psi

S_ℓ = longitudinal stress, psi

T = temperature, °C; or absolute, °K

T_s = stagnation temperature, °K

TOP = total obscuring power, lb ft^{-2}

t = thickness, in.

t = time, sec

t_p = time to consume pyrotechnic, sec

u = projectile travel, in.

U_i = film exposure, m-c-sec

V = meteorological range, mi

V = volume, in.^{3}

V = voltage, volt

V_b = battery voltage, V

V_o = initial free volume, in.^{3}

V_s = signal voltage, V

VF = visibility factor

V_λ = visibility function, dimensionless

v = velocity, cm sec^{-1} or ft sec^{-1}

v_m = muzzle velocity, ft sec^{-1}

v_e = equilibrium parachute descent rate, ft sec^{-1}

W = rate of emission, W m^{-2}

LIST OF SYMBOLS (Con't.)

W = radiated power, erg sec^{-1}

W = weight, mg or lb

W_c = parachute canopy weight, lb

W_e = effective projectile weight, lb

W_p = weight of pyrotechnic, lb

W_λ = monochromatic emissive power, erg (sec-cm^2-cm)$^{-1}$

W_λ = radiant flux emitted per unit area per unit increment of wavelength, W (cm^2-μ)$^{-1}$

x = distance, m or ft

x = magnesium content, %

x = volume expansion ratio, dimensionless

x_m = maximum plume width, m

x_m = travel to muzzle, in.

Y = smoke yield ratio, dimensionless

y = height, m or ft

y = pressure ratio, dimensionless

y_t = maximum plume length, m

Z = impedance, ohm

z = piezometric efficiency, dimensionless

Δ = deflection, in.

δ = angle of yaw, rad

η_o = actual response quantum efficiency, dimensionless

η_s = effective response quantum efficiency, dimensionless

ϵ = emissivity of the surface, dimensionless

ϵ = scattering or extinction coefficient, ft^2 lb^{-1}

LIST OF SYMBOLS (Con't.)

ϵ = strain, in. in.$^{-1}$

θ = angle, rad

λ = slant range, m

λ = wavelength, cm

λ_m = wavelength at the point of maximum emission, cm

ρ = density, g cm^{-3} or slug ft^{-3}

ρ = radius of gyration, in.

ρ_o = density of gas at equilibrium pressure, g cm^{-3}

σ = Stefan-Boltzmann constant, 5.67×10^{-5} erg (cm^2-sec-$^\circ$K^4)$^{-1}$

σ = scattering coefficient, m^{-1}

ϕ = angle of elevation, rad

ω = angular velocity, rad sec^{-1} or rev sec^{-1}

PREFACE

The Engineering Design Handbook Series of the Army Materiel Command is a coordinated series of handbooks containing basic information and fundamental data useful in the design and development of Army materiel and systems. The handbooks are authoritative reference books of practical information and quantitative facts helpful in the design and development of Army materiel so that it will meet the tactical and technical needs of the Armed Forces.

This handbook, *Design of Ammunition for Pyrotechnic Effects*, is Part Four of the Military Pyrotechnics Series which includes:

Part One, Theory and Application, AMCP 706-185

Part Two, Safety, Procedures and Glossary, AMCP 706-186

Part Three, Properties of Materials Used in Pyrotechnic Compositions, AMCP 706-187

Part Four, Design of Ammunition for Pyrotechnic Effects, AMCP 706-188

Part Five, Bibliography, AMCP 706-189.

This handbook was written by The Franklin Institute Research Laboratories, Philadelphia, Pennsylvania. All material was prepared for the Engineering Handbook Office of Duke University. Technical guidance was provided by an interservice committee with representation from Picatinny Arsenal, Edgewood Arsenal, and Frankford Arsenal of the Army Materiel Command, and Eglin Air Force Base, Naval Ammunition Depot (Crane) and Naval Weapons Center (China Lake). Mr. Leo Frey of Picatinny Arsenal served as committee chairman.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The US Army Materiel Command policy is to release these Engineering Design Handbooks to other DOD activities and their contractors and other Government agencies in accordance with current Army Regulation 70-31, dated 9 September 1966. It will be noted that the majority of these Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

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Comments and suggestions on this Handbook are welcome and should be addressed to:

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DESIGN OF AMMUNITION FOR PYROTECHNIC EFFECTS

CHAPTER 1

INTRODUCTION*

1-1 SCOPE

This handbook embraces the areas to be considered in the design of pyrotechnic ammunition with emphasis on the engineering aspects of the terminal effects. Associated topics to be considered during the design – such as light, sound, heat, ignition, and ballistic considerations – are covered briefly with the expectation that the reader will use pertinent references in this and the related handbook series for detailed information. Consideration is given not only to design with respect to performance but also to producibility, reliability, maintainability, cost, safety, and human factors.

1-2 PURPOSE

The purpose of this handbook is to provide a reference of fundamental design information to facilitate generation and evaluation of new designs. Approaches are presented that have been used in the past and which are likely to result in successful conclusions and thereby conserve time, materials, and money. The subject matter should serve as a refresher for the more experienced designer and as a basic guide for those not familiar with this type of ammunition.

1-3 ROLE OF PYROTECHNIC AMMUNITION

Pyrotechnic munitions are used to produce terminal effects that are audible, visible, thermal, mechanical, or physiological as required in offensive or defensive military tactics and during military training. The complexity of military operations demands close coordination among aircraft, vehicles, ships and troops under all environmental conditions; and reliable pyrotechnic devices are often the most appropriate means of creating the necessary effect. A wide variety of pyrotechnic devices is in use ranging from simple candles to sophisticated munitions. Typical applications are shown in Table 1-1. A typical device is illustrated in Fig. 1-1 that shows Photoflash Cartridge, M112, used for night photography. Pyrotechnics may be classified in several different ways as shown in Table 1-2.

From the applications listed in Table 1-1 one can imagine the variety of compositions and devices that fall into the pyrotechnic classification. Under conditions of high confinement, or initiation by shock, some pyrotechnics – such as photoflash compositions – can react very rapidly and explode; however, pyrotechnic compositions as a rule will react exothermally at relatively slow rates upon ignition (as compared with explosives) in a self-sustaining manner to produce various forms of energy or products. Although it may appear that there is considerable overlapping in the areas of pyrotechnics, propellants, and explosives, there are distinctions to be noted. Explosives and propellants may consist of one homogeneous substance, pyrotechnics are normally heterogeneous, self-sufficient mixtures of at least two finely divided solid materials. Pyrotechnic mixtures contain

*Prepared by Raymond G. Amicone; major contributors were Gunther Cohn, Charles T. Davey, and Michael G. Kelly.

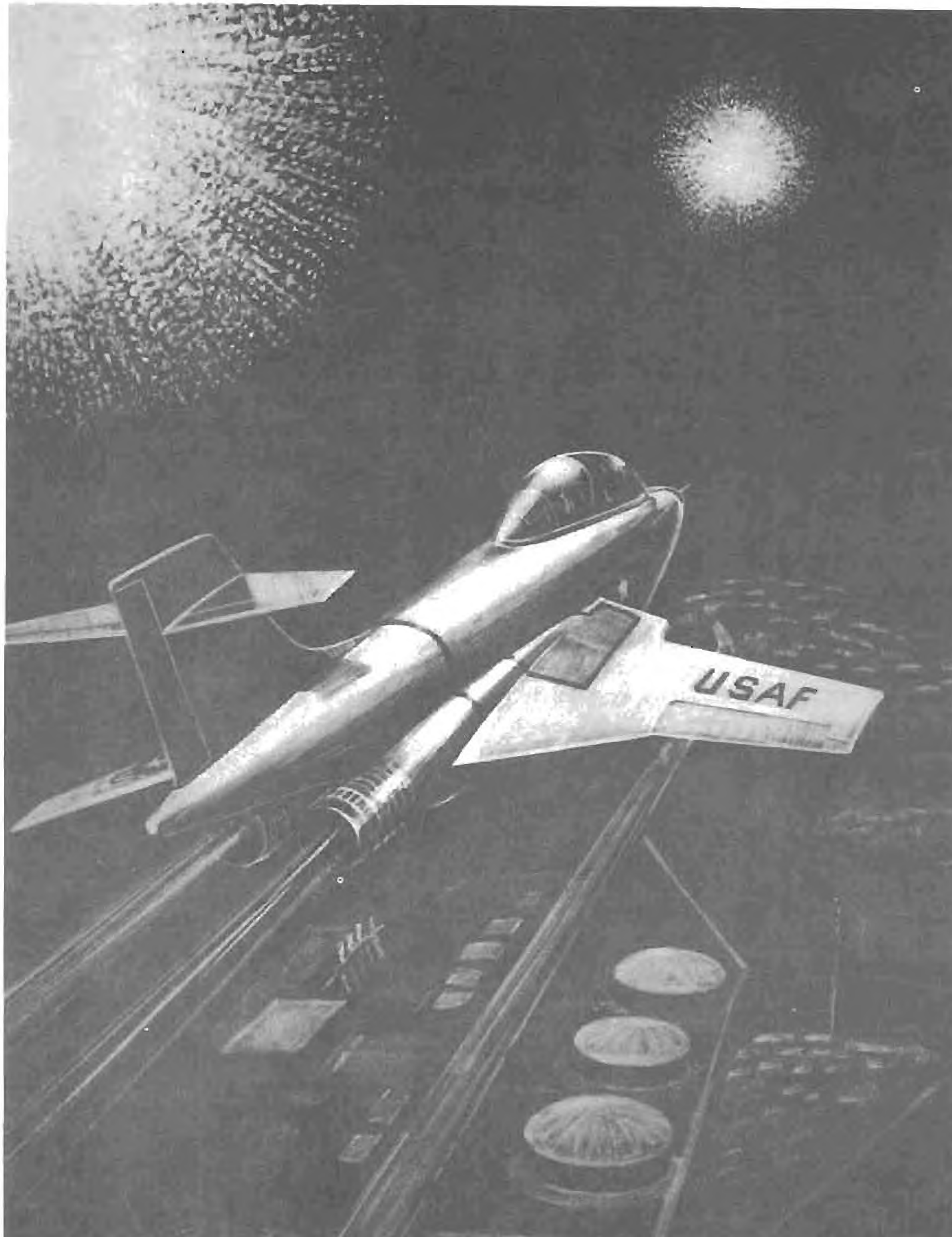

Figure 1-1. Photoflash Cartridge, M112

TABLE 1-1

TYPICAL PYROTECHNIC DEVICES

Devices	General Function (Effective Time Period)	Applications
Flares	Illuminate targets or areas (minutes)	Reconnaissance, bombardment, identification of targets, parachute operations, prevention of enemy infiltration
Flares	Serve as visible location marker (minutes)	Target location, bomb release lines, missile location, decoys
Signals	Provide visual communications with light (seconds to minutes) and smoke (minutes to hours)	Used by ground troops and aircraft, search and rescue operations
Photoflash bombs, cartridges	Provide high-intensity light (milliseconds)	Aerial night photography
Tracers	Mark projectile flight (seconds)	Missile tracking, fire control
Incendiaries	Generate intense heat (minutes)	Destroy targets, documents, equipment
Gas generators	Produce gas to perform mechanical work	Mechanical motions, cut reefing lines

TABLE 1-2

METHODS OF CLASSIFYING PYROTECHNICS

Classification	Types
Tactical use	Ground, aircraft
Effect produced	Illuminants, smokes, etc., see Table 1-1
Device	Flares, signals, cartridges, bombs, etc., see Table 1-1
Method of projection	Hand-launched, projectors, pistols, mortars, guns
Speed of descent	Free falling, parachute

powdered fuel and oxidizer, which, upon ignition will interact at a relatively slower rate than the rapid decomposition of propellants or explosives. Also, ammunition designated as the pyrotechnic type is normally intended to produce the terminal effects cited in Table 1-1 rather than purely propulsive or shattering actions that fall within the province of propellant and explosive classifications, respectively.

CHAPTER 2

BASIC PRINCIPLES

SECTION I VISIBLE AND NONVISIBLE RADIATION

2-1 ILLUMINATION PROPERTIES

2-1.1 INTENSITY

Light is a form of radiant energy that extends from the ultraviolet to the infrared range of the electromagnetic spectrum. The intensity of a point source is determined by measuring the radiant flux emitted from the direction of the source per unit solid angle in watts per steradian.

Visible light is that portion of the radiant energy that is capable of producing visual sensation. The human eye cannot perceive the ultraviolet at the short wave side of the spectrum nor the infrared at the long wavelengths. Human perception of light is discussed more fully in par. 7-1.

Since visual sensation varies with wavelength, a measurement unit of luminous flux designated as the lumen is used to take into account the limitation of the response of a standard observer to radiant flux. One lumen is defined as the luminous or visible flux emitted within a unit solid angle (one steradian) by a point source having a uniform luminous intensity of one candle[1]*. If the source has an energy distribution $E_\lambda = f(\lambda)$, and the visibility function is $V_\lambda = g(\lambda)$, then the luminous flux, F (lumens) may be expressed as follows

$$F = 685 \int_0^\infty V_\lambda E_\lambda \, d\lambda, \text{ lm} \tag{2-1}$$

V_λ has a maximum value of unity at a wavelength of 555 mμ. $E_\lambda = d\lambda$ is the radiant flux emitted in the wavelength interval $d\lambda$ containing the wavelength λ.

The total radiated power (per steradian) W in watts is

$$W = \int_0^\infty E_\lambda \, d\lambda, \text{ watt sr}^{-1} \tag{2-2}$$

and the luminous efficiency K is

$$K = \frac{658 \int_0^\infty V_\lambda E_\lambda \, d\lambda}{\int_0^\infty E_\lambda \, d\lambda} = \frac{F}{W} \tag{2-3}$$

where

F = luminous flux, lm

E_λ = energy distribution, W sr^{-1} mμ^{-1}

V_λ = visibility function, dimensionless

λ = wavelength, mμ

W = total radiated power, W sr^{-1}

K = luminous efficiency, dimensionless

Recent definitions of luminous intensity, based on the radiation from a blackbody at the solidification temperature of molten platinum has resulted in a larger coefficient (given in Eq. 2-3) and a redefinition of the candle (c)[2]. The term *candela* (*cd*) often is

*Superscript numbers refer to References listed at the end of each chapter.

used instead of candle to distinguish it from the older definition based on a series of carbon filament lamps[1].

The intensity of a point source is

$$I = \frac{dF}{d\omega}, \text{c} \tag{2-4}$$

where

I = intensity, c

F = luminous flux, lm

ω = unit solid angle, sr

Sources which have a finite area are sometimes given an intensity value by the use of Lambert's Law which stated mathematically is

$$I_\alpha = I_o \cos\alpha, \text{c} \tag{2-5}$$

where

I_α = intensity at angle α, c

α = angle subtended between a normal to the radiating surface and a ray from the source center to the point of observation, rad

I_o = intensity normal to the source, c

Eq. 2-5 must be used to correct for the reduction in intensity at angles other than normal. Point sources are considered to have uniform intensity.

2-1.2 BRIGHTNESS

Brightness is a term applied to describe the magnitude of a light source of a finite size in terms of intensity per unit area. A light source may be considered either as a self-luminous object or an object which diffuses light by reflection or transmission.

The unit for brightness is the *lambert* which is $1/(4\pi)$ c-cm^{-2} which is equivalent to 1 lm cm^{-2}.

2-1.3 SURFACE ILLUMINATION

For a spherical surface concentric about a point source of light, the illumination E of the inside surface of the sphere is

$$E = \frac{F}{A} = \frac{4\pi I}{4\pi r^2} = \frac{I}{r^2}, \text{ lm m}^{-2} \tag{2-6}$$

where

E = illumination, lm m^{-2}

F = luminous flux, lm

I = intensity, c

A = surface area, m^2

r = radius of the sphere, m

If a point source of intensity I candles illuminates a plane surface at a distance x meters from the source and the angle between the ray from the source and a normal to the surface is θ radians, then the illumination of the surface is

$$E = \frac{I}{x^2}\cos\theta \tag{2-7}$$

This equation is normally applied to objects that are small compared with the distance of the object from the light source as shown in Fig. 2-1. If the object size (width) is approximately equal to the distance of the source, as could be the case with large illuminated surfaces, then the surface will not be illuminated uniformly. Under these conditions it is necessary to take into account the differences in the source to object distance and the angle between the ray from the source and the surface. This is true for flares at various altitudes as discussed in par. 3-1.3.

2-1.4 CONTRAST

Optical contrast between two or more materials is the result of differences in either brightness or color. Contrast is most often the

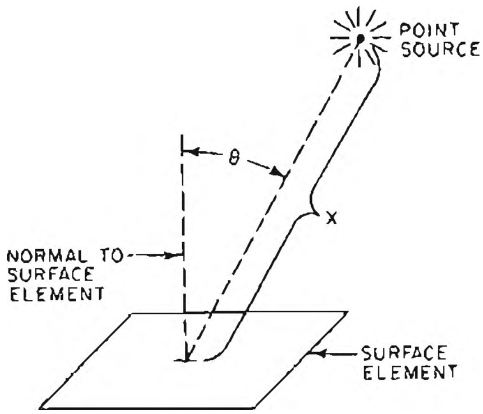

Figure 2-1. Relationship of Surface Illumination Variables

result of differences in reflected light. The brightness contrast C_b of an object may be expressed as

$$C_b = \frac{B - B'}{B} \quad (2\text{-}8)$$

where

C_b = brightness contrast, dimensionless

B = object brightness, c-m^{-2}

B' = background brightness, c-m^{-2}

It has been found that brightness contrast plays a more important role in the ability to distinguish an object than color contrast[3]. Overall contrast C_o is given by

$$C_o = (C_b^2 + C_c^2)^{1/2} \quad (2\text{-}9)$$

where

C_o = overall contrast, dimensionless

C_b = brightness contrast, dimensionless

C_c = color contrast, dimensionless

Color contrast contributes less than 0.25 in most instances; and where color contributions are this large, brightness contrast is usually over 0.25. Visibility under field conditions is primarily dependent upon brightness contrast. Normally color contrast is not considered in the design of illuminating devices.

The angle that an object subtends from the eye is important in terms of brightness contrast. The larger the object, the lower the least perceptible brightness contrast. Fig. 2-2 is a plot of brightness and least perceptible contrast for five values of subtended viewing angle. Note that an object subtending an angle of 121 minutes of arc requires approximately four orders of magnitude less brightness than an object subtending 3.6 minutes of arc for the same threshold of brightness contrast.

Visual acuity is often expressed as the reciprocal of the angle in minutes of arc for which an object can be distinguished under normal (daylight) lighting conditions. An accepted value for normal acuity is one. That is to say, an object that subtends one minute of arc can be distinguished by the average human observer. This permits one to express the height y of an object that can be seen as a function of distance under average conditions

$$y = x \tan \theta, \text{ m} \quad (2\text{-}10)$$

where

y = height of the object, m

x = distance from the observer to the object, m

θ = angle, rad

For angles as small as one minute, the tangent of the angle is equal to the angle in radians which in this case is 0.00029. Thus

$$y = 0.00029x, \text{ m} \quad (2\text{-}11)$$

At a distance x of 1000 m an object 0.29 m in diameter and with average contrast (0.1 to 0.2) should be visible under daylight conditions (10^3 cd/m^2). Objects subtending less than 1 minute of arc may be visible under ideal conditions.

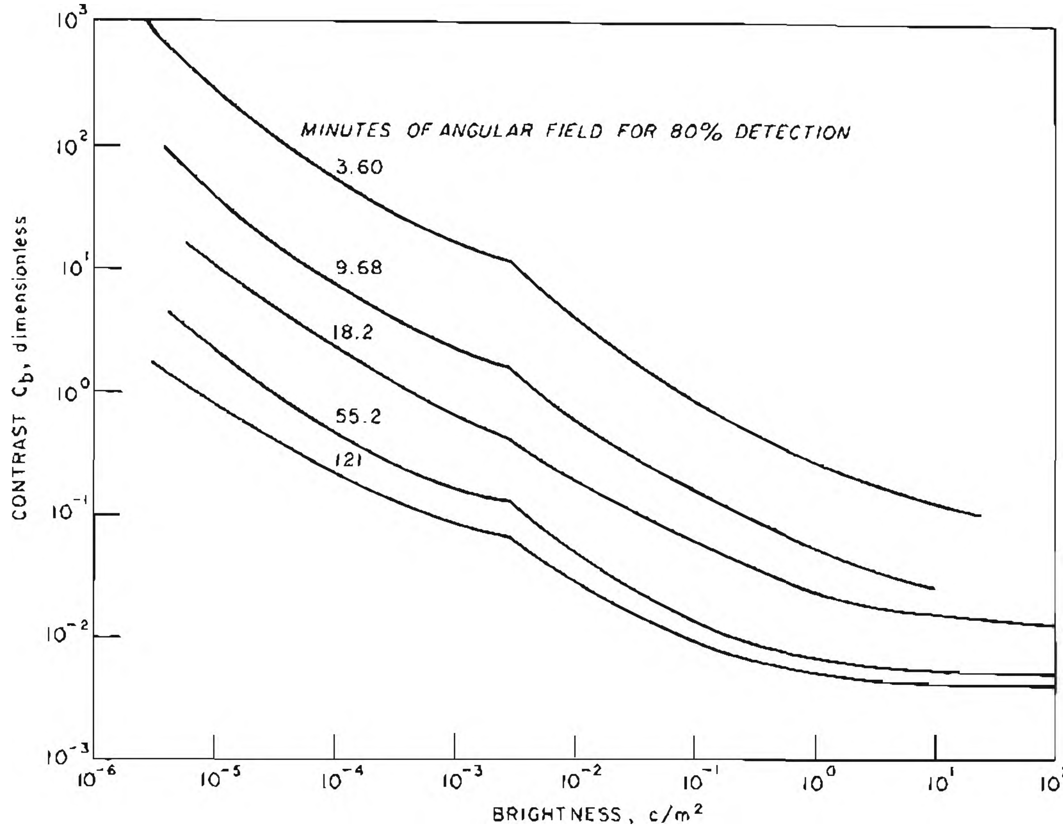

Figure 2-2. Thresholds of Brightness Contrast for Five Angular Fields

2-2 SPECTRAL DISTRIBUTION

2-2.1 DISCRETE SPECTRA

Discrete spectra are those radiant energies which divide light in distinct, separate patterns of wavelength or color. Discrete spectra are generally further divided into *line spectra* and *band spectra*[4]. A *line spectrum* is characteristically produced from atoms that are in a gaseous state. When gases are excited to a state of producing light, the spectral lines are bright against a darker background when viewed spectroscopically. If the gas is in the path of a light comprised of many frequencies, and this light is examined spectrographically then the lines appear dark. The atoms of the gas have extracted energy selectively from the source light, resulting in *absorption spectra*. Thus isolated atoms absorb radiation as well as emit it, at discrete wavelengths.

Band spectra appear wider in frequency range than line spectra and are most generally produced from molecules in a gaseous state. The band spectrum of a compound is in reality made up of closely spaced line spectra that appear as groups. The lines comprising bands in a band spectrum become more crowded toward one end of the spectrum.

Line and band spectra occur because of the distinct energy levels that exist in the atomic and molecular structure. Excitation of the atoms and molecules result in the release of energy as described by the equation

$$hf = E_2 - E_1, \text{erg} \quad (2\text{-}12)$$

where

E_2 = higher energy level of an atom or molecule, erg

E_1 = lower engrey level of an atom or molecule, erg

h = Planck constant, 6.63×10^{-27} erg-sec

f = frequency of light emitted, Hz

Since the structure of the atoms of a specific element are the same, then the energy levels of a specific element are the same and identification of the element may be made by examination of its spectrum.

2-2.2 CONTINUOUS SPECTRA

Continuous spectra occur when solids are heated to incandescence. They have no observable line or band structure and are considered to contain all possible frequencies.

The continuous visible spectrum from a solid begins with a red glow as the solid is heated; and as heating is continued, changes from red through orange, yellow, and finally white as the temperature is increased[3].

Predictions of the spectral distribution and intensity of radiation produced from a heated solid body are based on a "blackbody" radiator. A blackbody is defined as one that will absorb all of the radiation incident upon it and is, therefore, a theoretically idealized object. The radiation emitted by a perfect blackbody radiator at any temperature is given by the Stefan-Boltzmann law

$$W = \sigma A T^4, \text{erg sec}^{-1} \quad (2\text{-}13)$$

where

W = radiated power, erg sec^{-1}

σ = Stefan-Boltzmann constant, 5.67×10^{-5} erg (cm^2-sec-°K^4)$^{-1}$

A = area of emitting surface, cm^2

T = absolute temperature, °K

The intensity of radiation from a blackbody at a given temperature varies with the wavelength according to Planck's equation

$$W_\lambda = \frac{2\pi c^2 h}{\lambda^5 [e^{hc/(k\lambda T)} - 1]}, (\text{erg sec}^{-1}\ \text{cm}^{-2})\ \text{cm}^{-1} \quad (2\text{-}14)$$

where

W_λ = monochromatic emissive power, (erg sec^{-1} cm^{-2}) cm^{-1}

c = speed of light, 3×10^{10} cm sec^{-1}

k = Botzmann constant, 1.38×10^{-16} erg °K^{-1}

λ = wavelength, cm

This equation is plotted in Fig. 2-3[3] for temperatures from 1500° through 3000°K in 500 deg K increments[5]. Observe that the wavelength of maximum incident flux density decreases (the frequency increases) as the temperature is increased.

2-2.3 COLOR EFFECTS

Spectral characteristics are related with color effects, and predominance of a particular color may be of importance in the application of light. Physically, colors are associated with particular wavelengths. Physiological concepts of color involve the human as a receiver of these wavelengths[3]. Color is comprised of hue, saturation or purity, and brightness—all of which influence color perception. One concept of the relationship of these properties is presented in Fig. 2-4[3]. Hue refers to the color itself, i.e., blue, green, or red, represented by points along the circumference of the hue circle. Brightness is associated with objects from black to white along a line perpendicular to the circular surface of the hue circle and through its

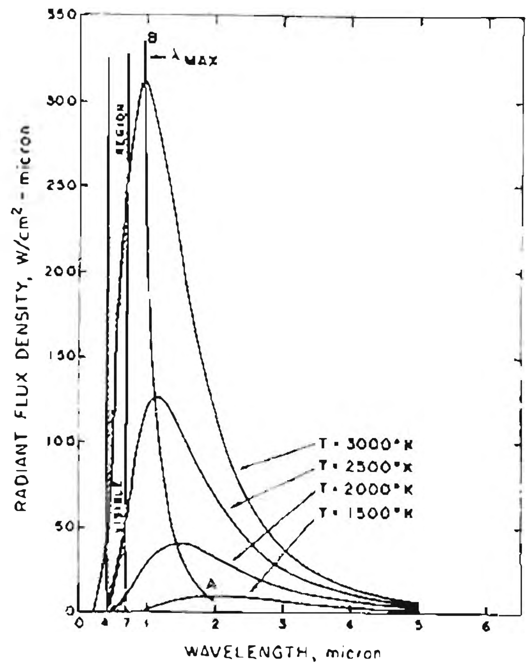

Figure 2-3. Planck's Law: Radiance as a Function of Wavelength for Various Temperatures

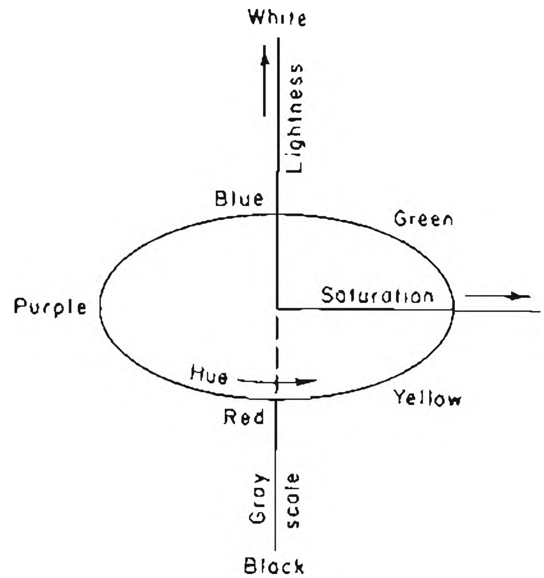

Figure 2-4. Dimensions of the Psychological Color Solid

center. Saturation depends upon the extent to which a hue differs from a gray value of the color and is represented by the length of the radius extending perpendicularly from the brightness line. Note that saturation involves essentially monochromatic light. Colors may be added to produce any desired hue by the addition of primary colors green, blue-violet, and red as indicated by the additive color circles of Fig. 2-5[3]. Proper mixtures of blue and red produce magenta; red and green produce yellow; and blue and green, cyan. Complementary colors, e.g., red and cyan, when added produce white.

The subtraction quality of color comes into play in transmission, absorption, and reflection. In transmission, the light transmitted will be the complement of the color if the incident light is white. A red transmitting filter will strongly absorb cyan. Similarly, opaque reflecting bodies absorb the complement of the color that is actually seen (reflected) from incident white light.

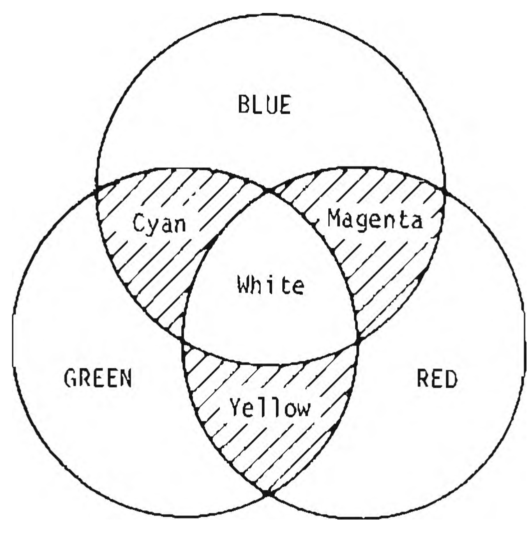

Figure 2-5. Additive Mixture of Primary Colors

The trichromatic color matching theory states that over a wide range of conditions almost any color may be matched by additive mixtures of three fixed primary colors. The relative light intensity of the three primary colors (usually λ_{red} = 700.0 nm, λ_{green} =

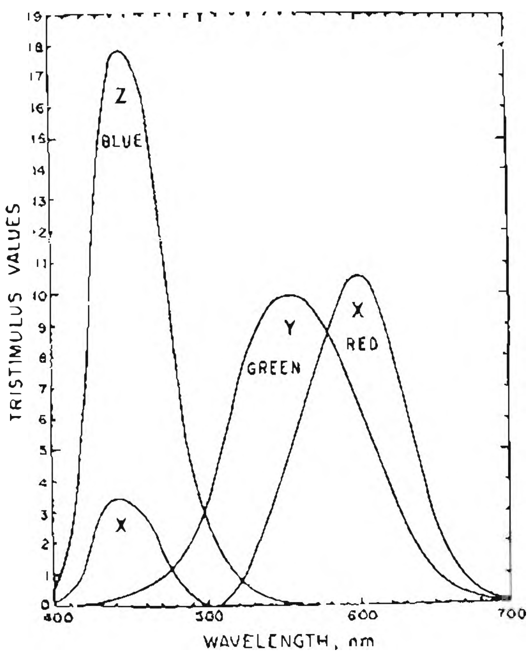

Figure 2-6. Tristimulus Values of the Spectrum Colors According to the 1931 I.C.I. Standard Observer

546.1 nm, λ_{blue} = 435.8 nm) needed to match almost any wavelength in the visible spectrum is shown in Fig. 2-6[3]. The relationship in this figure is that adopted in 1931 by the International Commission on Illumination (I.C.I.) for a "standard observer".

This standard permits a direct comparison of color observations and permits more simple computations. A chromatic diagram may be drawn using the tristimulus values X, Y, and Z from Fig. 2-6 as primary standards. The X, Y, and Z values are the amounts of the three I.C.I. primaries required to match a unit amount of energy having the indicated wavelength. The coordinates for the chromaticity diagramed are defined by

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z},$$

$$z = \frac{Z}{X+Y+Z} \qquad (2\text{-}15)$$

Since only two of these are required, x and y are plotted to form a diagram of the type illustrated in Fig. 2-7[3].

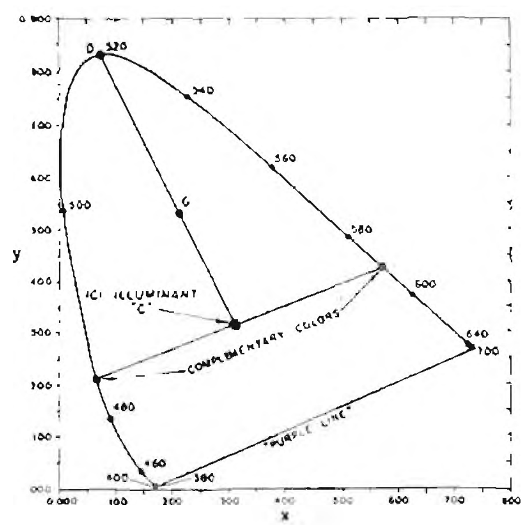

Figure 2-7. I.C.I. Chromaticity Diagram

The "purple line" forming the base of the triangle extends from 380 to 700 nm. No readily perceptible colors exist along this line. All other points on the triangle are the loci of monochromatic colors. The center C of the triangle is the white point designated by the I.C.I. as the light produced by "Illuminant C" corresponding closely to average daylight. Complementary colors fall on the periphery of the color triangle at points where a straight line intercepts Illuminant C. Any color, say G, falling on a straight line from C to a point on the triangle, say D, may be considered a mixture of illuminant C and the light at the wavelength D. This wavelength at D is called the *dominant wavelength*. A mixture of two colors represented by points located anywhere on the diagram will result in a color located on a straight line connecting the two points (colors).

2-3 INFRARED AND ULTRAVIOLET RADIATION

In par. 2-1.1 the term luminous efficiency

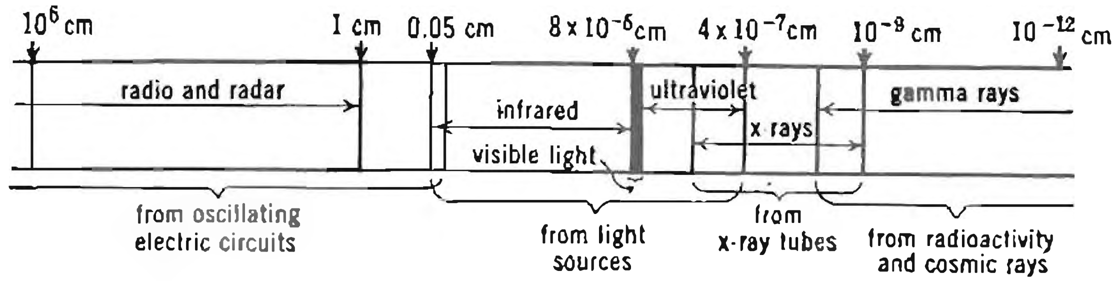

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Figure 2-8. A Complete Spectrum of Electromagnetic Radiation

is defined, comparing the energy radiated in the visible spectrum to the total radiated energy. Normally incandescent light sources are not very efficient, a majority of the radiated energy being outside the visible limits, in the infrared[4]. Wavelengths longer than 0.75 micron and shorter than 0.4 micron are not visible but they play an important role in natural phenomena as well as providing "illumination". Their spectral regions are shown in Fig. 2-8[2]. Infrared systems are covered in another handbook[5].

Infrared (IR) radiation is emitted by an incandescent object at a temperature far lower than that at which radiation is seen by the human observer. While the unaided eye cannot perceive IR radiation, many electronic devices are capable of detecting differences in the magnitude of radiation. More detailed information is given about these detectors in par. 5-2. IR is generated by heating a source. If IR alone is to be produced, then the temperature of the body must be kept low enough so that no appreciable visible light is emitted. An alternative is to heat the object to a temperature higher than that producing IR alone and to filter the radiation that is not desired.

The wavelengths included in the infrared spectrum extend from 0.75 micron to about 1 mm. The longer wavelength overlaps the spectral range of microwave energy in an area that is not clearly defined. The infrared spectrum is often subdivided into three regions: (1) the photoelectric infrared covering a range from 0.72 to 1.5 microns, (2) the near infrared covering a range from 1.5 to 20 microns, and (3) the far infrared that extends from 20 microns to 1 mm.

The *photoelectric infrared* region is amenable to the use of most of the same instruments used in the visible range with the exception of human vision. Photographic emulsions can respond to wavelengths up to 1.2 microns and photoelectric cells can be made that are responsive up to 10 or 15 microns.

In the *near infrared* transparent materials are readily available and are used in optical instruments to provide prisms and lenses. In this region as well as in the far infrared, radiation must be detected by the heating effect on a detector element.

There are very few solid materials that readily transmit energy in the *far infrared* region. Optical systems using the far infrared generally rely upon reflection techniques made possible by appropriate choices of gratings and optical components.

The photometry of the IR and UV regions is the same as that for visible light in that source power is normally expressed in watts and reception of radiation is normally stated in watts per unit of area.

Ultraviolet radiation begins at a wavelength of approximately 0.4 micron and extends into the region of shorter wavelengths overlapping longwavelength X rays at around 0.09 micron. The solar spectrum is cut off below 0.29 micron due to absorption by ozone in the outer atmosphere. Oxygen and water vapor in the air strongly absorb wavelengths below 0.2 micron and those wavelengths are known as the vacuum ultraviolet, because their transmission requires a vacuum. For wavelengths in the vacuum UV shorter than 0.1 micron, there is no known transparent solid.

2-4 TRANSMISSION OF LIGHT

2-4.1 REFLECTION

Light travels in straight lines in space at a speed of 3×10^8 m sec^{-1} and, in the absence of any inhomogeneity or particulate matter, is relatively unattenuated. The illumination is reduced only by spreading of the light from its source as shown by Eqs. 2-6 and 2-7. When light strikes a surface appreciably different from the one in which it is traveling, it may be reflected, absorbed, or transmitted, or all three of these may occur to some degree at the same time. The interface between different media through which light is passing usually results in reflection, the amount and type of which is dependent upon the condition of the interface[6].

Specular surfaces are considered ideally flat and free of irregularities; these, of course, are not normally found in practice. A *glossy* surface approaches the specular surface. *Matte* surfaces tend to be more diffuse reflectors and either *semi-gloss* or *semi-matte* are somewhere between glossy and matte. *Diffuse* surfaces tend to reflect light equally in all directions because the surface is rough and causes light to scatter.

2-4.2 ABSORPTION

Absorption occurs as light passes through any real medium. Transparency is a term given to the ability of a material to transmit light, and it is defined as the ratio of the intensity I_t of the transmitted light to the intensity I_i of the incident light, hence the transparency is always less than unity in practice, i.e.,

$$\text{transparency} = \frac{I_t}{I_i} < 1 \tag{2-16}$$

Opacity is the reciprocal of transparency and optical density is the $\log_{10}$ of the opacity, i.e.,

$$\text{opacity} = \frac{1}{\text{transparency}} = \frac{I_i}{I_t} \tag{2-17}$$

$$\text{optical density} = \log_{10}\left(\frac{I_i}{I_t}\right) \tag{2-18}$$

The atmospheric scattering is of main interest to the designer of pyrotechnic devices. Absorption however becomes important in parts of the ultraviolet and infrared portion of the spectrum. Light passing through a distance of atmosphere is attenuated by an amount dependent on the scattering coefficient σ

$$F = F_o e^{\sigma x}, \text{lm} \tag{2-19}$$

where

F = observed luminous flux, lm

F_o = initial luminous flux, lm

σ = scattering coefficient, m^{-1}

x = length of path through atmosphere, m

Small droplets preferentially scatter the shorter wavelengths and, as a consequence, the transmitted light under these circumstances is red. Larger particle sizes selectively scatter the red light, if the particles are slightly larger than the longest red wavelength, with the result that the transmitted light is blue or green.

2-4.3 ATTENUATION

Scattering is a part of the attenuation of light that arrives at an object, and therefore has an effect on the ability of a human to see an object. Contrast is also attenuated because of the effects these factors have in light interaction between the object and an observer. As would be expected, the apparent contrast of an object when viewed through a medium which absorbs and scatters light is reduced. The reduction in contrast is brought about by an imbalance in the attenuation of light reflected from the object and the background and by additional light supplied from scattering in the atmosphere between the object and the observer.

The apparent brightness contrast C_x of an object when viewed at a distance of x meters is given by

$$C_x = \frac{(B - B')e^{-\sigma x}}{B'e^{-\sigma x} + G} \qquad (2\text{-}20)$$

where

C_x = brightness contrast at distance x

B = brightness of the object, lm m^{-2}

B' = brightness of the background, lm m^{-2}

σ = scattering coefficient, m^{-1}

G = glare scattered and reflected in the same direction as light from the object by particles, lm m^{-2}

SECTION II HEAT

2-5 THERMAL PROPERTIES

2-5.1 QUANTITY OF HEAT

Heat is a form of energy and conversion factors are available to permit expressing the quantity in equivalent mechanical or electrical terms. Units of heat currently in use are *calorie* (cal), *kilocalorie* (kcal), and *British thermal unit* (Btu).

The gram-calorie is the amount of heat required to raise the temperature of a mass of one gram of water one degree centigrade. The specific temperature range of 14.5° to 15.5°C is often specified, because specific heat of water is not completely uniform over the entire temperature range[7]. This measure of heat energy is sometimes referred to as the 15-degree calorie. The Btu is the heat energy required to raise the temperature of one pound of water one degree on the Fahrenheit scale. It is sometimes specified as the average value in the interval from ice to steam to introduce more precision.

2-5.2 TEMPERATURE

Temperature is a second fundamental quantity in heat measurement, the first being quantity of heat. Increase in heat energy does not necessarily call for an increase in temperature, e.g., increased application of heat to an ice-water mixture does not necessarily change the temperature.

Temperature has been defined as that quantity which determines whether a body is in thermal equilibrium with one or more other bodies. Temperature difference determines the direction of heat flow. Heat will always flow from a body with a higher temperature to one with a lower temperature when the bodies are in contact. If the bodies are at the same temperature, then there is no heat flow and the bodies are said to be at thermal equilibrium.

Historically, several temperature scales have been used in temperature measurements. These are illustrated in Fig. 2-9. While the centigrade or Celsius and Fahrenheit scales establish their zero near or at the freezing point of water, the Kelvin and Rankine scales base their zero point on absolute zero in temperature. Recently an international scale of temperature was established based on the triple point of water that has been sealed in a glass tube at a low pressure (4.579 mm Hg)[2]. Water vapor, water, and ice can coexist in equilibrium at a temperature of 0.0100°C and this triple point can be reproduced within 0.0001 deg C or better. The international scale defines the triple point as 273.16°K which makes a difference of 0.01 deg C between the currently used centigrade scale and the one defined in this international standard.

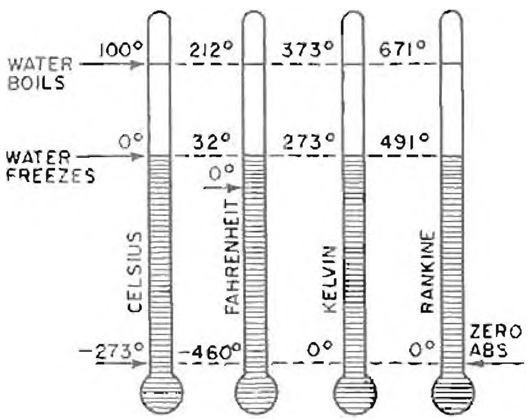

Figure 2-9. Comparison of Temperature Scales

2-5.3 HEAT CAPACITY

In effect, heat capacity is a measure of the ability of a body to absorb and store heat energy. The heat capacity of a substance per unit mass, which is the *specific heat*, may be defined as the quantity of heat required to raise the temperature of a unit mass of the substance one degree. The units of specific heat may be calories per gram per degree centigrade or Btu per pound per degree Fahrenheit. The *heat capacity* of a body is the heat required to raise the temperature of the body one degree. It may be found by taking the product of the mass and the specific heat.

2-5.4 PHASE CHANGES

Matter may exist in solid, liquid, or gaseous states. By a change in ambient temperature, pressure, or both, it is possible to cause the substance to change from one state to another. The transition from the solid state to the liquid state in crystalline matter is accompanied by a change in energy in the form of heat. At constant pressure, the amount of heat energy absorbed or liberated per unit mass without a change in temperature at the transition point is constant for any given material. In going from the liquid to the crystalline state or vice versa there is an energy interchange from thermal to potential energy or the reverse of this.

The *heat of fusion* of a substance is the quantity of heat required to change a unit mass of the substance at constant pressure from the solid to the liquid phase without a temperature change. The *heat of vaporization* is the quantity of heat required to change a unit mass of a substance at constant pressure from the liquid to the vapor phase without a change in temperature.

The heat of fusion is the same numerically as the heat of liquefaction and the heat of vaporization is the same as the heat of condensation. Only the direction of the heat flow changes.

2-5.5 HEATS OF REACTION

When a substance burns, it liberates an amount of heat in the reaction process. This reaction is a chemical one in which fuel is oxidized. The *heat of explosion* rather than the heat of combustion is often used to describe the heat liberated from explosives[a]. The heat of explosion is determined either in an atmosphere of nitrogen or in an atmosphere of air. The heat of explosion is usually less than that of combustion for the same material.

2-6 TRANSFER OF HEAT ENERGY

2-6.1 CONDUCTION

A heat source applied to a conducting medium causes agitation of the atomic structure near the heat source that is passed along to adjacent atoms or molecules without the atoms or molecules changing their average position[7]. This transfer of heat from one part of a body to another or to other bodies in physical contact is called conduction. Free electrons that are detached from their parent atoms contribute to heat conduction and determine to a large degree the excellent conduction properties of metals. Fourier's law states

$$\frac{dQ}{dt} = -kA\left(\frac{dT}{dx}\right), \text{ cal sec}^{-1} \quad (2\text{-}21)$$

where

Q = quantity of heat, cal

t = time, sec

k = coefficient of thermal conductivity, (cal sec^{-1} cm^{-2})(°C/cm)$^{-1}$

A = area, cm^2

T = temperature, °C

x = distance, cm

This is the fundamental relationship for heat transfer by conduction. The equation may be simplified under steady-state conditions of heat flow.

Fig. 2-10 shows a slab of area A and thickness x. The left of the slab is kept at temperature T_2 and the right at temperatures T_1. After thermal equilibrium has been reached, the quantity of heat flow Q through the slab in time t may be determined by

$$Q = \frac{kA(T_2 - T_1)t}{x}, \text{ cal} \quad (2\text{-}22)$$

The coefficient k, often called the *conductivity*, determines how well a material conducts heat. Typical values for metals (normally considered good conductors of heat) are 0.49 for aluminum, 0.92 for copper, and 0.12 for steel. The values of k for insulators are low – e.g., cork, 0.0001; concrete, 0.002; and rock wool, 0.0001.

Compound walls, comprised of slabs of more than one material, have a heat flow Q in time t that may be computed by

$$Q = \frac{A(T_2 - T_1)t}{\sum_{i=1}^{n} x_i/k_i}, \text{ cal} \quad (2\text{-}23)$$

where

x_i = thickness of the ith wall, cm

k_i = thermal conductivity of the ith wall, (cal sec^{-1} cm^{-2})(°C/cm)$^{-1}$

For some configurations the expression of the heat flow becomes complicated and geometry dependent. Such configurations may require the use of elemental sections of materials comprising a particular heat flow problem. These situations may require the use of calculus for solution.

2-6.2 CONVECTION

Heat transfer in fluids may be produced by the physical mixing of hot and cool material. Convection may be forced or naturally produced by motion resulting from differences in density of the hot and cool fluids.

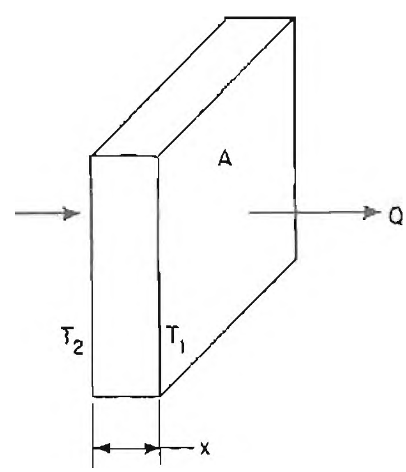

Figure 2-10. Concept of Thermal Conductivity in a Slab

Convective transfer[3] of heat is expressed by

$$Q = h_t A \Delta T, \text{ cal} \quad (2\text{-}24)$$

where

Q = quantity of heat transferred, cal

h_t = heat transfer coefficient, cal cm^{-2} °C^{-1}

A = area, cm^2

ΔT = temperature difference, °C

The coefficient h_t in Eq. 2-24 is complicated by a number of factors and must usually be obtained experimentally under conditions closely approximating those of the desired configuration. For this reason convective processes are seldom analyzed in great detail on a strictly theoretical basis.

2-6.3 RADIATION

Radiation differs from either conduction or convection in that heat is transmitted by electromagnetic waves, requiring no medium for transfer[7]. Radiation of heat is like that of light, radio waves, and X rays, differing only in the wavelength of frequency.

When radiant heat energy reacts with a surface that is not transparent, the energy is absorbed and the surface becomes warmed. The nature of the surface, mainly the color and the roughness, determine how efficiently the radiant energy is transformed into heat. Similarly, the radiator is affected by the color, roughness, and temperature. The energy radiated per unit area and per unit time is determined by these factors.

At lower temperatures of the radiator, the rate of emission per unit area and per unit time is small and the wavelength of the radiant energy is relatively long. Fig. 2-3 shows the distribution of emission for various temperatures for a blackbody radiator. As the temperature is increased, the rate of emission W increases very rapidly following the Stefan-Boltzmann law* which is expressed by the relation

$$W = \epsilon \sigma T^4, \text{ watt m}^{-2} \quad (2\text{-}25)$$

where

W = rate of emission, watt m^{-2}

ϵ = emissivity of the surface, dependent upon material and temperature, dimensionless

σ = Stefan-Boltzmann constant, 5.670 × 10^{-8} W m^{-2} °K^{-4}

T = absolute temperature, °K

The value of the emissivity varies from 0 to 1, depending upon the nature of the surface of the radiating material. A perfect radiator would have an emissivity of one. Generally, rough surfaces have a higher emissivity than smooth surfaces.

Wien discovered that the maximum radiation from a blackbody occurred at a given specific wavelength for a given temperature, and Wien's displacement law relates the wavelength in terms of the temperature and a constant

$$\lambda_m = b/T, \mu \quad (2\text{-}26)$$

where

λ_m = wavelength at a point of maximum emission, μ

b = Wien displacement constant, 2897 μ°K

T = absolute temperature of the source, °K

Planck's theoretical equation determines the flux emitted per unit area and per unit wavelength by a blackbody. In this sense Planck's equation provides a most versatile

*Both the Stefan-Boltzmann and Planck equations are presented in par 2-2.2 in a slightly different form. The equations and constants presented here are more amenable to radiation work and for that reason are repeated in this form.

means of determining the radiation produced from a source that may be considered a blackbody. Planck's equation is

$$W_\lambda = \frac{C_1}{\lambda^5 [e^{C_2/(\lambda T)} - 1]}, \text{ watt cm}^{-2}\ \mu^{-1} \quad (2\text{-}27)$$

where

W_λ = radiant flux emitted per unit area per unit increment of wavelength, watt cm^{-2} μ^{-1}

C_1 = $2\pi c^2 h = 3.741 \times 10^{-12}$ W cm^2

c = speed of light, 3×10^{10} cm sec^{-1}

h = Planck constant, 6.625×10^{-34} W sec^2

C_2 = $hc/k = 1.438$ cm°K

k = Boltzmann constant, 1.38054×10^{-23} W sec °K^{-1}

λ = radiation wavelength, μ

T = absolute temperature, °K

SECTION III SOUND

2-7 INTENSITY

The intensity of a traveling sound wave is defined as the time average rate at which energy is transported by the wave per unit area through a surface perpendicular to the direction of propagation[7]. Mathematically the intensity is given by

$$I = \frac{P^2 \times 10^{-7}}{2\rho_o v}, \text{ W cm}^{-2} \quad (2\text{-}28)$$

where

I = intensity, W cm^{-2}

P = pressure, dyn cm^{-2}

ρ_o = density of the gas at equilibrium pressure, g cm^{-3}

v = speed of propagation, cm sec^{-1}

Since for air, ρ_o and v are often considered constant, $I \propto P^2$ and hence a measurement of pressure is also a measure of intensity. Intensity is usually expressed in decibels (dB). The dB sound level is the logarithm of the ratio of the ambient sound intensity I to some reference intensity I_o that is generally accepted as 10^{-6} W cm^{-2}. The intensity corresponds to a pressure of 0.0002 dyn cm^{-2}. The intensity level, dB of sound, may be determined by

$$dB = 10 \log_{10}\left(\frac{I}{I_o}\right) \quad (2\text{-}29)$$

The reference intensity level is chosen because this level is also the threshold level of human hearing. This sound level is that which the average human being can just begin to hear. As a matter of interest, some typical dB intensities of noise levels were collected by the N.Y. City Noise Abatement Commission that provide some idea of the meaning of the term dB as shown in Table 2-1[7].

TABLE 2-1

NOISE LEVELS FROM COMMON SOURCES

Source or Description of Noise	Noise Level, dB
Threshold of pain	120
Riveter	95
Elevated train	90
Busy street traffic	70
Ordinary conversation	65
Quiet automobile	50
Quiet radio in home	40
Average whisper	20
Rustle of leaves	10
Threshold of hearing	0

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2-8 WAVELENGTH

One of the basic concepts of sound is wavelength. The product of the wavelength and the frequency is the propagation velocity. In a single, uniform medium and under identical conditions, sound velocity is a constant. Since the velocity is constant, then wavelength varies inversely as frequency; accordingly high-frequency sounds have shorter wavelengths than low-frequency sounds.

Concepts of wavelength, pitch, and intensity are illustrated in Fig. 2-11[9]. In this figure, pitch is used in place of frequency; they are related. The sound source is shown as a cantilever beam that has been plucked and is vibrating. The shorter beam of the same cross section and material results in a higher frequency, and this is a generally true condition in structures that are subject to vibration.

2-9 EFFECT OF THE MEDIUM

Sound conducting media determine how far a sound may be conducted with enough energy content to still be heard or detected. In addition, some media have different values of attenuation throughout the spectral range.

The speed of sound ν in a solid medium is given by

$$\nu = \sqrt{\frac{E}{\rho}}\text{, cm sec}^{-1} \tag{2-30}$$

where

ν = speed of sound, cm sec^{-1}

E = Young's modulus of the medium, dyn cm^{-2}

ρ = density of the medium, g cm^{-3}

For a gas such as air, the speed of sound is given by

$$\nu = \sqrt{\frac{1.4\,P}{\rho}} \tag{2-31}$$

where

ν = velocity of sound, m sec^{-1}

P = pressure, N m^{-2}

ρ = density, kg m^{-3}

The attenuation in air may be computed by classical methods, and the result is the attenuation characteristic plotted in Fig. 2-12[10]. Curve C shows the theoretical value of attenuation for dry air. Measurements in dry air yield the results shown in curve B. Note that

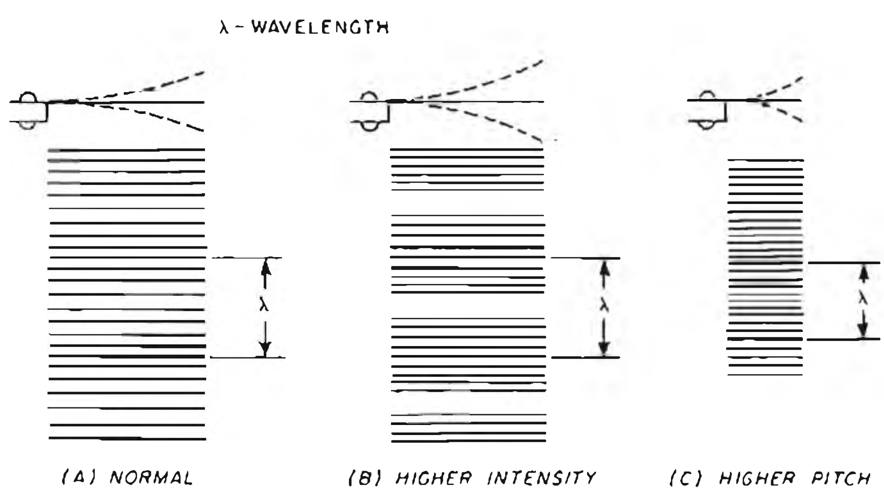

Figure 2-11. Concept of Sound Wavelength, Pitch, and Intensity

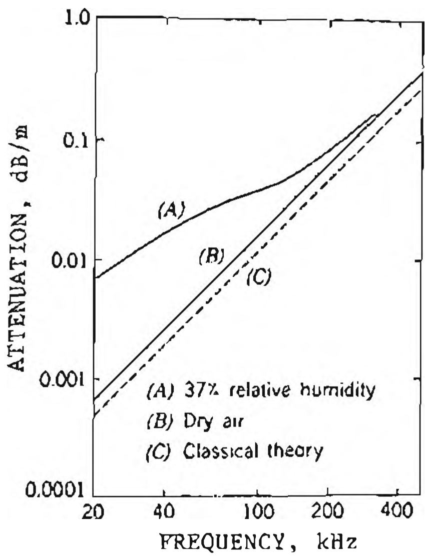

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Figure 2-12. Attenuation of Sound in Air in Decibels per Meter as a Function of Frequency

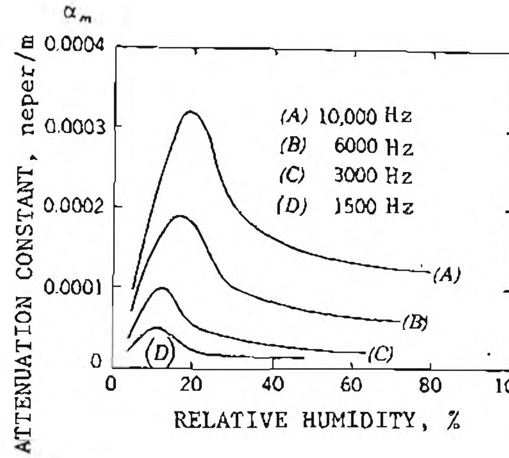

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Figure 2-13. Molecular Attenuation in Air as a Function of Relative Humidity

the measured attenuation is larger than would have been anticipated from theory, When water vapor appears in the air, a different type of attenuation occurs due to the kinetics of the water molecule. The effect of water vapor is shown in curve A. In dry air, the normal relaxation time for the oxygen molecule is about 2 seconds, hence the molecule is not excited. The presence of the water vapor molecule changes the characteristics so that the oxygen molecule is excited by sound with the result that more energy is extracted.

Excess attenuation, greater than that described in Fig. 2-12, occurs as a result of the presence of water vapor in the manner illustrated in Fig. 2-13[10]. The excess attenuation peaks at some value of relative humidity, and this peak shifts to the right as frequency is increased.

Sound is also refracted in air by layers of air that are of different temperature or pressure—i.e., of different density—so that determination of the sound transmission characteristics under practical conditions is difficult if exact conditions are to be met. Under practical conditions, computations are based on dry air, corrections for relative humidity and frequency are applied, and the worst-case attenuation is taken into account. Theory is checked by measurement in the development process.

The transmission of blast pressures presents a slightly different problem from that of the sounds of explosions[11]. The front end of this progressing wave operates in air that is compressed, hence the velocity of the front of the wave tends to increase. The trailing portion of the wave, on the other hand, operates in a region of reduced pressure. The net result is that the trailing end slows, and the physical length of the wave increases as the wave propagates.

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CHAPTER 3

PYROTECHNIC TERMINAL EFFECTS

SECTION I VISIBLE LIGHT

3-1 ILLUMINATION

3-1.1 REQUIREMENTS

A large and important class of pyrotechnic devices are those which are used for illumination[1,2]. Artificial illumination may be needed to observe enemy troops, weapons, or vehicles; to aid in the accomplishment of a search or rescue task; for night photography; and other similar tasks. Visual inspection dependent on artificial illumination for military purposes may be roughly divided into three categories.

1. *Detection* consists of merely recognizing the presence of an object or target within the field of the observer's vision. Detection of targets of relatively high contrast may be accomplished with illumination levels of 0.1 footcandle or less. Since target motion and the use of peripheral vision enhance target detectability, this level of illumination is not absolute.

2. *Recognition* generally requires between 0.1 and 1 footcandle and involves the ability of the observer to identify the shape or size of a target after it has been detected.

3. *Identification* requires illumination levels high enough to allow the observer to distinguish enough details to make a "friend or foe" type of decision.

Actually, the illumination levels needed for detection, recognition, or identification will vary considerably—depending on the size, range, and contrast of the target; environmental conditions including haze, glare, and battle conditions; and the ability and physical condition of the observer. It is generally conceded that illumination levels between 0.1 and 10 footcandles will satisfy most visibility requirements provided that the target contrast exceeds 0.1 footcandle and that target size subtends a visual angle of 5 min of arc or greater. For comparison a full moon provides 0.02 footcandle, a clear, moonless night sky provides about 0.0001 footcandle of illumination, and a heavy overcast daytime sky about 10 footcandles.

The illumination levels recommended for detection, recognition, and identification are merely guidelines for average field conditions—i.e., normal visibility (5 or 6 miles), average contrast targets (at 0.1 footcandle), average size target (subtends 5 min of arc), and no excessive battle fatigue. If unusual field conditions are encountered, the recommended illumination levels may have to be increased by an order of magnitude or more. Colored targets and moving targets will aid in detection and thus require slightly less illumination.

3-1.2 EFFECT OF FIELD CONDITIONS

The visibility nomograph in Fig. 3-1[1] serves as an aid in estimating the necessary light levels for various field conditions. To use this nomograph the designer must know or estimate the target contrast, the size of the target, the sky-ground ratio, the meteorological visibility, and the liminal optical slant range of the target.

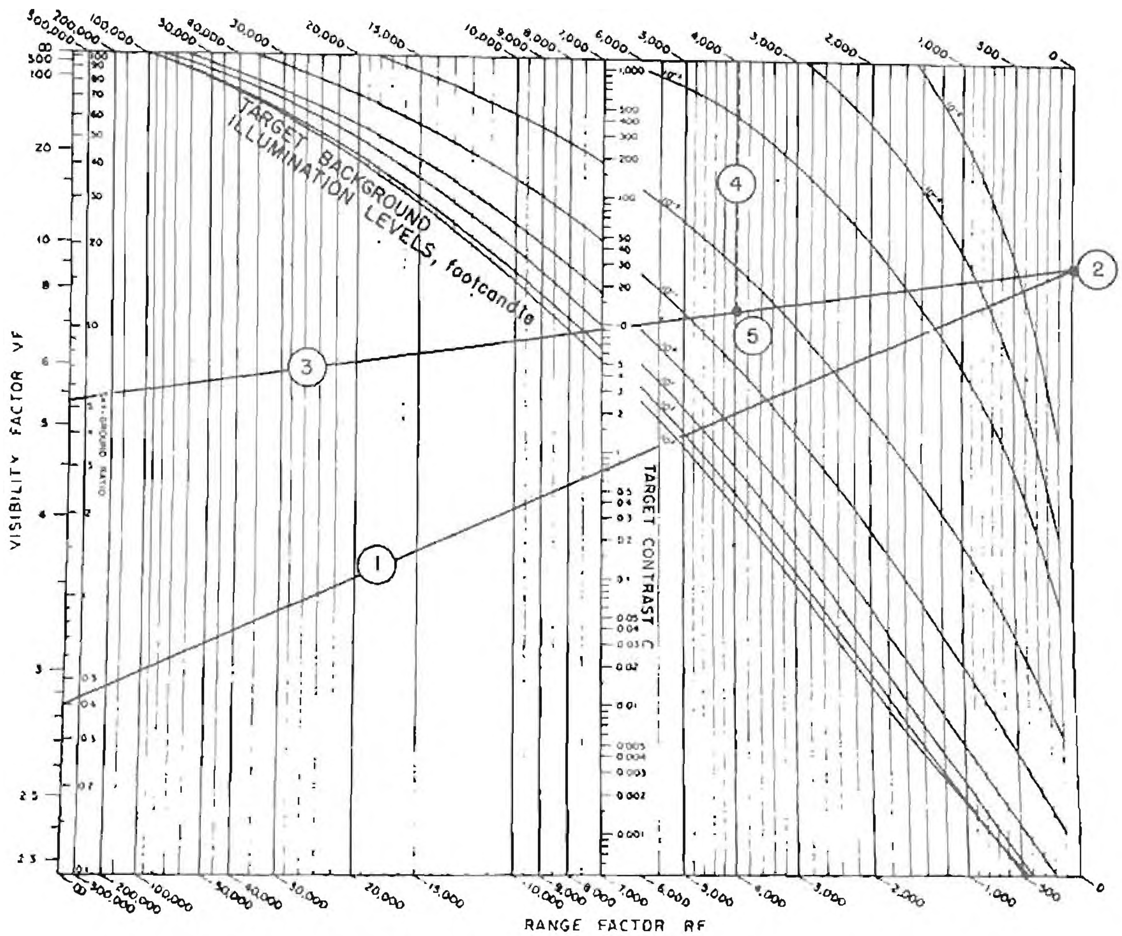

Figure 3-1. Visibility Nomograph

1. *Estimation of Target Contrast*—Assume that the brightness of the target and background are directly proportional to their total diffuse reflectances. Table 3-1[2] lists values of diffuse reflectances (in the luminous or visible radiant energy range), for various natural objects. As an example, the brightness contrast C_b of a tank painted olive drab located on a background of dry sand would be

$$C_b = \frac{B - B'}{B'} \tag{3-1}$$

where

B = brightness (reflectance) of object, %

B' = brightness (reflectance) of background, %

$$C_b = \frac{0.08 - 0.25}{0.25} \approx -0.68$$

The negative sign indicates only that the tank is darker than the sand and probably will appear as a silhouette. The nomograph (Fig. 3-1) will normally predict the illumination level required for liminal (just barely perceptible) visibility of the target. To estimate the illumination required for more positive sighting of the target, it is customary to divide the calculated target contrast in half before entry into the nomograph. For easy visibility, the contrast should be divided by a factor of four.

2. *Estimation of the Sky-ground Ratio*—

TABLE 3-1

TOTAL DIFFUSE LUMINOUS REFLECTANCE OF VARIOUS NATURAL OBJECTS

	%
Class A. Water Surfaces	
1. Bay	3-4
2. Bay and river	6-10
3. Inland water	5-10
4. Ocean	3-7
5. Ocean, deep	3-5
Class B. Bare Areas and Soils	
1. Snow, fresh fallen	70-86
2. Snow, covered with ice	75
3. Limestone, clay	63
4. Calcareous rocks	30
5. Granite	12
6. Mountain tops, bare	24
7. Sand, dry	25
8. Sand, wet	18
9. Clay soil, dry	15
10. Clay soil, wet	7.5
11. Ground, bare, rich soil, dry	10-20
12. Ground, bare, rich soil, wet	5.5
13. Ground, black earth, sand loam	3
14. Field, plowed, dry	20-25
Class C. Vegetative Formations	
1. Coniferous forest, winter	3
2. Coniferous forest, summer	3-10
3. Deciduous forest, summer	10
4. Deciduous forest, fall	15

	%
5. Dark hedges	1
6. Coniferous forest, summer, from airplane	3
7. Meadow, dry grass	3-6
8. Grass, lush	15-25
9. Meadow, low grass, from airplane	8
10. Field crops, ripe	10
Class D. Roads and Buildings	
1. Earth roads	3
2. Black top roads	8
3. Concrete road, smooth, dry	35
4. Concrete road, smooth, wet	15
5. Concrete road, rough, dry	35
6. Concrete road, rough, wet	25
7. Buildings	9
8. Limestone tiles	25
Class E. Miscellaneous	
1. Black velvet	1
2. Newspaper	50
3. Aluminum	53-85
4. Aluminum paint	75
5. Gray paint	70
6. Olive drab paint	8
7. Russian vehicles	5-35
8. Nylon fabric, olive drab	10
9. Human skin, Caucasian	45

The sky-ground ratio is the ratio of the sky brightness to the ground brightness. This factor is of importance if the visual field in which the tank appears is composed of both sky and "nonsky" background. If the visual field is composed only of sky or only of some other background (the ground as viewed beneath an aircraft, for instance), then the sky-ground ratio will be 1. Table 3-2[1] will be helpful for estimating the sky brightness when it is applicable. The background brightness can be estimated by knowing the brightness of the illuminating source and multiplying it by the reflectance of the background. Since the visibility nomograph (Fig. 3-1) will often be employed to determine the illumination, (i.e., it will not be known previously), the *expected* illumination level must be used to estimate background brightness. In the sand and tank example, the background brightness of dry sand (reflectance = 0.25) under 0.1 footcandle of expected illumination would be

$$0.25 \times 0.1 = 0.025 \text{ footcandle}$$

If there is a full moon then the sky brightness would be 0.01 footcandle and the sky ground ratio would be

$$\frac{0.01}{0.025} = 0.4$$

3. *Estimation of the Visibility Factor*—The visibility factor VF is expressed as

TABLE 3-2

SKY BRIGHTNESS

Ambient Condition	Brightness,† millilamberts
Hazy*	10,000
Clear	1,000
Light Overcast	100
Heavy Overcast	10
Twilight	1
Deep Twilight	0.1
Full Moon	0.01
Quarter Moon	0.001
Starlight	0.0001
Overcast Starlight	0.00001

*The maximum brightness condition which is likely to be encountered is that of the sky on a slightly hazy day at noon.
†1 footcandle ≃ 1 millilambert

$$VF = V\sqrt{\frac{100}{A}} \qquad (3\text{-}2)$$

where

V = meteorological range, mi

A = target area, ft^2

As an example, if it is a clear night with a meteorological range of 6 mi and the target area is 125 ft^2 (the approximate area of a small tank) then the visibility factor would be

$$6\sqrt{\frac{100}{125}} = 5.38$$

It should be noted that visibility as normally reported in weather forecasts is about 3/4 of the meteorological range. Meteorological range for various weather conditions is listed in Table 3-3[1].

4. *Estimation of the Range Factor*–The range factor is dependent upon the liminal optical slant range and the area of the target. (If the contrast value found in Step 1 was divided by a factor of 2 or 4 to give a margin of reliability in sighting then the term "liminal" is not applicable.) The range factor RF is found as follows:

$$RF = (OSR)_{lim}\sqrt{\frac{100}{A}} \qquad (3\text{-}3)$$

where

$(OSR)_{lim}$ = (liminal) optical slant range of the target, yd

With the foregoing example, if the target is at an optical slant range of 4400 yd then the range factor would be

$$4400\sqrt{\frac{100}{125}} = 3950$$

TABLE 3-3

VISIBILITY, METEOROLOGICAL RANGE, AND ATTENUATION COEFFICIENT FOR TYPICAL WEATHER CONDITIONS

Weather	Visible Range, yd	Meteorological Range, yd	Attenuation Coefficient, per mile
Dense Fog	50	67	136
Thick Fog	200	267	34
Moderate Fog	500	667	13.6
Light Fog	1,000	1,330	6.8
Thin Fog	2,027	2,700	3.4
Haze	4,050	5,400	1.7
Light Haze	6,080	8,100	1.13
	8,110	10,800	0.85
Clear	10,100	13,500	0.68
	12,200	16,300	0.57
	14,200	18,900	0.49
	16,200	21,600	0.42
	18,300	24,400	0.38
Very Clear	20,300	27,100	0.34
	22,300	29,700	0.31
	24,300	32,400	0.28
	28,400	37,900	0.26
	32,400	43,200	0.21
Exceptionally	36,500	48,700	0.19
Clear	40,500	54,000	0.17
	48,900	65,200	0.14
	75,200	100,000	0.09
	146,000	195,000	0.04
Theoretically Pure Air	339,000	452,000	0.02

It is possible to estimate the $(OSR)_{lim}$ if the illumination level is known by simply reversing this procedure. Thus

$$(OSR)_{lim} = \frac{RF}{\sqrt{\frac{100}{A}}}, \text{ yd} \qquad (3\text{-}4)$$

5. *Estimation of the Illumination Level*—All necessary values have been derived, and it is now possible to enter the nomograph of Fig. 3-1 and make an estimate of the illumination level. For clarity, the previously derived values are summarized:

(1) An olive drab tank on dry sand has been estimated to have a target brightness contrast of −0.68.

(2) The sky-ground ratio has been estimated as 0.4.

(3) The visibility factor was computed to be $VF = 5.38$.

(4) The range factor was computed as $RF = 3950$.

To use the nomograph, Fig. 3-1, a straight line (1) is drawn from the sky-ground ratio through the value of target contrast and extended to intersect the right-most vertical line at (2) (zero range factor). From this point of intersection a second straight line (3) is extended back (to left ordinate) to intersect the computed visibility factor. A vertical line (4) is now drawn from the computed range factor so that it intersects the second (drawn) line at (5). This intersection will fall on or near the illumination level curves and will thus give the designer an estimate of the illumination level necessary to observe the target. The resulting illumination required to detect the tank under the stated conditions falls between 0.01 and 0.1 footcandle.

Fig. 3-1 predicts or uses the *liminal range* of visibility. The *sighting range* or distance at which the target may be seen with some confidence is found by dividing the contrast by two before entry into the nomograph. For easy visibility the contrast should be divided by at least four.

3-1.3 EFFECT OF FLARE HEIGHT AND INTENSITY

Now that the designer has been given a method of estimating the illumination level necessary to observe a given target under given conditions, it becomes necessary to determine in a practical manner the intensity and/or the height over the target of the illuminant flare which is to provide the desired illumination. The most general description of the relationship among ground illumination, flare intensity, and flare height is expressed by

$$r^2 + h^2 = \frac{I}{E} \cos\theta, \text{ ft}^2 \qquad (3\text{-}5)$$

where

r = range (radius) or distance of the target from a point directly beneath the flare, ft

h = height or altitude of the flare, ft

I = intensity of the flare, c

E = illumination level measured at the target, footcandle*

θ = angle included between the line from the illuminating source to the target (considered as a point) and the normal to the target surface at this point, deg

Fig. 3-2 illustrates these parameters. In Fig. 3-3[2] several possible solutions to Eq. 3-5 are plotted for various values of r, h, I, and E. Many practical problems which the designer is likely to encounter can be quickly solved with the aid of Fig. 3-3.

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*See Eq. 2-6 for the relationship of illumination and intensity. A footcandle is in units of ft^{-2}.

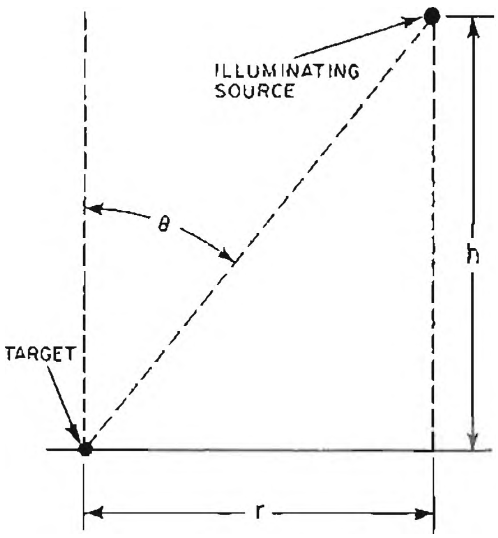


Figure 3-2. Target Illumination Variables

The designer may have calculated (as previously described) or been given a desired illumination level. In addition, it is usually specified that this illumination level be maintained at a given range or radius from the point beneath the flare and for a given length of time. A descent rate for the flare may also be given. With these factors, it is usually the job of the designer to estimate the intensity (in candles) of the flare which can best accomplish the job. Ideally, the designer will be given some freedom of choice with regard to the height at which the flare begins to burn so that the flare intensity value will be as small as possible. The following examples will illustrate the usefulness of Fig. 3-3 in the determination of flare parameters.

Example 1: It is desired to illuminate a radius of 3000 ft to a level of at least 0.1 footcandle for a period of 120 sec. What intensity flare should be used if the initial burning height is 5000 ft? Assume that the flare descends at an equilibrium rate of 10 ft $\sec^{-1}$.

Solution: If the initial height of the burning flare is 5000 ft, then at a descent rate of 10 ft $\sec^{-1}$, the burnout height would be 5000

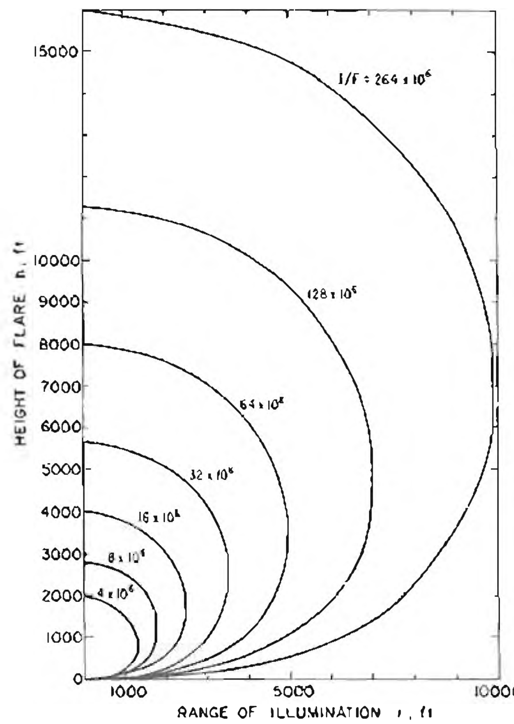


Figure 3-3. Relationship of Flare Height and Radius (Range) of Illumination for Various Values of I/E

ft – (10 ft $\sec^{-1}$ X 120 sec) = 3800 ft. A vertical line is drawn at 3000 ft on the radius of illumination scale of Fig. 3-3 and extended up to intersect the horizontal lines drawn from 5000 and 3800 ft on the height scale. It is seen that an I/E ratio of about 40 X 10^6 will yield the desired illumination level between 5000 and 3800 ft. This corresponds to a flare intensity of

$$(0.1 \text{ footcandle}) \times (40 \times 10^6 \text{ ft}^{-1}) = 4 \times 10^6 \text{ c}$$

Note that a 4 X 10^6 candle flare is rather large but also that the most effective or efficient drop height/flare intensity combination has not been chosen. If no restriction were placed upon the drop height then a 2.5 X 10^6 candle flare initiated at about 2800 ft would be the most efficient combination—efficient because the desired 0.1 footcandle illumination level out to the 3000-ft radius would be maintained with the smallest possible intensity or flare size.

Example 2: What is the maximum radius of illumination which can be maintained at 0.1 footcandle with a 2×10^6 candle flare which is suspended in a relatively stationary position from a helicopter? Also, what is the best height for the flare to be suspended?

Solution: The I/E ratio is

2×10^6 candle/0.1 footcandle = 20×10^6 ft^{-1}

Referring to the curves of Fig. 3-3, it is seen that the maximum radius of illumination is about 2800 ft if the flare is suspended at 1900 ft.

Additional information on flare brightness is contained in Appendix A.

3-1.4 MULTIPLE SOURCE ILLUMINATION

The use of multiple sources may be desirable as a means of reducing the high contrast between light and shadow areas which characterizes a single source, as a method of increasing the illuminance when single sources of adequate intensity are unavailable, and as a way to increase the duration of illumination[2]. The last case can be considered as a special instance of the single source if the overlap in duration is not too great. The use of multiple sources to increase the illuminance requires as high a degree of simultaneity in functioning as possible. A multiple launch is to be preferred because sequential launching not only destroys the simultaneity of functioning but also distributes the units over an area. If the space separation is controlled by circling the launch vehicle, this may be minimized. The effect of space separation is not too severe if the distance between the units and the center of mass of the group does not exceed 10 percent of the source height. This separation may be difficult to achieve by sequential launch at relatively low altitudes if the aircraft ground speed is of the order of 500 kt. At 2000-ft altitude, the desired 200-ft separation would necessitate launching every 0.25 sec. This short interval is difficult to obtain with large flares which suggests that simultaneous launch (or a single larger flare) should be used only if point source illumination is essential. If it is not important to simulate a single source but it is required to increase the illuminance over an area, much larger distances between sources can be accepted.

Two situations are commonly encountered with respect to the pattern in which the sources are distributed. These two conditions will now be discussed in some detail.

If a long, narrow path is to be illuminated, the number and spacing of the flares is calculated from

$$E_p = \frac{I}{h^2}(F_1\cos^3 A_1 + F_2\cos^3 A_2 + F_3\cos^3 A_3 + \ldots F_n\cos^3 A_n) \quad (3\text{-}6)$$

where

E_p = illuminance at point P, footcandle

I = intensity of flare, c

h = source height, ft

F_i = factor, dimensionless

A_i = angle between vertical at the source S_i and the point P, rad

The point P_1 for which E_p is computed is directly below one of the sources. The value of F will be 0, 1, or 2 depending on the position of P with respect to the first and last source S_1 and S_n, respectively, as shown in Fig. 3-4[2].

When two sources S_2 and S_4 are located symmetrically with respect to a source S_3 above the point P, the value of F_n is 2. If only one source exists, as S_1, the value of F_n is 1. When no source exists the value of F_n is zero

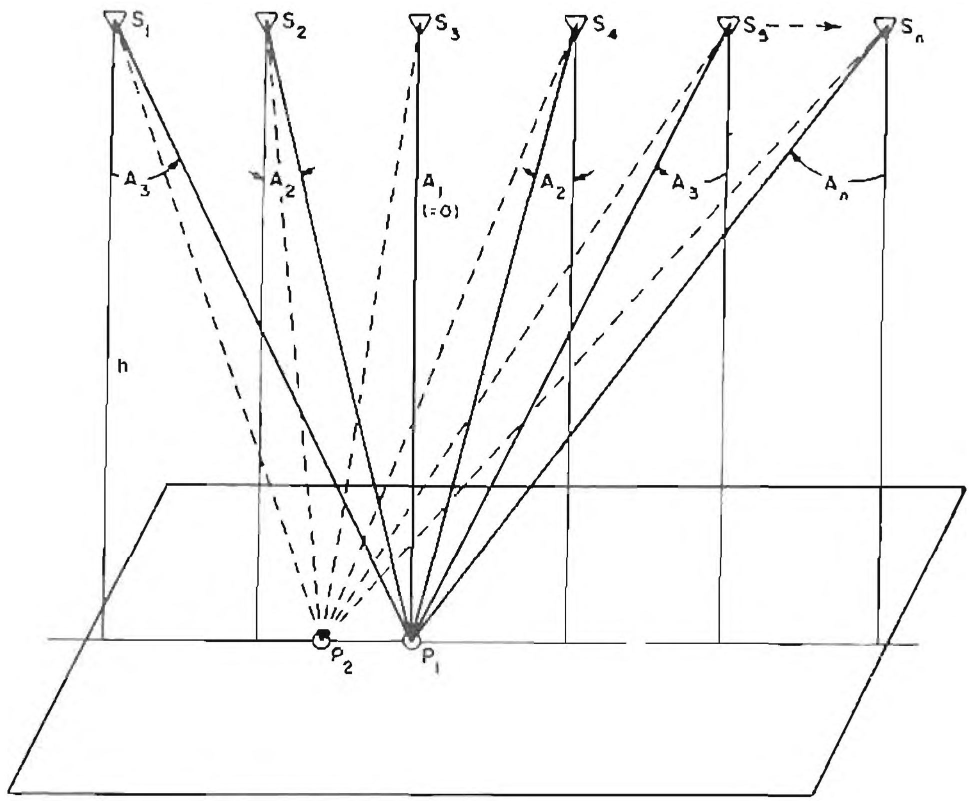


Figure 3-4. Linear, Symmetrically Distributed Source Geometry

Illumination is maximum directly below a flare and minimum half way between the flares. From a consideration of the values taken by $\cos^3 A$, as A increases it is evident that four terms of the series are sufficient for many practical problems, and corresponds to selecting a point located midway of a seven-source string. The minimum value of E_p may be estimated as 80 percent of E_{p_1} for reasonable values of height and separation. While individual cases may arise in which a detailed calculation is required, in many cases a separation equal to 40 percent of the source altitude will be found quite useful. For this separation, the value of E_{p_1} is the following at the center of a 7-flare string (in this particular configuration, $A_i = 0.4\, h(i-1)/h$)

$$E_{p_1} = \frac{I}{h^2}\,[1 + 2(0.83) + 2(0.47) + 2(0.26)] = 4.12\,\frac{I}{h^2}\text{, footcandle}$$

An increase in the number to nine flares increases the coefficient from 4.12 to 4.42. The increase of almost 30 percent in the number of flares used will increase the maximum illumination by only 7.5 percent.

If a circular path is followed and the sources are again uniformly distributed, the illuminance at a point on the ground below the center of the circular path will depend on the number of sources. In the general case, the relation is

$$E_p = \frac{nIh}{b^3} = \frac{nIh}{(h^2 + r^2)^{3/2}}\text{, footcandle} \tag{3-7}$$

where

E_p = illuminance at point P the center of circle on ground, footcandle

n = number of sources

I = intensity of flare, c

h = source height on circumference of circle, ft

r = radius of circle, ft

b = slant range $(h^2 + r^2)^{1/2}$, ft

For a radius $r = 0.4h$, the relation becomes $E_p = 0.8nI/h^2$.

3-1.5 FLARE LOCATION

Not only the level of the illumination but its direction has a strong influence on visibility of a target[2]. This arises from the degree to which long, confusing, deep shadows, or metallic glints from semispecular surfaces are produced by changes in the azimuth and elevation of the source with respect to the target-observer axis. Typically, studies of the optimum location of the source have shown that it should be either in front of or behind the target. An advantage of the order of 3x can result from source positioning in either location, which is of enough value to justify some effort to secure it.

In order to utilize this advantage, an observer will most often find it desirable to locate the source somewhere near, and behind, himself. If it cannot be placed behind the observer, the source must be thoroughly shielded on the observer's side to minimize the interference produced by glare. The change in the state of adaptation of the eye will occur in about 0.1 sec. It is, therefore, important to avoid even momentary exposures of the observer to the unshielded source. The need for this caution is further emphasized when it is recalled that the discrimination of brightness contrast is a function of the background luminance to which the eye is adapted. When the luminance level is below 0.1 footcandle, the ability to discriminate brightness differences decreases very rapidly. A level below 0.1 footcandle would be commonly encountered in night reconnaissance.

3-1.6 ESTIMATES OF FLARE SIZE

In the design of a flare, the diameter and length of the illuminant composition necessary to meet the required candlepower and burning time must be established. One approach to this problem is as follows:

(1) Multiply the product of the candlepower and burning time by 1.3. (The factor provides 30% excess of integrated illumination to allow for variations in candlepower and burning rates in individual illuminants.)

(2) Assume a cross-sectional area for the illuminant composition and divide the product of 1.2 times the candlepower by this assumed area. (This step gives the candlepower requirement, with a 20% excess, of one square inch of burning surface.)

(3) From the compilation of data on various compositions, pick the composition producing the closest candlepower per square inch and determine the volume using the following formula:

$$\text{Volume (illuminant composition)} = 1.3\,\frac{(CP)(BT)(BR)}{(cp)},\ \text{in.}^3 \qquad (3\text{-}8)$$

where

CP = candlepower required

BT = burning time required, sec

BR = burning rate of composition, in. sec^{-1}

cp = candlepower of candidate composition from 1 in.^{2} of burning area, in.$^{-2}$

This equation is not exact; a difference of 30 percent may result.

(4) Length (illuminant composition) = volume/area, in.

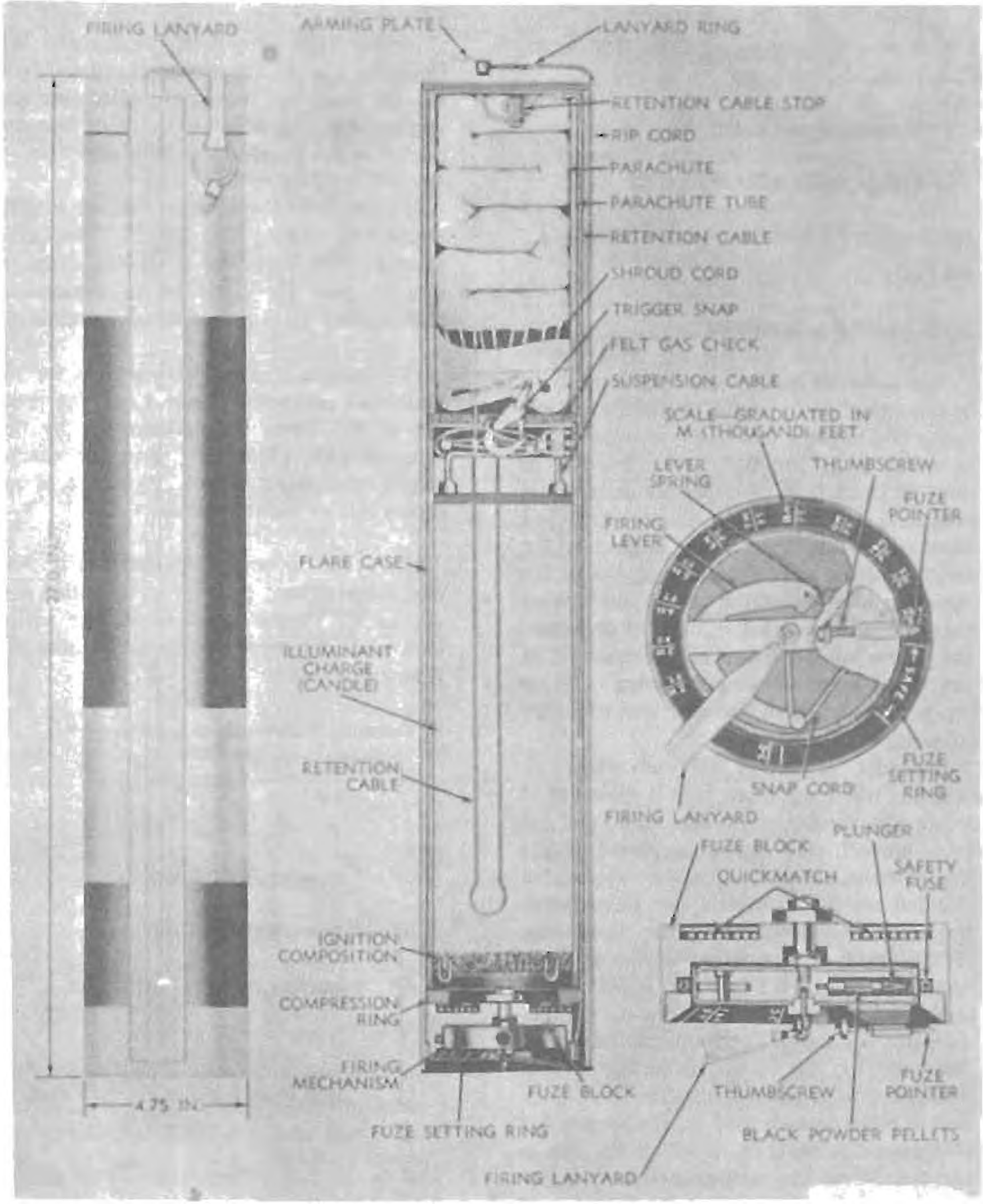


Figure 3-5. Flare, Aircraft, Parachute, Mk 5

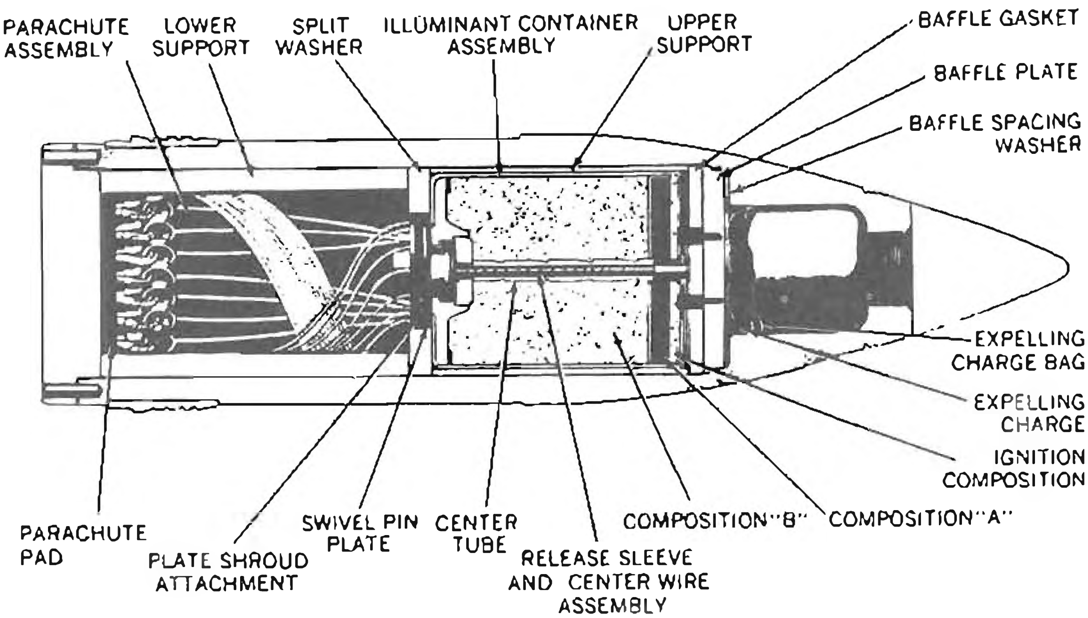


Figure 3-6. Illuminating Artillery Load, Mk 7

(5) If the length is not compatible with the overall flare size repeat steps (2), (3), and (4).

The weight of the illuminant composition is then obtained by multiplying the volume by the density.

Representative examples of illuminating flares are listed in Table 3-4[3,4] and illustrated in Figs. 3-5[3], 3-6[4], and 3-7[4].

3-1.7 TYPICAL ILLUMINATING CANDLES

In general, a pyrotechnic illuminating flare must provide from 0.05 to 10 footcandles of essentially white light for a time of at least 30 sec and in some instances 2 to 3 min[1]. Some of the air dropped flares may provide up to 2 million candlepower whereas a small hand-launched grenade may provide less than 55,000 candlepower to illuminate a nearby area (Table 3-4).

Although white light is often difficult to produce, it provides the best illumination for the greatest range of possible field conditions. For long burning flares (i.e., long burning as opposed to photoflash and tracer pyrotechnics), white or near white light is obtained with mixtures of a fuel which are usually magnesium and oxidizer such as sodium nitrate, potassium perchlorate, or potassium nitrate.

A binder is usually added to the fuel-oxidizer mixture to prevent segregation of particles when blending and loading, and to increase the mechanical strength of the finished candle. The binder may also, in some cases, enhance the burning efficiency, decrease friction and static sensitivity of the mixture, and provide additional control of burning rate. But probably the most important added feature the binder can give is good bonding to the case, which helps to promote laminar burning of the surface of the candle and avoid erratic burning along the side or breakup of the candle.

Resins, waxes, plastics, and oils have been used for binding agents. The most frequently used combination (see Appendix B for others) is magnesium/sodium nitrate/binder which produces a yellow-tinted white light of relatively high efficiency and intensity. By proper choice of ingredient composition, particle size, and binder type, this class of illuminant composition yields illumination values between 10,000 and 40,000 $in.^{-2}$, intensities between 50,000 and 800,000 $in.^{-2}$ of burning surface, and burning rates between 2 and 40 in./min. Further details concerning composition are found in Refs. 1 and 5.

The illuminating compositions are loaded into paper, aluminum, steel, or phenolic tubes and consolidated at 2,000 to 25,000 psi. The inside of the case is usually lined or coated to facilitate loading and provide moisture proofing. Metal liners also prevent erratic disintegration of the case, rapid heat conduction, or voids that could disrupt the laminar type of burning. The case diameters of existing types vary from about 1.5 in. for small surface flares of 40,000 CP to 8 in. for large aircraft flares of 3,000,000 CP or more. Case lengths vary from 5 to 36 in. with loaded weight ranging from 0.75 to over 40 lb. Further physical details may be obtained from Technical Manuals[3,4].

3-2 SIGNALING, MARKING, AND WARNING

3-2.1 TYPES OF DEVICE

According to MIL-STD-444[6], a marker is a sign for labeling a location on land or water, whereas a signal is a device designed to produce a sign for identification, location, or warning. Note that there is a certain overlap in these definitions; authorities disagree on the proper nomenclature in some applications. The discussion which follows will make clear some of the distinguishing features. Whereas signals and markers can take many

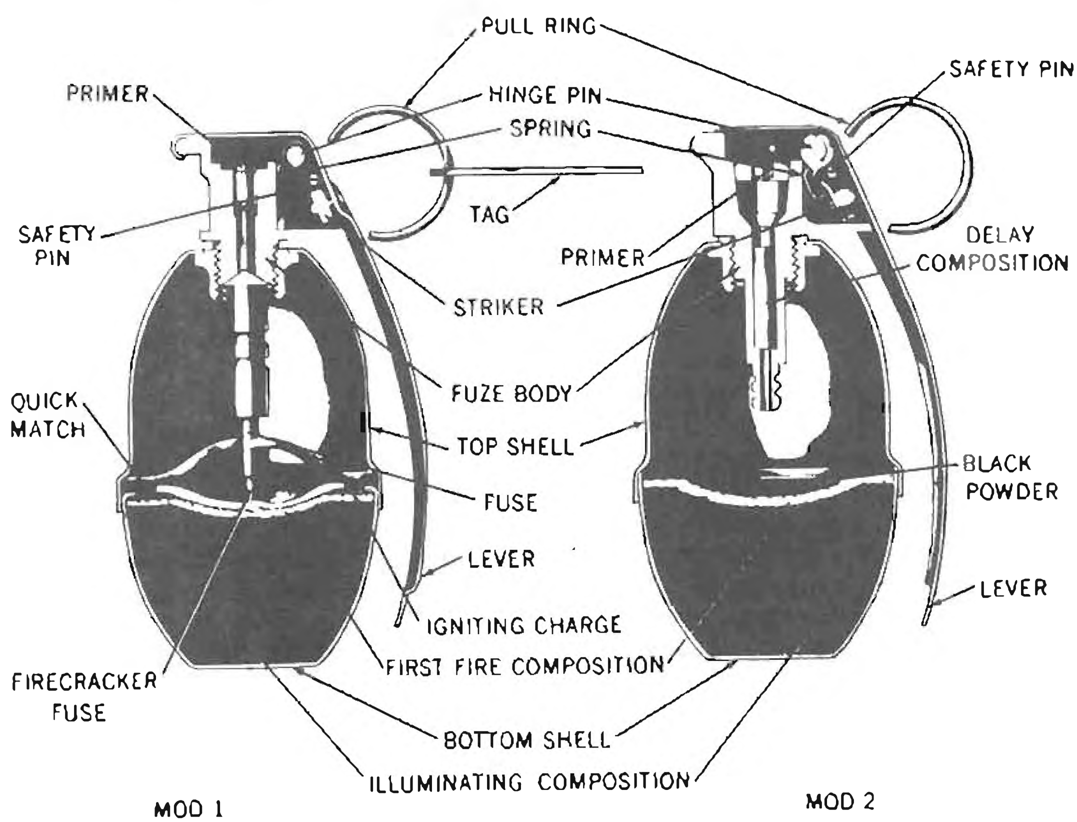


Figure 3-7. Illuminating Hand Grenade, Mk 1 Mods 1 and 2

forms, we are concerned in this handbook only with pyrotechnic devices, and in this paragraph specifically with devices that produce visible light.

Markers are used to identify a location, perhaps as a warning or to facilitate rescue. Markers can be active or passive, i.e., they are a direct source of light or are merely observable in reflected light. Signals are generally active. They convey some form of intelligence in accordance with a prearranged code. For example, a red star might mean to hold position whereas a green star might mean to advance.

Both signals and markers have similar design features. Their visibility criteria are the same. The outstanding difference between them is the length of burning time. Markers generally have a longer burning time than signals. One type of marine marker uses water for activation to produce acetylene and phosphine gases in a self-igniting mixture. This device burns for 45 min, producing a 9-in. flame. Railroad flares, called fusees, may be considered either marking or warning devices. These are made to burn for relatively long periods of time (20 min or longer) and with intensities of several thousand candlepower.

Light sources used as signals are generally smaller than flares in size, intensity, and duration of burning[3]. The star, a common signal, is like a miniature flare except that the burning front is uniformly distributed about the star rather than linearly as with flares. Stars are ejected singly or in multiples of two to five from aircraft or from the ground.

TABLE 3-4

TYPES AND EXAMPLES OF ILLUMINATING FLARES

Type	Launched From	Example(s)	Approx. CP	Burn Time, sec	Primary Use
Aircraft, Parachute Suspended	Aircraft	M138	1,500,000	360	Target Illumination
		Mk 45, Mod 0	2,000,000	210	Target Illumination
		M8A1	350,000	165 to 195	Emergency Night Landing
Airport, Surface	N.A.	M76	600,000	300 to 420	Illumination for Emergency Landing
Artillery Load, Parachute Suspended	6 in./47 gun	Mk 7, Mod 0	600,000	50	Target Illumination
	155 mm Howitzer	M485 Series	1,000,000	1200	Target Illumination
Cartridge, Parachute Suspended	60 mm Mortar	M83A2	145,000	25	Target Illumination
	4.2 in. Mortar	M30	500,000	70	Target Illumination
Surface Trip, Parachute Suspended	Ground	M48	110,000	20	Illumination of Infiltrating Troops
Surface Trip, Stationary	Fixed to Tree or Stake	M49	40,000	55	Illumination of Infiltrating Troops
Grenade	Hand	Mk 1	55,000	25	Illumination of Nearby Areas

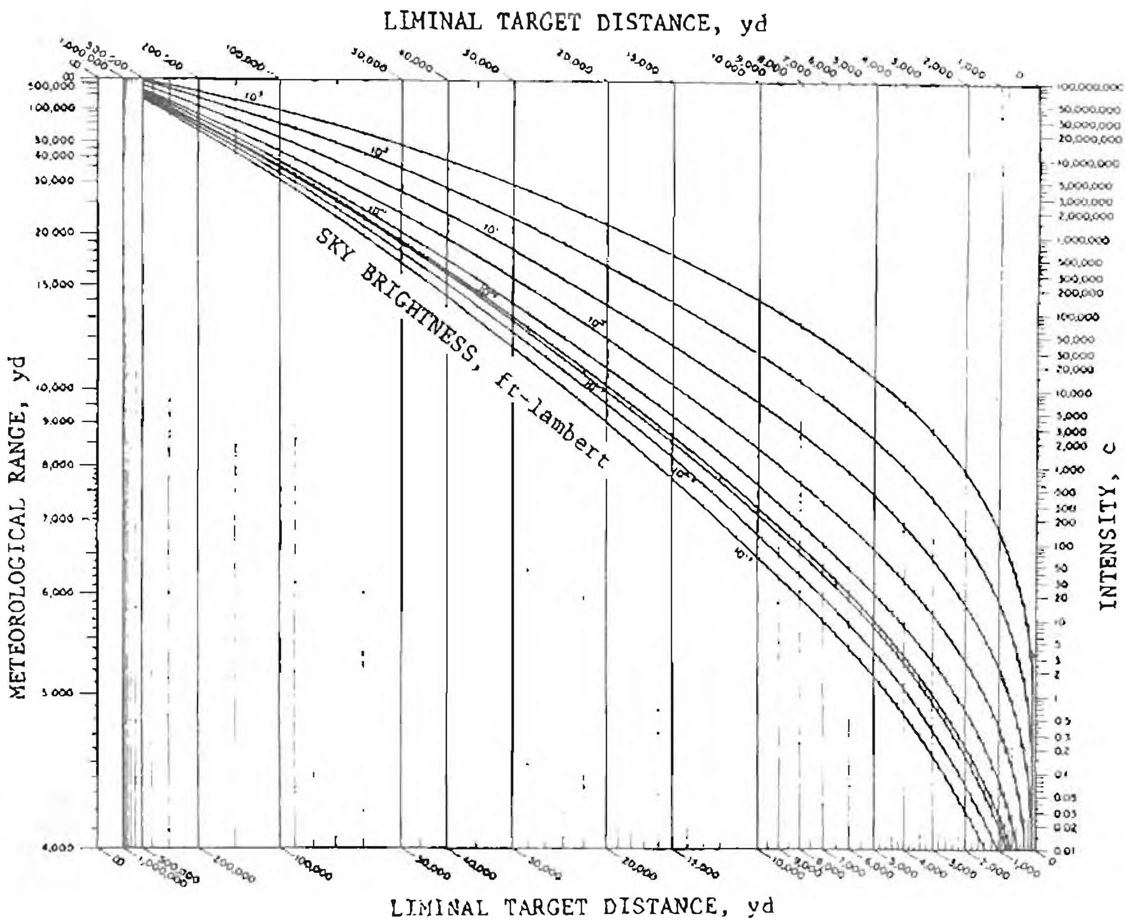


Figure 3-8. Visibility of Signals

Ground signals are usually shot upward and designed to operate at heights of from 600 to 2000 ft. Most of the stars are free-fall devices that are ejected as submissiles and burn for about 2.5 to 10 sec. The total weight of the star mixture seldom exceeds 0.5 lb. A few stars are parachute-supported or rocket-propelled.

3-2.2 VISIBILITY CONSIDERATIONS

Visibility considerations are used both to determine the limits of already-designed pyrotechnic devices and to establish the characteristics that to-be-designed devices must have to operate effectively. The effects of source brightness, background brightness, and meteorological range on liminal (threshold) visibility of light sources have been summarized in the form of a visibility nomograph shown in Fig. 3-8[1]. Effective use of this nomograph requires considerations of the following factors:

(1) The light sources are assumed to be point sources. Most of the currently used stars fulfill this condition when viewed from the liminal distance.

(2) The background brightness must be taken into account because it contributes to the liminal distance. Determination of background brightness in advance is admittedly inaccurate by most technical standards. Considerable judgment is necessary to select a

TABLE 3-5

INCREASE IN ILLUMINATION REQUIRED FOR POSITIVE RECOGNITION

Field Factor Applied to Threshold Candlepower	Detectability of Light Source
1	Light source difficult to find even if location is known.
2.5-5	Light source moderately difficult to find if location is approximately known and observer is on steady platform and has long time for search.
5-10	Light source easy to find under circumstances above.
20-30	Light source easy to find under reasonable circumstances at night, for example, search field no greater than 100 deg, observer can give his full attention. Difficult to find in daytime unless observer knows where to look.
100-150	Light source can be found under strenuous circumstances at night, and under most circumstances in the daytime if the search field is not too large.

proper value. Table 3-2 lists values of typical ambient condition for sky brightness. Note that the units in this table are millilambert while the units for sky brightness in the nomograph are ft-lambert. To convert millilambert to ft-lambert, the millilamberts are multiplied by 0.929. However, because of the inherent inaccuracy, nothing is gained by making this conversion. We may consider millilamberts and ft-lamberts equal.

(3) The meteorological range that is required is readily obtained from weather forecasts. The usual forecast reports visibility values; they are three-fourth of the meteorological range. Table 3-3 lists visibility and meteorological ranges for different weather conditions. Once again some judgment is necessary in the selection of the applicable weather conditions.

At this point we have all of the inputs required to determine liminal target distance in terms of intensity of the light source. The nomograph of Fig. 3-8 may now be used. However, one more consideration is required to make the information thus obtained useful.

A field factor must be applied to these data to allow for positive detectability of the signal. This factor, when multiplied by the intensity of the light source determined for liminal conditions, permits use of the information for field applications with more certainty. Table 3-5[1] lists the field factors needed for various conditions. It can be seen that if liminal conditions are used (field factor of 1), the light source will be difficult to find even if the location is known. If the approximate location is known and the observer is stationary, a field factor of 5 to 10 permits positive recognition of the signal. A field factor of 100 to 150 makes the liminal signal detectable at night even under adverse conditions and also under most circumstances in the daytime.

A number of basic signal colors is available. These include red, green, and yellow in addition to white. Flare color is important when conveying a message but color also plays a role in the transmission of light[7]. The human eye is more responsive to the green portion of the spectrum than to the other colors. However, red light is more easily transmitted through the atmosphere. This is true to the extent that red emitting devices, at the same emitting power, are more readily discerned that most other colors and under most circumstances.

3-2.3 HEIGHT CONSIDERATIONS

For signals that are projected from the ground or for those ejected from aircraft and observed from the ground, it is important to determine the height at which the flare ignites and to consider how far the observer can see this flare. To accommodate for the curvature of the earth, both the height of the observer and the height of the light source must be considered[1]. Assuming no obstructions, as would be the case on the ocean or on a prairie, the limiting range for direct line of sight is

$$x = 1.325\,(H + h),\ \text{mi} \qquad (3\text{-}9)$$

where

x = limiting range for direct line of sight, mi

H = height of the signals, ft

h = height of the observer, ft

Applying this equation to a star 100 ft in the air observed by a man with his eyes 5 ft off the ground results in a limiting direct line of view distance of 139 mi. This value represents a limiting condition, but does not imply that a man could actually see a flare from this distance nor that signals are designed for this criterion.

In most instances there are obstructions to line of sight. Trees, buildings, hills, and other obstructions limit the range of vision. For this reason, it is desirable to plan on projection heights greater than those allowed for flat, level ground.

3-2.4 TYPICAL DEVICES

A typical aircraft illumination signal is illustrated in Fig. 3-9[4]. This ground-launched signal for attracting aircraft is designed to be ignited by hand, whereupon it is immediately thrown into the water, where it will right itself; or it can be placed upright on the ground. To operate, the hand is placed around the signal in such a way as to hold the release lever against the body of the signal. The safety cotter pin is pulled and the signal is then thrown or placed. Ignition is accomplished by activation of the primer, that

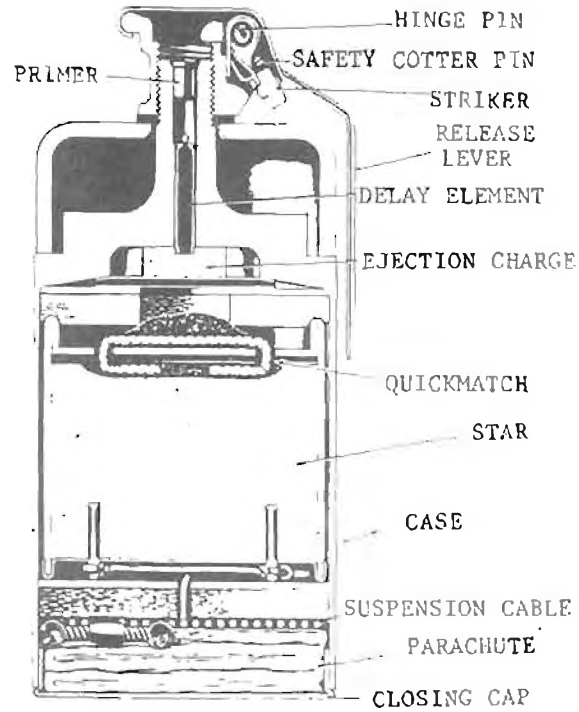


Figure 3-9. Aircraft Illumination Signal, Mk 6

ignites the 3-sec delay element. At the end of this delay, the ejection charge fires, propelling the lower portions of the signal skyward and igniting the quickmatch leading to the star composition. At operational altitude, the parachute opens and the signal burns for approximately 25 sec. The stars may be red, green, or white having the respective candlepower of 2400, 1500, and 27,000.

Pyrotechnic devices utilizing a dye are effective for marking locations on water. The Marine Location Marker, AN-MARK 1 (Fig. 3-10[4]) is typical of this group. The device is

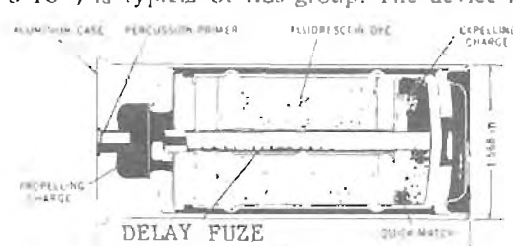


Fig. 3-10. Marine Location Marker, AN-Mk 1

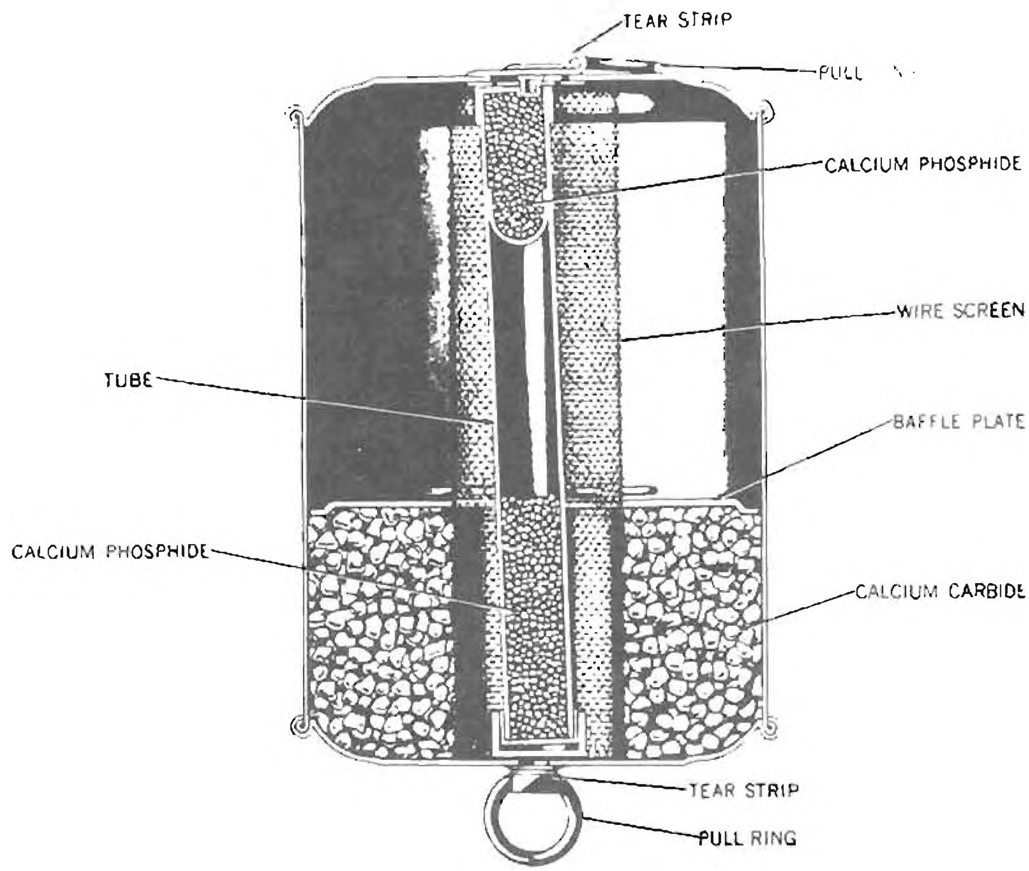


Figure 3-11. Marine Location Marker, Mk 2

fired from a pyrotechnic pistol and produces a green dye on the water surface. The primer ignites the propelling charge that projects the inner case and ignites a 10-sec delay fuze. The inner case floats on the water and the delay fuze ignites the expelling charge, bursting the inner case, and spreading a bright green fluorescent dye over the surface of the water.

The Marine Location Marker, MARK 2 operates on a different principle. Fig. 3-11[4] shows this device. When the tear strip is removed, and the device placed in water, the water reacts with the acetylene and phosphine filler. The filler ignites spontaneously in about 90 sec and then ignites the acetylene as it escapes from the upper hole in the can. The flame produced is about 9 in. long, persists for 45 to 55 min, and will reignite if extinguished by wave action.

3-3 TRACKING

Tracking applications of light-generating pyrotechnic devices vary widely thus requiring devices of different sizes and light outputs. One of the most widely known applications of tracking is in tracer ammunition. Ammunition employing tracers permits the gunner to follow the flight of projectiles and determine proper aiming to inflict maximum damage to the target. Pyrotechnic light sources are also used to track missiles and rockets visually or by camera.

Common small arm tracers are produced by packing pyrotechnic mixtures into a cavity in the base of a bullet. The tracer composition allows tracking of the projectile because the light emitted provides a sharp contrast to background light. Determination of the light intensity required for visibility may be made using the criteria presented in the nomograph for light signals (Fig. 3-8). The visibility of tracer ammunition is generally better than that of other types of signals because the gunner knows where the light will appear and because he has repeated opportunities to observe the light path. These considerations permit use of a smaller field factor.

The necessary burning time for a tracer composition is determined mainly by the range and velocity of the ammunition. Few tracers are required to burn longer than the maximum flight time anticipated for the projectile unless they are also intended to provide incendiary effects, an additional feature of many tracer projectiles (see par. 3-27 on combination effects).

The preferred color for tracer charges is red because of the good transmission qualities of red light but other colors and white also have been used. At times more than one color may be desirable, e.g., when a number of weapons are being fired at a single target.

Tracking flares are used for tracing the paths of bombs or missiles. In this application, several approaches are used for visual indications. The light output of the tracking flare may also be applied to instrumentation including photography.

The intensity and time needs for the illuminating charges vary in each application. Intensities for most of the tracking pyrotechnics, in terms of visibility, may be derived from the signal visibility criteria presented in Fig. 3-8.

3-4 PHOTOGRAPHY

3-4.1 GENERAL

Photography is the record of images produced on sensitized material by some form of radiant energy[8]. Photographs are associated with pyrotechnics in two main functions – (1) pyrotechnics provide a light source for taking photographs, and (2) photographs provide a means of evaluating pyrotechnic devices and systems using such devices.

Nondaylight photography began with flash powders, which are in reality pyrotechnic mixes. Currently there are a number of applications of photoflash cartridges and bombs in aerial reconnaissance and a number of applications in which photography is used in evaluating pyrotechnic devices. Par. 5-2.10 discusses the aspects of photography that relate to instrumentation and par. 3-3 describes some applications of pyrotechnic photography for tracking purposes.

The general subject of photography, of course, covers a much broader field than that within the scope of this handbook. Ref. 8, for example, treats the subject over a broad range, provides details on many general aspects, and furnishes information on specific processes and special equipment such as aerial cameras.

3-4.2 SENSITIVE FILMS

Essential to the process of photography are sensitive materials that convert light or other radiant energy into the permanent image desired. Film sensitivity may be learned from manufacturers or from military documents that the photographer commonly uses.

Extensive tests have been carried out to arrive at a means for expressing the sensitivity of films in such a way that photographers may use the film effectively knowing only the characteristics of the light source and the values of reflected light from the object being photographed[9]. These studies resulted in expressions for the speed of a film known as the ASA (after the former American Standards Association) speed. To arrive at the expression, a point was selected on the density-exposure curve where the slope is 0.3 times

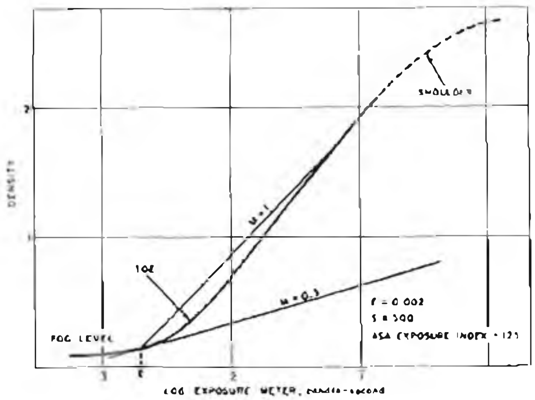
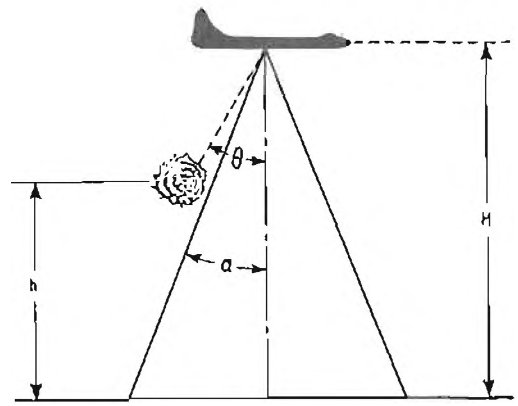


Figure 3-12. Typical Characteristics of Black and White Negative Material

the average slope of a subject having a range of log luminosities of 1.5. The process of determining the ASA speed from this curve is quite simple. Refer to Fig. 3-12[1] representing a typical black and white negative material. The meaning of the curve will become clear when considering the following facts. The density of the developed negative varies with the exposure. The greater the light intensity-time product striking the film, the darker (more dense) the negative. The main, S-shaped curve for this example has an area where only fog level is produced at exposures of less than 0.001 meter candle-seconds (−3 log units) whereas on the upper exposure area, the density becomes greatly increased to the point where there is little differentiation. The shoulder is where this begins to happen.

The ASA speed is now determined in the following manner. An average slope is determined for the sensitivity curve, in this case a slope of 1 was considered to be average. A line with 0.3 of this slope is then fitted to the sensitivity curve. The so-called sensitivity point is that point at which the 0.3 slope line becomes tangent to the sensitivity curve. The reciprocal of the exposure at this point is the film speed. In the example of Fig. 3-12 the exposure E is 0.002 m-c-sec, the film speed S is 500, and the ASA exposure index is 125.



θ = TRAIL ANGLE H = FLIGHT ALTITUDE
α = CAMERA HALF-ANGLE h = BOMB BURST ALTITUDE

Figure 3-13. Diagram of Bomb Burst and Trail Angle

The exposure index is one-fourth of the film speed.

3-4.3 LIGHT SOURCE REQUIREMENTS

In order to provide a light source for photography, some facts must be known about the subject, the camera, and the film. In normal flash photography the reverse is usually true; i.e., the characteristics of the light source, the ASA film speed, and the distance from the camera to the subject are known and govern the f-stop setting of the camera to gain proper exposure of the film.

In aerial photography, where pyrotechnic light sources are predominantly in use, two important conditions must be met – (1) the light source should be out of the field of view of the camera, and (2) the burst height of the pyrotechnic light source should be 0.6 of the flight altitude. These parameters are depicted in Fig. 3-13[1].

The intensity I required of a light source is determined by

$$I = \frac{6.4\, U_i\, (\lambda f)^2}{i}, \text{ c} \qquad (3\text{-}10)$$

where

I = intensity of the light source, c

U_i = film exposure, m-c-sec

λ = slant distance from camera to target, m

f = f-stop number of the camera, dimensionless

t = exposure time, sec

The U_i value in this equation is best determined experimentally. However, it may be chosen from characteristic curves of the films available (see Fig. 3-12). The center exposure value of the straight portion of the curve is usually selected as the value for U_i. In this curve, the exposure level there is about 0.03 m-c-sec.

The main use for photographic pyrotechnic light sources is for nighttime aerial photography. Let us determine the light required for a hypothetical mission. Suppose that an aircraft is flying at an altitude of 500 m (1640 ft). A photoflash bomb is required that will provide the light source for photographing objects on the surface of the earth from the aircraft within a camera angle of 30 deg. The camera has an f/4.5 lens, and the required exposure for the film is 0.03 m-c-sec. The exposure time needed is 0.01 sec.

Substituting these parameters into Eq. 3-10 the required light intensity is

$$I = \frac{6.4 \times 0.03 \times (500 \times \sec 30^\circ \times 4.5)^2}{0.01}$$

$$= 130 \times 10^6 \text{ c}$$

Examining the characteristics of photoflash bombs from any one of a number of possible sources (e.g., Ref. 1), we see that a number of devices have the required peak intensity. All six types of the T9E7, for example, have the required light output, the least intense being 550×10^6 c. Note also the example of the 175-lb photoflash bomb in Table 4-8 with an intensity of $1,300 \times 10^6$ c. The light source chosen could be more intense than that desired. This will require a computation of the f-stop of the shutter, using Eq. 3-10 with the intensity of the chosen source substituted for I.

It should be pointed out that the success of the photographic mission depends largely upon having the camera shutter open during the time that the pyrotechnic flash peaks in intensity. This deals with the next subject, i.e., synchronization.

3-4.4 SYNCHRONIZATION

Synchronization is provided in a number of ways. Modern devices allow for electronic control of synchronization. A double flash is used in some instances where the first flash signals a photocell in the aircraft that the main flash is about to ignite. The shutter opening and the light intensity of the main flash charge thereby occur nearly simultaneously, allowing for optimum use of light from the main flash charge.

A second method of aerial photography allows for self-synchronization. This technique, known as open-shutter, provides for opening the shutter prior to the actuation of the photoflash bomb or cartridge. The open-shutter technique is limited to events having low levels of background light.

To reduce this method to a mathematical expression, Eq. 3-10 can be rearranged as follows

$$\int I(t)dt = 6.4\, U_i(\lambda f)^2 \qquad (3\text{-}11)$$

The difference is that the left-hand term includes the intensity-time function as an integral. Often this integrated value is tabulated for pyrotechnic light producers in terms of integral light in the units of millions of candlepower seconds[1] (see Eq. 2-6).

3-5 SIMULATION

Simulation is the act of producing the effects of an event without duplicating the event. In the case of military weapons, simulation may be brought about for two main purposes, for training and for psychological purposes. Normally, simulators do not make use of the full battlefield effects of a weapon nor is their cost generally as great as that of the item for which the effect is being produced, although cost is not the primary consideration[3].

Most often simulators mimic battlefield sounds, flashes, and lights produced by service ammunition. In training use, they condition troops for battle without the exposure to the hazard of handling live ammunition.

Air-burst simulators provide a flash of light to simulate the airburst of artillery rounds. The light is accompanied by a sound report. Air-burst simulators may be fired from pyrotechnic pistols or from hand projectors. Generally, a minimum firing angle is specified for the launcher so that functioning will occur at an altitude sufficient to prevent injury to troops. Their main target effects are:

(1) Simulation of an air-bursting projectile by light and sound production

(2) Minimum production of fragments

(3) Convenient means of projection

(4) Adequate delay of burst to achieve proper altitude.

Other simulators employing light as a part of their action include those for ground burst (like the M115 that is similar to the air-burst simulator), booby trap flash simulators (like the M117), booby trap illuminating simulators (like the M118), and gunflash simulators (like the M110).

Target effects on light producing simulators depend to a large extent upon timing conditions desired.

Each type of simulator requires considerable study of the effects that are to be reproduced. For light producers, the influence is mainly that of vision along with association of what is seen with the circumstances surrounding the vision. If, for example, troops know they have no artillery in the area but suddenly see and hear air bursts in the vicinity, the troops will believe that enemy activity includes artillery after all. The tide of battle could be changed merely by simulation of artillery air bursts, perhaps by a very limited force.

Target effects on light producing simulators depend to a large extent upon the timing conditions desired. Visibility criteria of simulators are nearly the same as those for light sources in general. These criteria are discussed in par. 3-2. See also Ref. 1.

SECTION II NONVISIBLE LIGHT

3-6 IR RADIATION

3-6.1 GENERAL

Infrared (IR) radiation has become increasingly important in recent years for such applications as signaling and decoying. The real advantages of infrared radiation are manifold in specific situations but may be summed up as follows:

(1) Radiation occurs in portions of the electromagnetic spectrum not visible to the unaided eye.

(2) Temperatures normally associated with

radiation in the IR spectrum are lower than similar sources producing visible light.

(3) Radiation is capable of greater penetration of fog, smoke, and small particulates.

Some advantages are immediately seen in pyrotechnic applications, perhaps many of them not yet fully utilized. Signals, markers, and warning devices show promise when operated in the infrared region of the spectrum. These would be detectable only to persons properly equipped to receive energy at the proper wavelength.

Another important military use of infrared radiation rests in the detection of objects higher in temperature and/or emissivity than their surroundings. Advances have been made in techniques to accomplish this task to the point where human beings have been observed in a forest background[10]. This detection capability has nothing to do with pyrotechnics; however, pyrotechnic sources when properly designed and used, can effectively mimic the radiation produced by military targets[11].

3-6.2 CONSIDERATIONS FOR IR PYROTECHNIC DEVICES

It is generally believed that sources producing white light from high temperature flames or incandescent sources are good sources of IR energy[11]. This is not necessarily true. Radiation does not depend exclusively upon temperature, but also upon emissivity. One example indicative of high temperature and low emissivity are pyrotechnic reactions producing metal or metal oxide particles at high temperatures which often produce less radiation in the IR than lower temperature reactions. Similarly, some gaseous reactions are poor IR radiators even when the reactions proceed at high temperature.

Recently, the most efficient IR flare produces solid exhaust particles that have high emissivity throughout the spectrum.

3-6.3 IR TARGETS

The characteristics of many targets producing IR radiation are described in Ref. 11. Re-entry vehicles cause IR in the shock-heated air in front of the body, the vehicle surface, ablation product, and the wake. The body and its ablation are primary sources. Jet aircraft radiate IR from engine components (the turbine and exhaust), exhaust gases, aerodynamically heated surfaces, and from reflected sunlight.

Many targets exhibit differences in day-to-night conditions that are of interest to observers. Tanks, trucks, and industrial centers have IR hot spots that can be detected.

Simulation of these targets by pyrotechnic measures in the event of attack could introduce confusion to the attacking force.

3-7 TRACKING

In tracking applications, an IR scanner may be used to depict the position of a target emanating an IR signal. The signal may be implanted to provide intentional radiation in the IR spectrum or it may be inherent in the object being observed.

IR scanners of various types have been developed to yield a relative position of a target. Scanner type, requirements, and sensitivity are discussed in another handbook[11]. Passive scanners for thermal imaging frequently use mechanical scanners operating in wavelengths around 10 microns but wavelengths in the 3- to 5-micron region are also used.

Most scanning devices operate in such a way that a field is dissected by mechanical searching of specific sections in much the same manner as a television camera searches an area. Some arrangement provides for a sweep horizontally and vertically with a single sensor receiving radiation from one portion of the entire field of view of the scanner at a time. The display is synchronized with the

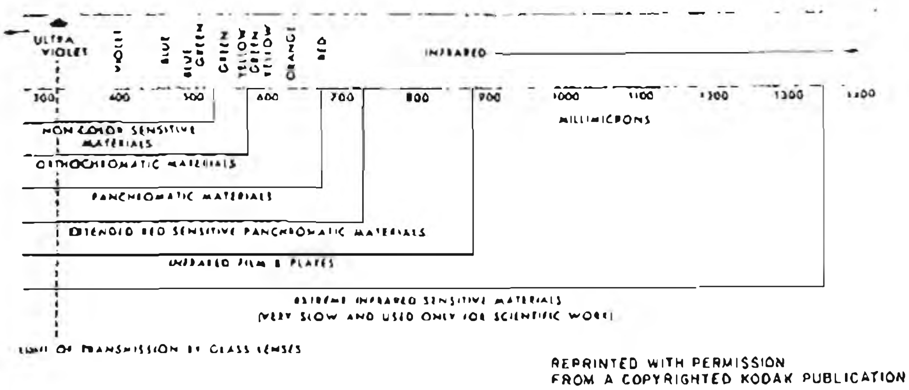


Figure 3-14. The Photographic Active Regions of the Electromagnetic Spectrum

area observed by the sensor; and the observation of an IR source in the field of view causes a difference in the display. The system is normally passive, i.e., it radiates no energy but merely receives whatever IR signals are present.

Scanners are used most frequently to observe objects unintentionally producing IR radiation. However, simply installing an IR radiator on a target to be tracked constitutes a tracking capability for the scanner. This phenomenon is of particular advantage where clutter on radar or visible light make the latter means of tracking undesirable.

3-8 PHOTOGRAPHY

3-8.1 GENERAL

IR photography encompasses many of the fundamental aspects of producing photographic images that are discussed in par. 3-4 and in Ref. 11. The difference between IR and conventional photography rests in the fact that IR photographs reach into longer wavelengths for responsiveness of the camera and film.

Fig. 3-14[12] indicates the regions of the active spectrum for photographic purposes. Photosensitive materials do not cover the entire infrared spectral region. The longest wavelength recorded photographically is about 1350 mμ. However, with most IR photography the range is from 700 to 900 mμ. Emulsions for IR photographs extending to longer wavelength would need to be continually cooled and even camera temperature and body temperature would fog the film. Alternative schemes for IR photography are made possible by the use of converters that convert IR energy into the active area of the film.

3-8.2 IR FILMS

Films sensitive to IR light may be obtained in either black and white or color. The ASA ratings on color and on black and white films serve only as a guide to film sensitivity because much of the radiation being used is neither visible to the photographer nor to the exposure meter[12].

Since IR films are sensitive to other than IR radiation, it is important to provide some form of filtering to minimize the effects of radiation in other regions of the spectrum. Each film has specific characteristics and is covered by recommendations concerning exposure conditions, including the filters to be used.

3-8.3 LIGHT SOURCES

Outdoor light is rich in IR. Haze elimination is accomplished by using IR film with daylight as a source. Ruby lasers have been used to photograph moving projectiles with a light duration of 0.2 μsec.

Photoflash lamps make good IR sources for photography because they produce more IR light in the active range of wavelengths than do service lamps or heat lamps. Photoflash lamps are occasionally coated with an IR transmitting, dark red filter. These lamps are designated R and are useful when bright, visible light must be restrained.

Electronic flash units provide an IR output that may be used for IR photography. Their IR efficiency compared with their visible light is about the same as that of photoflash bulbs and they have the advantage of relative coolness, small size, and short exposure time, all important attributes.

Ambient illumination poses little problem if synchronized photoflash bulbs or electronic flash units are equipped with filters to pass IR in the active range. Information on filters is available from manufacturers of which Ref. 13 is typical.

SECTION III SMOKE

3-9 MARKING, SIGNALING, AND WARNING

Smoke devices are used in much the same manner as light devices for marking, signaling, and warning except that smoke devices are more efficient in daytime operations. For a discussion of the differences among marking, signaling, and warning devices, see par. 3-2 1.

Smokes for signaling or marking must be clearly distinguishable from other smokes (and other clouds) produced for different uses. Hence, colored smokes are usually employed for this purpose because white, gray, and blanket smokes are very limited as signals. In addition, the use of several different colors allows more information to be sent and results in a clearer distinction between the smoke signals and a varying background. Important characteristics of a colored smoke include[1]:

(1) Visibility—condition under which the smoke cloud can be seen and the color recognized.

(2) Duration—time period over which smoke is produced by pyrotechnic ammunition.

(3) Persistence—total time during which a smoke cloud is visible.

(4) Volume—quantity of smoke emitted.

3-9.1 PHYSICAL CHARACTERISTICS OF SMOKE

3-9.1.1 PARTICLE SIZE

The value of a military smoke, regardless of its use, is related to the scattering reflection and absorption of incident radiation by small suspended particles. The number, size, and nature of these particles depend upon the smoke agent, the particular ammunition, and the method of release. Meteorological conditions—such as humidity, wind speed, wind direction, and air stability—affect the density, persistency, and subsequent behavior of the smoke cloud.

A smoke is a suspension in a gaseous medium—such as the atmosphere—of small particles that have a relatively low vapor pressure and that settle slowly in a gravity field. Particle sizes ranging from 0.01 to perhaps 5.0 microns in diameter in a gaseous suspension are classified as smokes. Colored smokes are composed of extremely small, primary particles of approximately 0.2 micron in diameter which coagulate into irregular filaments that may reach a length of several microns[1].

TABLE 3-6

SOME DYES WHICH HAVE BEEN USED IN BURNING-TYPE COLORED SMOKE MUNITIONS

Dye(s)
Red Smoke:
9-diethylamino-7-phenyl-5-benzo (a) phenazinone. Also known as 9-diethylamino rosindone
1-methylaminoanthraquinone
1-(2-methoxyphenylazo)-2-naphthol
2-quinolyl-2-indandione-1,3 (Rhodamine B) plus 1-(4-phenylazo)-2-naphthol
2-aminoanthraquinone plus 1-methylaminoanthraquinone
O-tolylazo-o-tolylazo-β-naphthol (Sudan IV); plus 2-quinolyl-2-indandione-1,3 (Rhodamine B); plus auramine hydrochloride
1-(tolylazoxylylazo)-2-naphthol
Green Smoke:
1,8-di-p-toluidinoanthraquinone
1,4-di-p-toluidinoanthraquinone
1-methylamino-4-p-toluidinoanthraquinone plus auramine hydrochloride
1,4-di-p-toluidinoanthraquinone plus dimethylaminoazobenzene
1,4-di-p-toluidinoanthraquinone plus auramine hydrochloride
1,4-di-p-toluidinoanthraquinone with quinophthalone (quinoline yellow)
Orange Smoke:
1-aminoanthraquinone
1-amino-8-chloroanthraquinone plus quinizarin
1-(4-phenylazo)-2-naphthol
9,10-dianilinoanthracene plus phthaloperinone
1-(4-phenylazo)-2-naphthol plus, 9,10-dianilinoanthracene

Dye(s)
Orange-Red Smoke:
1-(4-nitrophenylazo)-2-naphthol
Yellow Smoke:
Auramine hydrochloride
1-(4-dimethylaminophenylazo)-2-naphthol
1-(4-phenylazo)-2-naphthol (Sudan I) plus either auramine hydrochloride or quinophthalone (quinoline yellow)
N,N-dimethyl-p-phenylazoaniline
Blue Smoke:
1-hydroxy-4-p-toluidinoanthraquinone
Indigo
1-amino-2-bromo-4-p-toluidinoanthraquinone
1-amino-2-methyl-4-p-toluidinoanthraquinone (Alizarin Sapphire, Blue R. Base)
1,4-dimethylaminoanthraquinone
1-hydroxy-4-p-toluidinoanthraquinone
1-methylamino-4-p-toluidinoanthraquinone
N-(p-dimethylaminophenyl)-1,4-naphtholquinonimine
Violet Smoke:
1,4-diaminoanthraquinone
1,4-diamino-2,3-dihydroanthraquinone
1,5-di-p-toluidinoanthraquinone
1-methylamino-4-p-toluidinoanthraquinone plus 2-quinolyl-2-indandione-1,3 (Rhodamine B)
1-methylamino-4-p-toluidinoanthraquinone plus 1,5-di-p-toluidinoanthraquinone

3-9.1.2 VISIBILITY

The visibility of smoke clouds depends upon the light scattering ability of the smoke clouds and upon reflection in the direction of the observer. The illumination of the cloud and its contrast against a background are of primary importance in visibility. With respect to colored smokes used for signaling, the use of color can be deceptive. At low levels of illumination, there is a shift in the color observed if the cloud and the light source are viewed in the same direction from the observer or if the cloud is dilute or of too small particle size.

Contrast requirements for smoke clouds are about the same as those for other illuminated targets as discussed in par. 3-1.2. High winds have a definite adverse effect on the visibility of smoke clouds because they disperse the cloud rapidly. For more detailed information about the travel and persistence of smoke clouds, see Ref. 1.

TABLE 3-7

TYPICAL SMOKE COMPOSITIONS

Type	Composition, %		Application	Typical Devices
WHITE:				
HC-Type C	Hexachloroethane	45.5	Screening	Smoke pots
	Zinz Oxide	47.5	and	Smoke bombs
	Aluminum (grained)	7.0	Signaling	Grenades
Modified HC	Hexachlorobenzene	34.4	Screening	Smokes
	Zinc Oxide	27.6	and	projectiles
	NH_4ClO_4	24.0	Signaling	
	Zinc Dust	6.2		
	Laminac w/catalyst	7.8		
Modified HC	Dechlorane	33.9	Screening	Smoke
	Zinc Oxide	37.4	and	projectiles
	NH_4ClO_4	20.5	Signaling	
	Laminac w/catalyst	8.2		
Plasticized White	White Phosphorus	65.0	Screening	Chemical
Phosphorus (PWP)	Plasticizer	35.0	(antipersonnel)	mortar projectiles
	(Neoprene 100 parts)			
	(Carbon 75 parts)			
	(Zylene 44 parts)			
	(Litharge 15 parts)			
BLACK:				
	$KClO_3$ (200 mesh)	52.0	Screening	Grenades, etc.
	Anthrancene (40 mesh)	48.0		
COLORED:				
Red	Dye-MIL D-3718	40.0	Signaling	Navy floating
	$KClO_3$	24.0		drift signal
	$NaHCO_3$	17.0		
	Sulfur	5.0		
	Polyester resin	14.0		
Red	1-methylamino (AQ)*	45.0	Signaling	Rocket type
	1,4-di-p-toluidino (AQ)*	3.0		parachute
	$KClO_3$ (23μ)	35.0		ground
	Sugar, fine (11μ)	17.0		signals
Red	1-(methoxyphenylazo)-2-naphthol	80.0	Air marker Marking	90 mm Red marker
	NaCl	20.0	ground targets	projectile
Red	Dye (R)	40.0		
	$KClO_3$	28.0	Signaling	Improved
(plastic)	$NaHCO_3$	23.0		grenade
	Sulfur	5.0		fillings
	Polyvinyl acetate in ethyl acetate	3.0		

*(AQ)—Anthraquinone

TABLE 3-7 (Cont'd)

Type	Composition, %		Application	Typical Devices
Yellow	Benzanthrene	32.0	Signaling	Rocket type
	Indanthrene GK	15.0		parachute
	$KClO_3$ (23μ)	30.0		ground
	Sugar, fine (11μ)	20.0		signals
	$NaHCO_3$ (20μ)	3.0		
Yellow	Auramine Hydrochloride	40.0	Air marker, etc.	90 mm yellow
	NaCl	60.0		marker projectile
Yellow	Dye (Y)	40.0	Signaling	Improved
(plastic)	$KClO_3$	29.8		grenade
	$NaHCO_3$	23.2		fillings
	Polyvinyl acetate in			
	ethyl acetate	7.0		
Green	1,4-di-p-toluidino (AQ)*	28.0	Signaling	Rocket type
	Indanthrene GK			parachute
	(golden yellow)	12.0		ground
	$KClO_3$ (23μ)	35.0		signals
	Sugar, fine (11μ)	23.0		
	$NaHCO_3$ (20μ)	2.0		
Green	Dye (G)	40.0	Signaling	Improved
(plastic)	$KClO_3$	26.0		grenade
	$NaHCO_3$	24.0		fillings
	Sulfur	6.0		
	Polyvinyl acetate			
	w/ethyl acetate	4.0		
Violet	Violet dye,		Signaling	Rocket type
	MIL-D-3691	47.5		parachute
	$KClO_3$ (25μ)	28.0		ground
	Sugar, fine (10μ)	18.0		signals
	$NaHCO_3$ (20μ)	4.5		
	Asbestos	2.0		
Orange	8-chloro-1-amino (AQ)*	39.0	Signaling	Grenades
	Auramine	6.0		
	$KClO_3$	22.3		
	Sulfur	8.7		
	$NaHCO_3$	24.0		

*(AQ) – Anthraquinone

3-9.1.3 COLORED SMOKES

There are four basic methods of producing colored smokes[14]:

(1) Dispersion of finely powdered, colored materials

(2) Chemical reactions resulting in the formation of colored particles

(3) Detonation of an explosive, thereby scattering colored material

(4) Volatilization and condensation of a colored material

The first two methods are not satisfactory because they give smokes of small volume and dull color. The last two methods are feasible only if the coloring material is an organic dye. In general the anthraquinone dyes have proved to be superior in producing colored smoke clouds[1]. Table 3-6[1] lists some of the more satisfactory dyes.

The colors that are the most perceptible against the various backgrounds and display optimum visibility at a considerable distance are red, green, yellow, and violet. Methods to measure the quality of a colored smoke include mere observation or comparison to color charts and colorimeters. Typical smoke mixtures, including some white and black smokes, are shown in Table 3-7[1]. Most of the colored smoke mixtures that have been used—with the exception of the yellow smoke mixture containing auramine—are satisfactorily insensitive to friction and impact under normal loading conditions. Yellow smoke mixtures containing auramine are impact-sensitive and require more care in handling and loading.

Colored smoke mixtures are nontoxic under ordinary field concentrations. In general, toxic materials should not be employed as ingredients in signaling devices. Therefore, before experimentation with a particular dye is undertaken, it is important to gain all available information pertaining to the potential hazards involved in its use.

3-9.1.4 TOTAL OBSCURING POWER

The total obscuring power (TOP) ($ft^2\ lb^{-1}$) of a smoke is obtained by multiplying the volume (ft^3) of smoke produced per pound of material and the reciprocal of the smoke layer (ft) necessary to obscure the filament of a 40-W Mazda lamp[15]. The TOP for some white smokes, at low altitudes where atmospheric constituents are plentiful, is shown in Table 3-8[1].

The so-called "standard smoke" is a smoke of such a density that a 25-candlepower light is just invisible when observed through a layer 100 ft[1]. Table 3-9[1] compares some white smoke agents at low altitude in terms of the weight of smoke agent required to produce 1000 ft^3 of standard smoke. The importance of atmospheric constituents is illustrated in Table 3-10[1] where the weight of smoke per unit weight of smoke agent is tabulated.

TABLE 3-8

TOTAL OBSCURING POWER OF WHITE SMOKES

Chemical	TOP, ft^2/lb
White Phosphorus	4600
$TiCl_4 + NH_3$	3030
SO_3	3000
FS	2550
$HCl + NH_3$	2500
HC Mixture	2100
$SiCl_4 + NH_3$	1960
FM	1900
Oleum	1890
$SnCl_4$	1860
$PCl_3 + NH_3$	1600
$PCl_5 + NH_3$	1800
$HClSO_3 + NH_3$	1600
$SiCl_4$	1500
$HClSO_3$	1400
BM Mixture	1400
Berger Mixture	1250
FM + 1,2-Dichloroethane	1235
SO_2Cl_2	1200
$Cl_2 + NH_3$	750
$AsCl_3$	460
Type-S Mixture	460
Crude Oil	200

3-9.2 TYPICAL DEVICES

Ammunition such as hand grenades, mortar and artillery projectiles, float signals, rockets, and bombs are used with colored smoke

TABLE 3-9

WEIGHT OF SMOKE AGENTS REQUIRED TO PRODUCE 1,000 ft^3 OF STANDARD SMOKE

Compound	oz
Phosphorus	0.060
$FM + NH_3$	0.090
SO_3	0.094
FS	0.110
HC Mixture	0.120
FM	0.150
Oleum	0.151
Crude Oil	2.000

TABLE 3-10

WEIGHT OF SMOKE PRODUCED PER UNIT WEIGHT OF SMOKE AGENT AT 75% RELATIVE HUMIDITY

Agent	Amount
Fog Oil	1.0 (does not produce aqueous solution)
Zinc Chloride	2.5 (water vapor absorbed)
Ferric Chloride	3.1 (water vapor absorbed)
Aluminum Chloride	5.0 (water vapor absorbed)
Phosphorus	7.11

mixtures for signaling purposes. Fig. 3-15[1] illustrates a canister containing the smoke composition that is ejected from the projectile when the fuze functions. Table 3-11[1] outlines the characteristics of typical colored smoke devices of the ejection-type. Fig. 3-16[1] is an illustration of a colored marker projectile.

Five different colored smoke compositions with burning rates of 2-3 in. min^{-1} were developed and tested for the 2.75-in. low-spin folding-fin aircraft rocket (LSFFAR)[16]. The

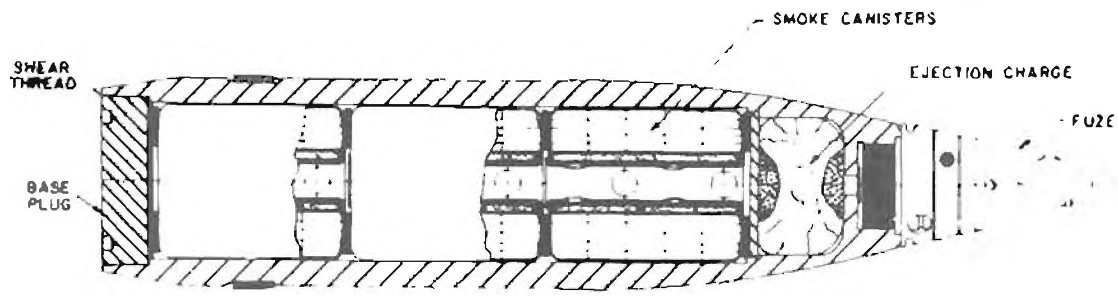


Figure 3-15. 105 mm Colored Smoke Projectile, M84

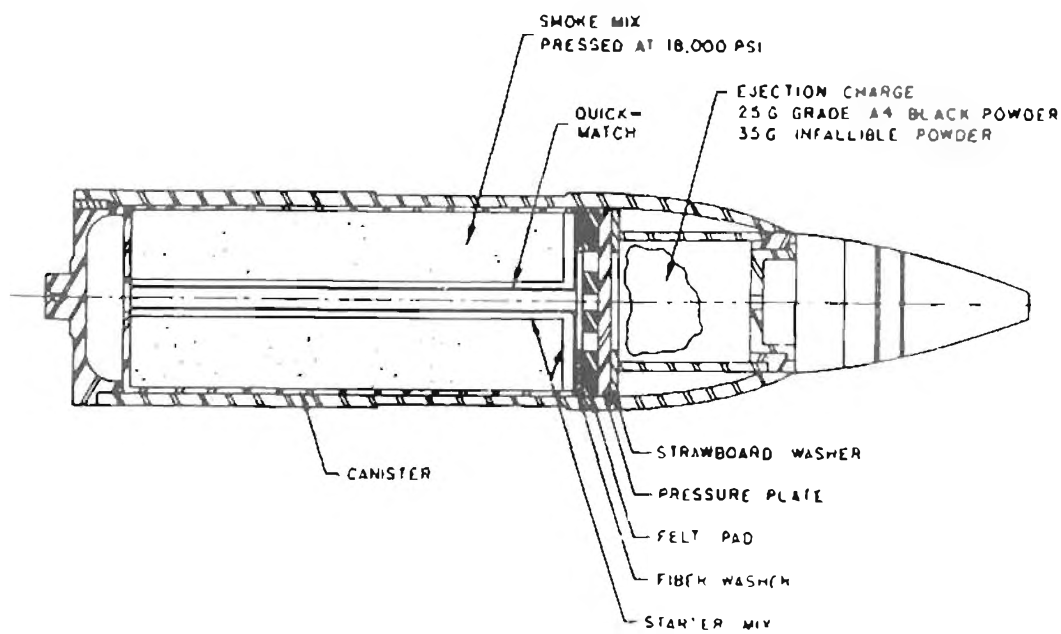


Figure 3-16. 4.2-in. Colored Marker Projectile, Colored Smoke, E75

TABLE 3-11

CHARACTERISTICS OF TYPICAL EJECTION-TYPE COLORED SMOKE DEVICES

Characteristic	4.2-in. Colored Smoke Projectile	M18 Colored Smoke Hand Grenade
Dimensions, in.	Overall—4.2 in. dia by 20 in. long (approx.)	2.5 in. dia by 4.5 in. high
	Canister—3.7 in. dia by 9.3 in. long (approx.)	Six smoke emission holes
Weight	Projectile—23 to 24.5 lb Ejection charge—25 g Grade A black powder 35 g infallible powder	11.5 oz make mixture
Fuze	M54 Time and SQ	M201A1 1.2 to 2 sec delay
Propellant	M6	
Loading Pressure	18000 lb/in.^{2}	
Smoke Duration		50-90 sec
Applications	Time-fuzed for air-burst signaling and/or base-ejected for marking ground positions. Uses red, yellow, green or violet colored smoke for signaling, spotting, or outlining a position	Grenade is thrown or launched from a rifle or carbine by using a M2A1 Grenade Projection Adapter. Uses red, yellow, green, or violet colored smoke for signaling
Visibility	Very good	Easily identified at altitude of 10,000 ft against background of green and brown; clearly seen at a distance of 3 mi.

smoke cloud was to be detected and identified at a short range of 6000 m. Colors were red, yellow, green, violet, and blue.

The Land Warfare Laboratory (LWL) Target-Marker consists of three AN-M8 White Smoke Grenades in two concentric cylinders with an airspace between the cylinders providing a flotation capability[17]. It was used primarily as a landing zone marker for air mobile operations in Vietnam. The marker generally produces a smoke cloud of 3-min duration.

The Signal, Smoke, Ground: Red, M62 (Fig. 3-17[3]) produces six red smoke streamers of about 250 ft in length down from the height of the signal's trajectory. It is fired from a Rifle Grenade Launcher of the M7 series attached to the M14 Rifle. These smoke streamers may be seen up to 5 mi on a clear day. They may be expected to persist for

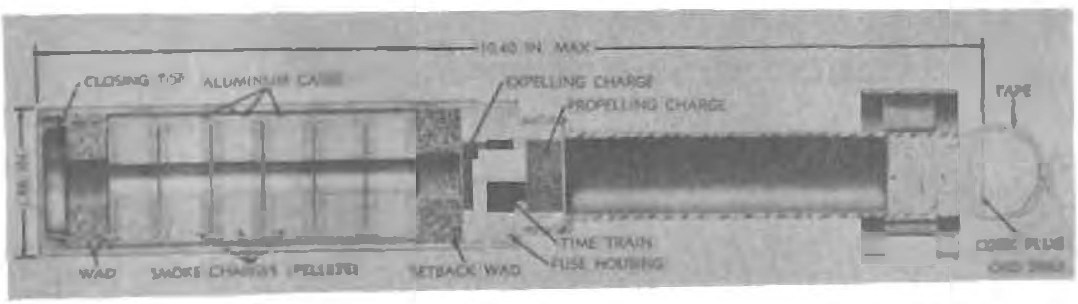


Figure 3-17. Signal, Smoke, Ground: Red, M62

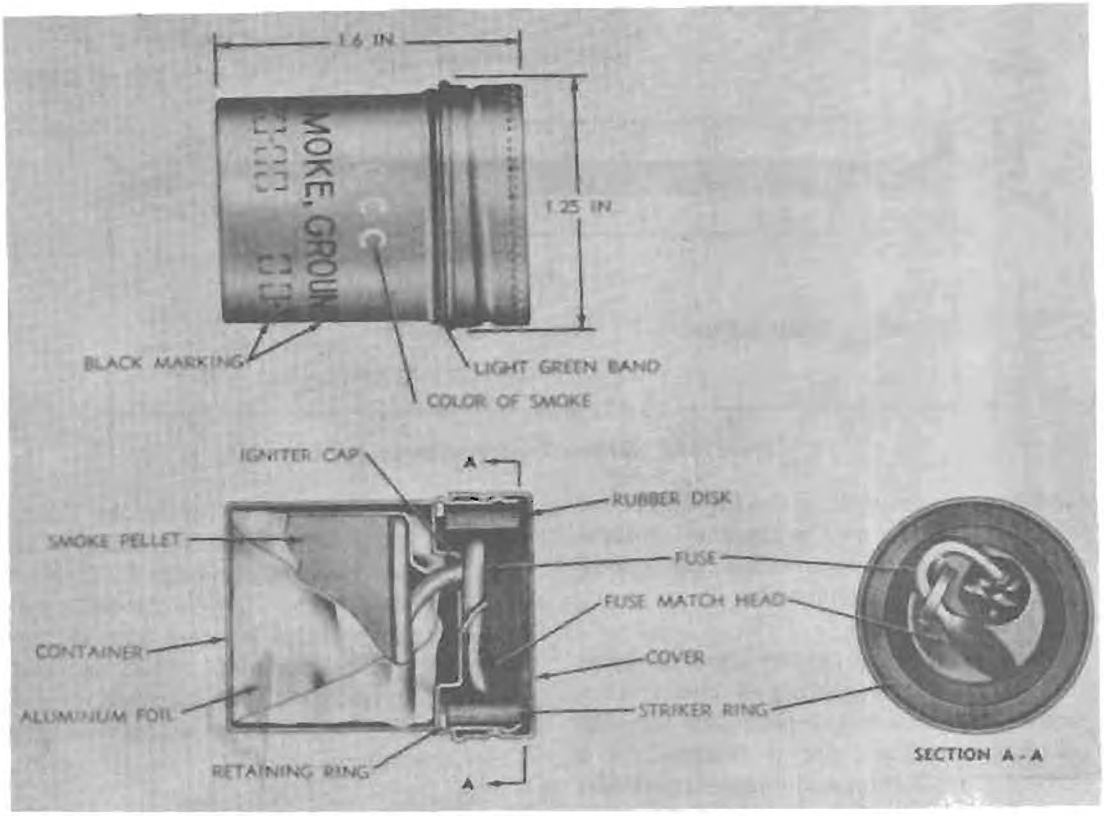


Figure 3-18. Signal, Smoke, Ground: White, XM166

about 20 sec in a wind of 5 mph.

The Signal, Smoke, Ground: White, XM166 is a self-contained unit used by ground troops to signal aircraft or to convey information to each other (see Fig. 3-18[3]). The fuze is ignited by either rubbing the fuze match head with the striker ring or holding a flame close to it. Within 3 to 5 sec, the smoke pellet is ignited, emitting a white smoke cloud that lasts for 13 to 30 sec. The smoke cloud is visible at a slant range of 3280 ft from aircraft flying at an altitude of 1000 ft.

The XM144 Hand-held Ground Signal series was developed to eliminate major deficiencies of the standard M125 and T133 Signal series. Improvements include flight stability, increased height of burst, elimination of smoke and luminous trails at launch, and improved color definition of smoke components[18]. Maximum altitude of functioning is 750 ft with 60-sec smoke duration of Smoke Parachute, XM150, and a burning time of 7 to 8 sec for the Smoke Streamer, XM153[18]. Colors of smoke include green, red, yellow, and violet.

3-10 TRACKING

3-10.1 USE AND CHARACTERISTICS

Optical tracking of projectiles, high speed aircraft, and missiles both at sea level and high altitudes is aided by the use of smoke producing devices such as generators or tracers. The ability to locate and track vehicles along the flight path is optimized by these devices, and the loss of significant data is minimized. Because of the wide range of

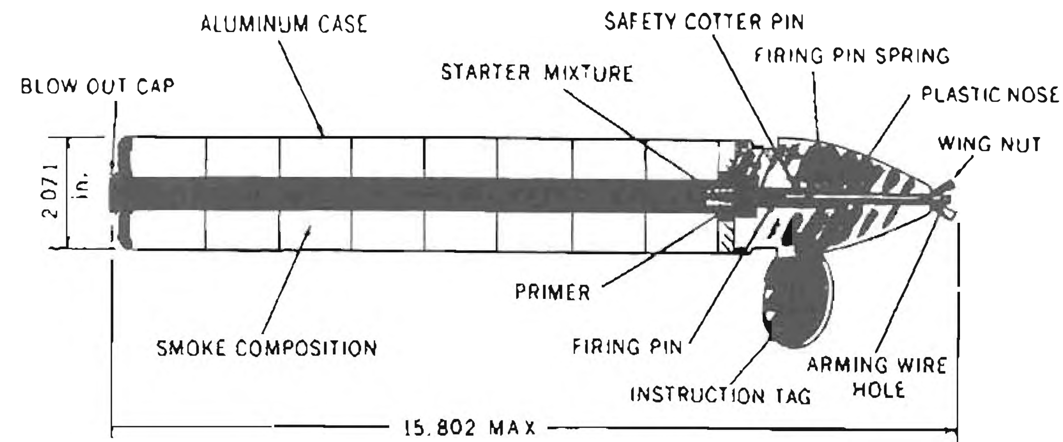


Figure 3-19. Smoke Tracking Device, Mk 1 Mod 0

conditions encountered in the tracking of test vehicles operating over a range of altitudes and speeds, the requirements for optical tracking aids vary considerably.

There is no single smoke agent or generating system that will satisfy all requirements. Hence, numerous smoke producing methods are necessary. Each one is designed for a particular application and emphasizes certain ideal characteristics. The ideal tracking smoke should have the following characteristics[1]:

(1) Be efficient on a weight and volume basis

(2) Must function at altitudes where pressure is low, and water vapor and oxygen concentrations are small

(3) Must function over the military temperature range and from ground to high altitude

(4) Require little power for generation and dispersion

(5) Be as nontoxic, nonexplosive, and noncorrosive as possible with regard to smoke chemicals and products.

3-10.2 TRACKING DEVICES

The pyrotechnic devices used for tracking are designed to provide visual displays to assist ground observers in tracking the flight paths of missiles and bombs.

Fig. 3-19[4] illustrates the Smoke Tracking Device Mk 1 Mod 0 that is attached in pairs by specially designed clamps to 250-lb Mk 86, 500-lb Mk 87, and 1000-lb Mk 88 low-drag bombs. It provides a violet colored smoke display for a minimum of 25 sec and a maximum of 52 sec. The aggregate weight of the principal pyrotechnic components of this device is approximately 17.5 oz.

The red smoke tracking flare, Type 47, (Fig. 3-20[19]) was developed at Picatinny Arsenal to provide a smoke-producing device to aid in visual tracking during test flights of high velocity missiles. The technical requirements were[19]:

(1) Disseminate a copious red smoke for 90 ± 10 sec to permit tracking of a missile with a velocity of approximately 3000 fps

(2) Be easily attached to the missile and be streamlined

(3) Be capable of being ignited by the missile launching circuitry

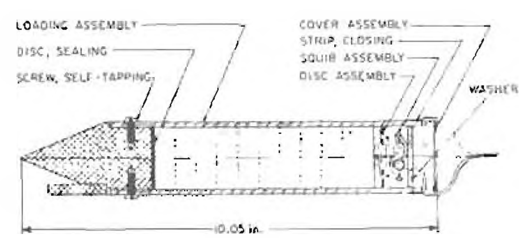


Figure 3-20. Type 47 Tracking Flare

TABLE 3-12

CHARACTERISTICS OF TYPICAL OIL SMOKE POTS

Characteristic	Type Device	
	Floating	Training
Size, in.	13 high by 13 dia	5.7 high (including fuze) by 2.5 dia
Venturi Orifice Diameter, in.	0.0890	0.076
Weight, lb	14.5 (oil) 12.0 (fuel)	0.24 (oil) 0.22 (fuel)
Oil Agent	SGF No. 1 or 2	SGF No. 1 or 2
Fuel Block Composition	*Fast-Burning Top Mixture* 86% NH_4NO_3 11% Charcoal 3% Linseed Oil *Slow-Burning Base Mixture* 82% NH_4NO_3 8% NH_4Cl 7% Charcoal 3% Linseed Oil	82% NH_4NO_3 11% Charcoal 4% KNO_3 3% Linseed Oil
Ignition	Bouchon Fuze (M208) "spits" through venturi igniting quickmatch and starter	Bouchon Fuze (M201A1) (similar to floating type)
Burning Time, min	12 ± 1.5	1.2 ± 0.25
Application	Screening, used singly or in multiple on land or water	Grenade type, used for training purposes
Obscuring Power	—	Single pot fills a 13,000-ft^3 room and totally obscures objects 4-6 ft away.

(4) Pass environmental and vibration tests.

3-11 SCREENING

3-11.1 PROPERTIES OF SCREENING SMOKES

A screening smoke is an aerosol consisting of very small solid or liquid particles suspended in the atmosphere. Individual particles of the aerosol obstruct light rays by either reflection or refraction. Maximum efficiency is obtained by the largest possible number of the smallest effective particles[20]. Optimum size of the particles in a smoke cloud should be 0.5 micron. Screening smokes are usually white and can be used to[1]:

(1) Conceal movements, equipment, and installations of friendly forces from ground observation

(2) Blanket installations and friendly aircraft from attack

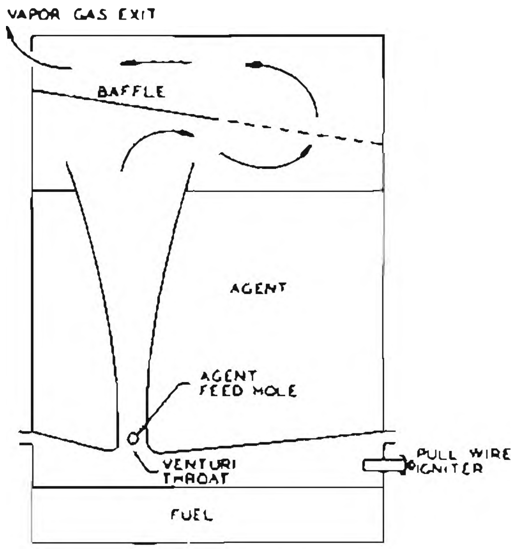


Figure 3-21. Typical Venturi Thermal Generator

(3) Establish dummy screens for deception

(4) Communicate

(5) Form a thermal radiation attenuation screen.

There are three types of smoke screen:

(1) Blanket screen—formed by the merging of individual smoke screens

(2) Smoke haze—formed much the same as blanket but less uniformly dense

(3) Smoke curtain—a dense, vertical deployment to conceal objects at ground level.

It is important that the maximum effect be obtained per unit weight of smoke producing material because of the large amount of smoke required. Total weight required depends upon the weight of the material available to form smoke particles and the efficiency of conversion of the smoke producing material into smoke particles having optimum light scattering and obscuring capability. For

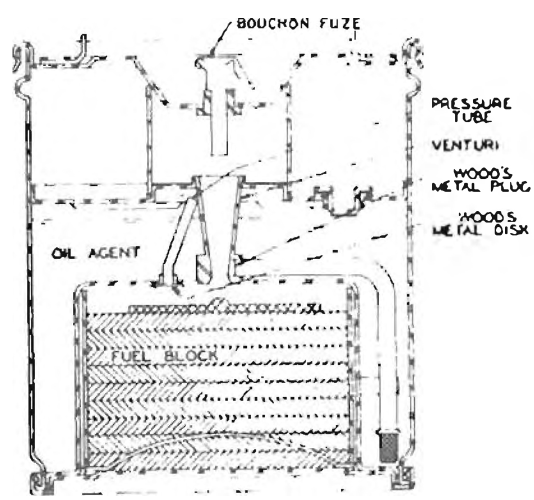


Figure 3-22. Typical Oil Smoke Pot (Floating)

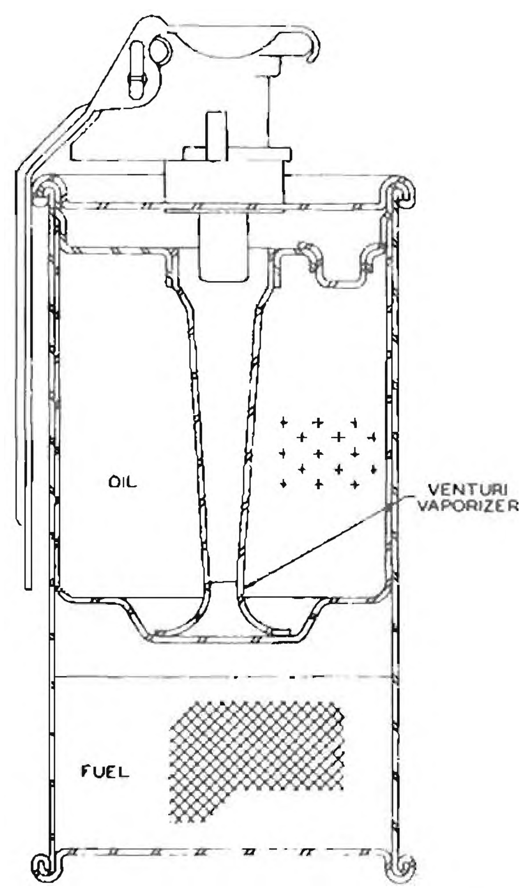


Figure 3-23. Typical Oil Smoke Pot (Training)

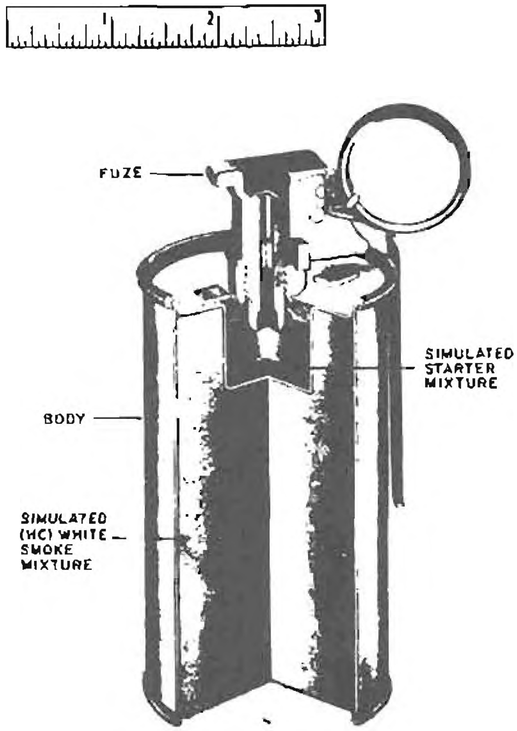


Figure 3-24. HC Smoke Hand Grenade, AN-M8

military screening purposes, the formation of smoke particles by condensation is the only practical way. The hot vapor is usually produced by volatilization or by chemical reactions in which one reactant is normally a component of the atmosphere. Examples of the three most widely used screening smokes are[1]:

(1) Oil smoke–generated by volatilization and condensation of oil

(2) Zinc chloride smoke–generated by combination of volatilization and chemical reaction

(3) White phosphorus smoke–generated by chemical reaction with the atmosphere.

Specific properties of military smoke materials used for screening include[1]:

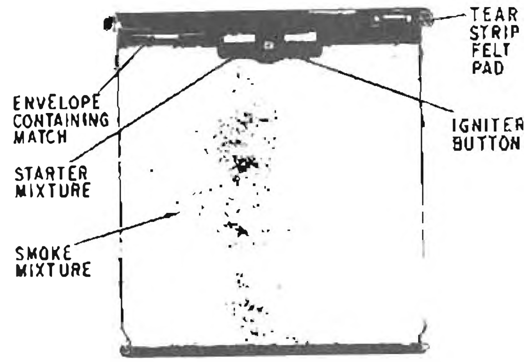


Figure 3-25. HC Smoke Pot, Mk 3 Mod 0

(1) Availability of large quantities at low cost

(2) Easy dissemination by inexpensive equipment

(3) Persistence

(4) Effectiveness at low concentrations

(5) Nontoxicity; i.e., noncorrosive to equipment, nonirritating to eyes, throat, and skin

(6) Suitability for large-scale manufacture.

3-11.2 SMOKE GENERATION

3-11.2.1 OIL SMOKES

The operation of a venturi-type thermal generator to produce oil smoke involves the atomization of the liquid, the vaporization of the droplets produced, and the dispersion of the vapor in a stream of hot gases. A schematic illustration of a typical unit is shown in Fig. 3-21[1]. It contains a fuel block that, on burning, produces the hot gases, a chamber containing the liquid to be vaporized and dispersed, and a high-velocity vaporizer tube in the form of a venturi. Characteristics of typical venturi-type thermal generators are given in Table 3-12[1]. Figs. 3-22[1] and 3-23[1]

TABLE 3-13

VARIATION OF BURNING TIME OF TYPE-C HC SMOKE MIXTURE WITH ALUMINUM CONTENT

Aluminum Content, %	Burning Time, sec
9.0	55
8.4	64
8.0	65
7.5	71
7.0	84
6.5	96
6.0	107
5.5	147
5.5	200

are examples of a floating smoke pot and a training smoke pot, respectively. For information regarding total obscuring power and volume of white smokes produced from oil, see Tables 3-8, 3-9, and 3-10.

3-11.2.2 ZINC CHLORIDE SMOKES

Zinc chloride is one of the most reactive agents used for generating smoke. Although toxic, zinc chloride produced as a result of a pyrotechnic reaction is widely used for screening purposes[21].

The smoke mixture, HC, made available during the early part of World War II, now consists of approximately equal amounts by weight of zinc oxide and a chlorinating agent such as hexachloroethane or carbon tetrachloride and a few percent of aluminum. See Ref. 1 for the chemistry of zinc chloride smoke production. Table 3-13[1] lists the variation of burning time of type-C HC smoke mixture with aluminum content. Figs. 3-24[1] and 3-25[1] show typical devices using HC type smoke mixtures. Details and specifications for these devices are given in Table 3-14[1].

An investigation was undertaken to eliminate some of the difficulties encountered in manufacturing, storing, and functioning of the AN-M8 Grenade shown in Fig. 3-24. It was found that by the addition of a plastic binder Laminac 4116 (American Cyanamid), the processing and stability were improved but corrosion was still evident[22].

TABLE 3-14

CHARACTERISTICS OF TYPICAL DEVICES USING HC MIXTURE

Characteristic	Device: HC Smoke Hand Grenade (AN-M8)	Device: HC Floating Smoke Pot (M4A2)
Size, in.	5.7 high 2.5 dia Four smoke emission holes in top	13 high 12 dia Three vent holes in top
Charge	HC Mixture	HC Mixture
Weight	19 oz Type-C	23.5 to 27.5 lb
Ignition	M201A1 Fuze plus ignition mix and starter mix	M207A1 Fuze plus first fire charge and delay charge
Burning Time	105-150 sec	10-15 min
Application	Thrown, 1.2-2 sec delay—may be launched from M14 Rifle or carbine for screening or marking.	Screening

3-11.2.3 WHITE PHOSPHORUS SMOKES

White smoke consisting of small droplets of phosphoric acid has been used widely for military purposes. Methods employed to form phosphorus pentoxide for military smokes include[1]:

(1) Burning in air of white phosphorus

(2) Burning in air of phosphorus vapor

(3) Burning in air of phosphine.

TABLE 3-15

CHARACTERISTICS OF TYPICAL DEVICES USING PHOSPHORUS FILLING

Characteristic	Device	
	WP Smoke Hand Grenade (M15)	Projectile (T91 HE Water Marker)
Size, in.	4-1/2 high 2-3/8 dia	12-3/4 long 1-3/4 dia
Charge Weight	15 oz PWP	2.6 lb Comp B. 0.66 lb Stabilized Red Phosphorus
Ignition	M206A1 Fuze HE burster	M500A1 Fuze Comp. B
Screening Capability	Scatters WP over a 20 yd radius	Explodes on impact—50 ft high; 50 ft dia; cloud duration 3 min—25 mph wind
Application	Thrown, bursting charge explodes, 4-5 sec delay	Used in 90 mm munition (white marker)

Phosphorus vapor is extremely toxic and causes bone decay; however, it is not present after the smoke is formed. There is little effect on metals by phosphorus smokes.

White phosphorus is used mainly in bursting type ammunition to produce smoke screens. It is the most efficient smoke producer on a weight basis, but screening effectiveness in bursting type munitions is slight. Smoke concentration many times that required for effective screening results because most of the charge burns within seconds following the burst. There is also a temperature rise in the cloud surrounding the burst that makes the cloud tend to pillar. Two ways to improve smoke producing effectiveness are[1]:

(1) Reduce the heat of combustion

(2) Control the rate of combustion by reducing the fragmentation of the phosphorus.

Various methods for controlling the fragmentation of phosphorus have been tried including the addition of steel wool, plastic tubes, and wire screens. Alteration of the physical properties so as to produce a plastic mass with low shattering characteristics is the most promising. Plasticized white phosphorus (PWP) was developed for controlling the fragmentation and the pillaring of the smoke[2,3]. The characteristics of typical smoke producing devices are summarized in Table 3-15[1]. Table 3-16[4] summarizes typical screening devices most of which use WP as the filler material. Refer to Tables 3-8, 3-9, and 3-10 for total obscuring power, smoke volume, and rate of smoke production per unit weight of phosphorus compounds.

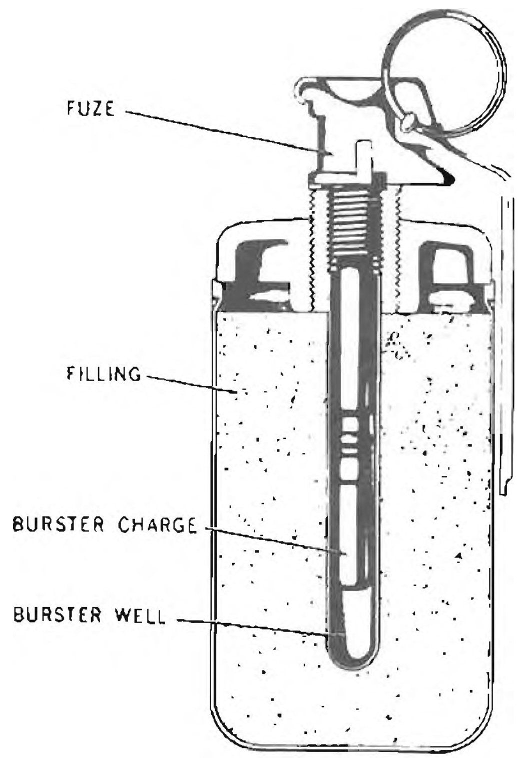


Figure 3-26. WP Smoke Hand Grenade, M15

TABLE 3-16

SCREENING DEVICES SUMMARY

Item	Filler	Filler Weight	Delay, sec	Length, in.	Diam, in.	Weight, lb
Smoke Pot, HC Mk 3 Mod 0	HC	32 lb	None	9.5	8.5	34
Smoke Pot, SGF2, AN-M7 and AN-M7A1	SGF oil	10.5 lb	8-20	13.75	12.5	37
Grenade, Hand, Smoke, HC, AN-M8	HC	19 oz	2	4.5	2.5	1.80
Grenade, Hand, Smoke, WP, M15	WP	16 oz	4-5	4.5	2.38	1.90
Grenade, Rifle, Smoke, WP, M19A1	WP	8.48 oz	None	11.25	2.0	1.49
Grenade, Hand or Rifle, Smoke, WP, M34	WP	15 oz	4-5	.5.5	2.37	1.50
Smoke Pot, M6 (Formerly SGF2 Oil Smoke Candle M6)	SGF oil	0.22 lb	2	5.5	2.5	1.82
Projectile, 5 in./38-cal, WP, Mk 30 Mods	WP	7.1 lb	NA[1]	20	5	54.4
Projectile, 5 in./38-cal, WP, Mk 44 Mod 1	WP	7.1 lb	NA	20	5	54.4
Cartridge, 81-mm, Smoke, WP, M57 and M57A1	WP	4.06 lb	NA	23	3.19	11.4
Cartridge, 81-mm, Smoke, WP, M370	WP	1.6 lb	NA	20.76	3.18	9.34
Rocket, Smoke, 3.5-in., WP, M30	WP	2.33 lb	NA	23.55	3.5	8.90
Warhead, 5-in. Rocket, Smoke, PWP, Mk 4	PWP	19.65 lb	NA	36.67	5	50.84

[1]NA = not applicable

Fig. 3-26[4] illustrates WP Smoke Hand Grenade, M15. Operation is as follows. The 4-5 sec delay element is ignited when the striker hits the primer. The delay element ignites the burster charge that bursts the grenade body and scatters WP over a radius of 20 yd. It produces white dense smoke for about 60 sec.

3-11.2.4 LIQUID SMOKE AGENTS

FM smoke agent $TiCl_4$ is extremely reactive resulting from formation of hydrated oxides, or from mixing with atmospheric moisture. It is often disseminated from aircraft spray tanks. Liquid FM is very corrosive to metal if moisture is present[1].

FS smoke agent consists of a mixture of 45% chlorosulfonic acid and 55% sulphur trioxide, and is slightly more reactive with water than FM smoke agent. It is also disseminated from aircraft spray tanks. This smoke is corrosive and very irritating to nose and lungs[1].

TABLE 3-17

PROPERTIES OF SMOKE AGENTS

	CODE	COLOR OF SMOKE	OBSCURATION TOP	PHYSICAL PROPERTIES		TOXICITY	EFFECT ON MATERIALS	DISADVANTAGES	USES
				DENSITY	PHYSICAL STATE				
Crude Oil	–	Black	250 – 400	0.8	Liquid	Nonirritating, nonhazardous	Noncorrosive	Low TOP; clogs flues technique not applicable to grenades.	Naval Engines
White Phosphorus	WP	White	4600	1.8	Solid	WP particles cause severe burns which heal very slowly. Smoke is nonhazardous, nonirritating	Incendiary – Acidic vapors	Antipersonnel; Pillaring; poor storage	Grenades, Projectiles
Titanium Tetrachloride	FM	White	1900	1.7	Liquid	Irritates eyes and respiratory senses; liquid burns like strong acid.	Attacks metals certain plastics and fabric.	Corrosive, irritant; liquid burns; clogs dispensing nozzles.	Aircraft Spray Tanks, Projectiles
Sulfur Trioxide – Chlorosulfonic Acid	FS	White	2500	1.9	Liquid	Irritates eyes, skin and respiratory tract. Liquid burns like strong acid.	Attacks metals, certain plastics and fabrics.	Corrosive, irritant, liquid burns on exposed skin.	Aircraft Spray Tanks, Projectiles
HC Smokes	HC	Gray-White	2100	–	Solid	$ZnCl_2$ is toxic. Mask should be worn in prolonged exposures.	Noncorrosive	Slow rate of cloud formation, some hazard in prolonged explosure.	Grenades, Projectiles Smoke Pots
Red Phosphorus Smokes	RP	White	1000	–	Solid	Nonirritating, nonhazardous	Slightly corrosive	Low TOP; slow cloud formation	Navy Float Signals; Projectiles
Dye/Pyro Signal Smokes	--	Red, Green Yellow, Violet	–	–	Solid	Nonirritating, nonhazardous	Noncorrosive	Not a screening smoke; poor obscuration	Signal Grenades Navy Distress Signals
Oil Droplet Smokes	SGF	White	–	0.85	Liquid	Nonirritating, nonhazardous	Noncorrosive	Generating equipment required. Technique not applicable to grenades.	Field Generator Helicopter Aircraft Spray Tanks
LWL Organometallic Smoke Agent	–	White	3000 (estimated)	0.9	Liquid	Nonirritating, non hazardous	Noncorrosive	Liquid blisters skin	Grenades; Projectiles Aircraft Spray Tanks

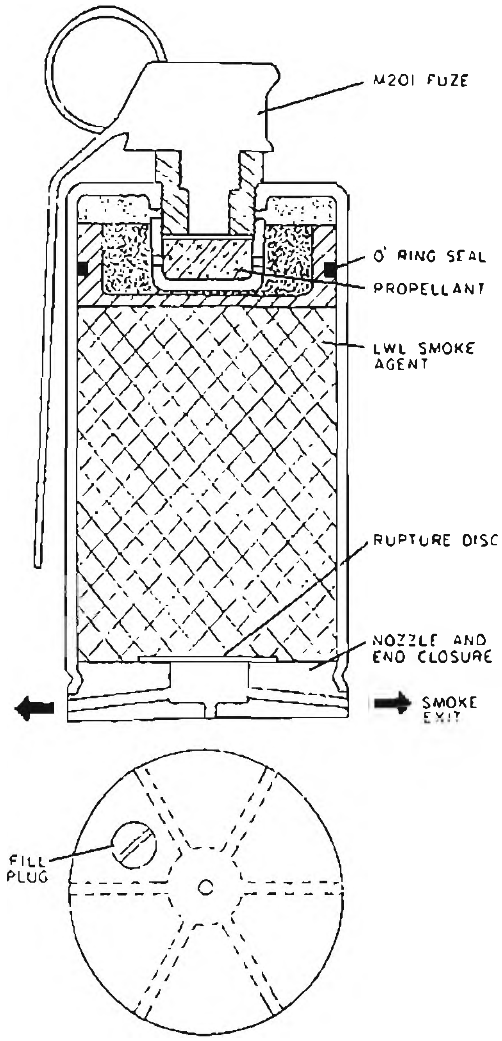


Figure 3-27. Piston Smoke Grenade

3-11.2.5 NEW DEVELOPMENTS IN SCREENING SMOKES

A new organometallic smoke agent has been developed by the Army Land Warfare Laboratory (LWL) for use from both helicopters and fixed-wing aircraft[24]. This agent is superior to present liquid smoke agents (FM and FS) in the generation of high obscuration smoke screens. The smoke cloud is also nonirritating, nontoxic, noncorrosive, stable, and less dependent on humidity and temperature than either FM or FS liquid smoke agents. A smoke grenade, Fig. 3-27[25], has been developed to dispense the LWL liquid smoke agent that provides improved performance over devices presently being used. Table 3-17[25] compares the new smoke agent with the more common agents.

3-12 SIMULATION

Pyrotechnic devices that produce effects designed to simulate the appearance of combat weaponry are used in training exercises to familiarize troops with battle conditions without exposing them to the dangers of lethal ammunition. In addition, some devices are used in actual combat to mislead or confuse the enemy. There are a number of these devices whose primary effects are sound and flash but they also emit smoke.

Those devices which emit smoke include detonation simulators, flash artillery simulators, projectile air burst simulators, and atomic explosion simulators. See par. 3-22.1 for more detailed information about these devices.

Care should be exercized in selecting the smoke mixture so that the smoke cloud is nontoxic and nonirritating to personnel. Par. 3-11.2 lists the smoke mixtures that could be

TABLE 3-18

SIMULATOR SUMMARY

Item	Display	Length, in.	Diameter, in.	Weight, oz
Simulator, Detonation, Explosive, Mk 2	Flash, Smoke, Sound	2	0.6	0.4
Simulator, Flash Artillery, M110	Flash, Smoke, Sound	7.8	1.9	10.7
Simulator, Projectile, Air Burst, M27A1B1	Flash, Smoke, Report	8.9	1.9	9.3

used for this purpose. Desirable features of the devices include long shelf life, mass producibility, minimum cost, and optimum effect. Table 3-18[1] summarizes several of these devices.

3-13 RIOT CONTROL

3-13.1 SMOKE GENERATION

In riot control, agent smokes are produced in much the same manner as in signaling. In many cases, a vaporization process is followed by a condensation process in which the agent condenses to form the disperse phase of the smoke. Agent smokes may be disseminated by a vapor condensation process, a dispersion process, or a combined process. For smoke that is disseminated as a particulate cloud the process usually involves the formation of small particles of the dispersed phase and the distribution of these particles in the air. The physiological effectiveness of materials disseminated depends strongly on the particle size. While visibility of the smoke may or may not be important, the volume of smoke and its duration is important. It is also necessary that the vaporization and condensation processes be efficient and produce a minimum of undesired changes in the agent dispersed.

3-13.2 FORMATION OF DISPERSED PHASE

The dispersed phase can be formed in three ways[1]:

(1) Condensation processes in which molecules of the vapor unite to form the particles of the dispersed phase

(2) Dispersion processes in which the particles are formed by the breaking up of a solid or liquid material

(3) Combined processes.

3-13.2.1 CONDENSATION PROCESS

The dispersed phase of most particulate clouds (smoke) is produced by condensation from the vapor phase and involves the uniting of vapor molecules to form large particles[1]. The two steps involved in the formation of a dispersed phase by this method are:

(1) Production of the vapor in a supersaturated state

(2) Condensation of the supersaturated vapor.

The supersaturated vapor usually results from the cooling of a warm vapor or a chemical reaction. In either event, the excess vapor will condense to form the particles of the dispersed phase. Condensation of a vapor is facilitated by the presence of foreign particles. In many cases of military interest, the evaporation of the substance produces the supersaturated vapor followed by the mixing with cooler air of the relatively warm vapors produced.

3-13.2.2 DISPERSION PROCESS

The dispersion process involves the subdivision of a solid or liquid into fine particles. In the case of a solid substance, it may be disrupted and dispersed into fine particles by application of energy, or the solid may be preground to the desired size and then dispersed into the suspending medium. In the case of a liquid, energy applied to it causes the liquid to break up into small droplets. See Ref. 1 for more details.

3-13.2.3 COMBINED PROCESS

In many instances, the dispersed phase of smokes is obtained by condensation of a vapor phase that is formed by evaporation of the smoke producing agent. To facilitate the transfer of heat to and the removal of the vapor from the surface of the agent, the smoke producing agent is often atomized. Particulate clouds can be developed by the atomization of a solution containing a nonvolatile or slightly volatile solute of a volatile solvent.

Figure 3-28. Cartridge, 2-WRD

3-13.3 DEVICES

The "Handy Andy" 2-WRD Cartridge (E24 Riot-control, 40 mm, CS cartridge), see Fig. 3-28[26], is a pyrotechnic smoke projectile containing CS (o-chlorobenzylamalononitrile) that was developed to extend the range beyond that of hand-thrown CS grenades for use in riot-control situations. Of simple design, it has nonlethal characteristics, and is easy to use. It functions essentially as a hand-held or pyrotechnic-pistol-launched rubbery projectile that disseminates CS on reaching the target area. Tests performed from a fixed installation at an elevation of 45 deg showed a range potential of 189 to 353 ft.

The average CS vaporization efficiency of the unit when loaded with L1 mixture was 90% and the average burning time 17 sec. Optimum results were obtained on mixing, handling, filling, and firing the CS cartridge with pyrotechnic mixtures containing CS in formulation L1 as follows[26]:

Components	Parts by Weight
CS	42
Lactose, technical grade	20
Potassium chlorate, technical grade	26
Kaolin	12
Nitrocellulose	3.6

The M25A1 Riot Hand Grenade (Fig. 3-29[27]) is spherical in shape and slightly less than 3 in. in diameter. The filling consists of 3.5 oz of a mixture of magnesium oxide and finely pulverized CN. An integral fuze with a 1.4- to 3-sec delay is installed in the fuze well. For functioning details, see Ref. 27. The radius of effectiveness of the gas cloud is approximately 5 yd from the point of burst. The gas from this grenade will cause tear formation.

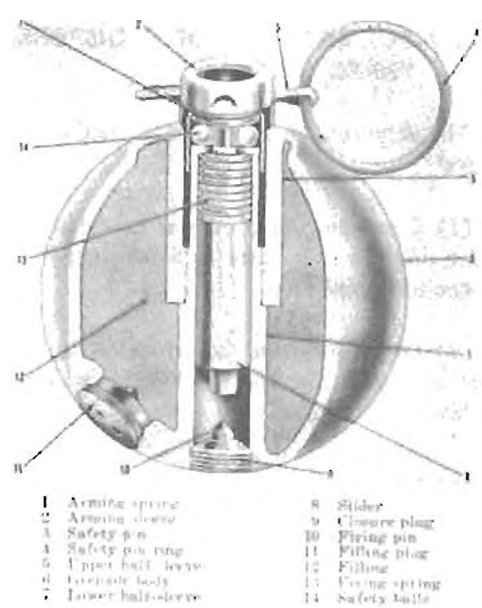


Figure 3-29. CN Riot Hand Grenade, M25A1

SECTION IV HEAT AND GAS

3-14 IGNITERS AND PRIMERS

3-14.1 INITIATION

3-14.1.1 THE INITIATION PROCESS

Explosive materials are initiated when energy of an externally applied stimulus is transformed into heat. The view that nonuniformity of heat distribution is essential to the usual initiation process has been called the "hot spot" theory of initiation. In explosive initiators, the energy available is concentrated by the use of small-diameter firing pins and, in electrical devices, by dissipating the energy in short and highly constricted paths. The addition of grit to primer mixes serves a similar function. Not only is nonuniformity of energy distribution essential to most initiation processes, but it is an important factor in the growth and propagation of practically all initiation processes in military devices.

The reaction rate inevitably reaches a level such that heat is generated faster than it can be lost. From this point on the reaction is self-accelerating and quite rapidly becomes explosive.

Although a general equation that includes consideration of all of the complicating factors would be completely intractable, the use of simplified models makes possible solutions that contribute to the understanding of the initiation process. However, simplification must be used cautiously. For example, it frequently appears that each explosive has a critical initiation temperature that is independent of dimensions. More detailed analyses have shown this to be an approximation that applies only to a specific class of initiators. Perhaps the most important implication of the foregoing is that the minimum energy required to initiate an explosive device is nearly proportional to the volume of material that is heated by the input energy pulse. It must be stressed that this approximation should be applied only to compare the performance of initiators of the same type.

3-14.1.2 ELECTRIC INITIATORS

Hot bridgewire electric initiators are the simplest and most direct illustrations of initiation by heat. Since a bridgewire can be measured, its volume, heat capacity, and resistance can be calculated. Since it is further possible to generate electrical pulses and currents of accurately known characteristics, these can be combined with the bridgewire characteristics to obtain accurate estimates of power, energy, and temperature.

A large number of experiments has been carried out in which the interrelationships of the variables that affect the operation of bridgewire initiators have been investigated. These investigations have verified the following principles[28]:

(1) The energy required to fire a hot-wire electric initiator is roughly proportional to the volume of the bridgewire if the energy is delivered in a short enough time.

(2) Closer analysis shows that the threshold temperature increases with reduced wire diameter. This trend is less marked when the explosive has a high activation energy (like lead styphnate).

(3) The energy required per unit volume also increases somewhat with decreasing bridgewire length. End losses probably account for this.

(4) For a specific initiator design, the energy requirement approaches a minimum as voltage, current, or power is increased. It increases indefinitely as power is reduced to a minimum.

(5) The relationship stated in (4) refers to the average power of a firing pulse. Pulse

shape has a secondary effect that is not easily measured.

(6) The current requirement varies approximately as the 3/2 power of the wire diameter and inversely as the resistivity of the bridgewire metal.

3-14.1.3 MECHANICAL INITIATION

Mechanical initiation is accomplished by means of a stab or percussion firing pin. Mechanical initiation is more difficult to analyze than electrical initiation. The most important function of the firing pin is to convert another form of energy into highly concentrated heat. As in electrical devices, the energy necessary is nearly proportional to the amount of heated material. It has been inferred from experimental data that stab and percussion initiation occur by different mechanisms. Kinetic energy appears to be the determining magnitude for stab initiation, momentum for percussion.

The standard firing pin for stab initiation is a truncated cone. Maximum flat diameter at the tip is 0.015 in. In general, the higher the density of the explosive, the more sensitive the stab initiator. Because the denser explosive offers more resistance to the penetration of the firing pin, the kinetic energy of the moving mass is dissipated over a shorter distance so that a smaller quantity of explosive is heated to a higher temperature.

Contrary to initiation by stab, the percussion firing pin merely dents the case and pinches the explosive between anvil and case. Energy must be supplied at a rate sufficient to fracture the granular structure of the explosive. Firing pins with a hemispherical tip have been shown to give greater sensitivity than a truncated cone. Tip radius has little effect on sensitivity but is typically 0.050 in.

3-14.1.4 INPUT REQUIREMENTS

The energy required for reliable initiation differs not only for different initiator types

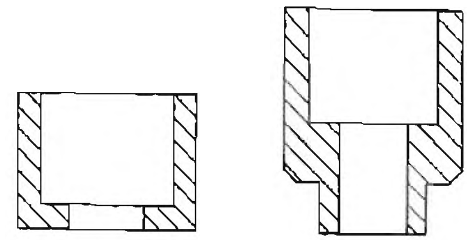


Figure 3-30. Charge Holders

but also for different models of the same type. Initiation values are established in input sensitivity tests[28]. For mechanical initiators, ball weight and drop height are specified; for electric initiators, applicable electrical parameters – such as capacitance, voltage, current, or pulse width – are given. Input specifications for specific initiators are listed in Ref. 29.

3-14.2 INITIATION OF PYROTECHNIC DELAYS

Pyrotechnic delays are ignited by an initiating assembly. Its purpose, whether it is mechanically or electrically activated, is to produce hot gases and particles that will impinge on the delay column. Delays are easily ignited by the flame of a primer; however, slow-burning delays require an igniter. For more details on vented and obturated delays and on delay compositions, see par. 3-21.

3-14.2.1 VENTED DELAYS

The initiator assemblies of vented delays 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. 3-30(A)[30]. Others use a chimney-type charge holder which may or may not sit on top of the delay column but provides for a free volume in which to vent gases (Fig. 3-30(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 is then 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. 3-49 illustrates the use of such a primer subassembly.

3-14.2.2 OBTURATED DELAYS

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. 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[28].

3-14.3 IGNITERS

In a pyrotechnic ignition train, the igniter is the intermediate component between the primer and the main pyrotechnic charge. It augments the flame output of the primer so as to ignite the main charge with greater reliability. Since many pyrotechnic compositions can be reliably ignited by the flame of a primer alone, igniters are often omitted. When igniters are used, they take many forms. The igniter could be a long cylindrical element filled with an initiating explosive, akin to the spit tube of artillery ammunition or like the basket filled with low explosives as used in rockets.

Pyrotechnic charges with ignition temperatures of 500°C or less require little in the way of complicated ignition trains; a primer will do. However, materials with ignition temperatures considerably above 500°C are more difficult to ignite[20]. Many of the illumination charges fall into this hard-to-ignite region and usually require some form of energy amplification in the form of intermediate mixes of igniter composition.

It is a rule of thumb that the igniter charge burn at several hundred degrees higher than the ignition temperature of the main charge. Furthermore, the ignition charge must be in intimate contact with the main charge. The production of hot slag or dross of the burning ignition charge then assists in igniting the main charge over relatively large areas.

At times it is difficult to recognize a particular component as an igniter. In some pyrotechnic devices, a first-fire mixture is used in place of an igniter. Having the same function as an igniter, the first-fire mixture consists of a readily ignitable mix that is loaded on top of the main pyrotechnic charge. Such a charge is used in the incendiary grenade shown in Fig. 3-34.

3-14.4 IGNITION OF PYROTECHNICS COMPARED WITH THAT OF SOLID PROPELLANTS

Ignition of solid propellants used in rockets and guns is similar in many respects to ignition of pyrotechnic mixtures. When raised to their ignition temperature, propellants undergo preignition reactions followed by an ignition reaction. If conditions are favorable, the reaction front moves at a nominally constant velocity.

Since some pyrotechnic compositions are relatively difficult to ignite, an ignition train similar to that used in other explosively

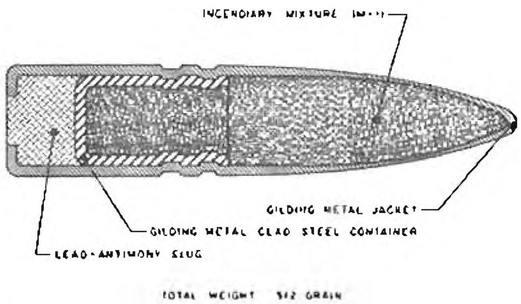


Figure 3-31. Typical Cal .50 Incendiary Bullet

loaded items is used to produce the stimulus required to initiate the main pyrotechnic composition. The initiating composition, on burning, produces sufficient heat to initiate an intermediate pyrotechnic composition that forms the second part of the ignition train.

A composite propellant resembles a pyrotechnic mixture in that it is an intimate mixture of a fuel and an oxidizer. In general, for all solid propellants, the temperature of the propellant a short distance below the burning surface is not affected by the combustion of the propellant. In propagative burning, as the burning surface advances, the unburned propellant is heated, and the temperature of the material increases to the point where the propellant decomposes into volatile fragments. In some instances liquefaction may occur prior to the chemical reactions that comprise the combustion process. For more details on the theory of ignition and propagative burning, see Ref. 1.

3-15 INCENDIARIES

Destructive fires are set off in a large variety of targets by the use of incendiaries. While aircraft, buildings, industrial installations, ammunition, and fuel dumps are among the principal targets for incendiary attack, it has also been used effectively against personnel, armored vehicles, and tanks. Incendiary compositions and devices can be classified based on their composition and use. Three large classes based on their use are[1]:

(1) Small arms incendiary ammunition used primarily against aircraft and fuel dumps.

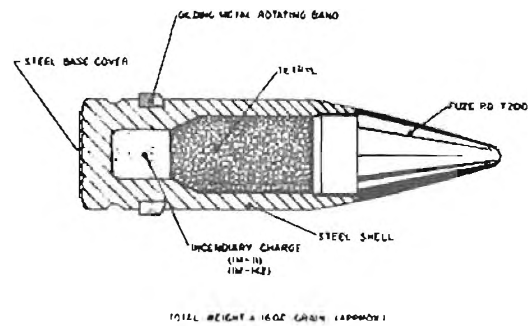


Figure 3-32.
Typical 20 mm High Explosive
Incendiary Projectile

(2) Other incendiary munitions including bombs, grenades, mortar and artillery projectiles. These are used to initiate fires in buildings, industrial installations, ammunition, fuel dumps, and other targets in combat zone.

(3) Special incendiary devices used for the destruction of materials and documents.

3-15.1 SMALL ARMS INCENDIARIES

Small arms incendiaries are used primarily for starting destructive fires in aircraft fuel. They have been developed to meet the needs of the using services and now include ammunition up to 40 mm. The types include incendiary bullets, armor-piercing bullets, and high explosive incendiary projectiles. A typical incendiary cal .50 bullet is shown in Fig 3-31[1]. Unfuzed incendiary rounds up to 20 mm are usually initiated by the heat produced when the metal nose crushes on impact. Ammunition, 20 mm and larger, is provided with fuzes that initiate on impact. Fig. 3-32[1] illustrates a typical 20 mm high explosive incendiary projectile that is fuzed.

The target effect in an aircraft depends upon the amount of energy transferred to the fuel. This is a function of the temperature reached and the characteristics of the

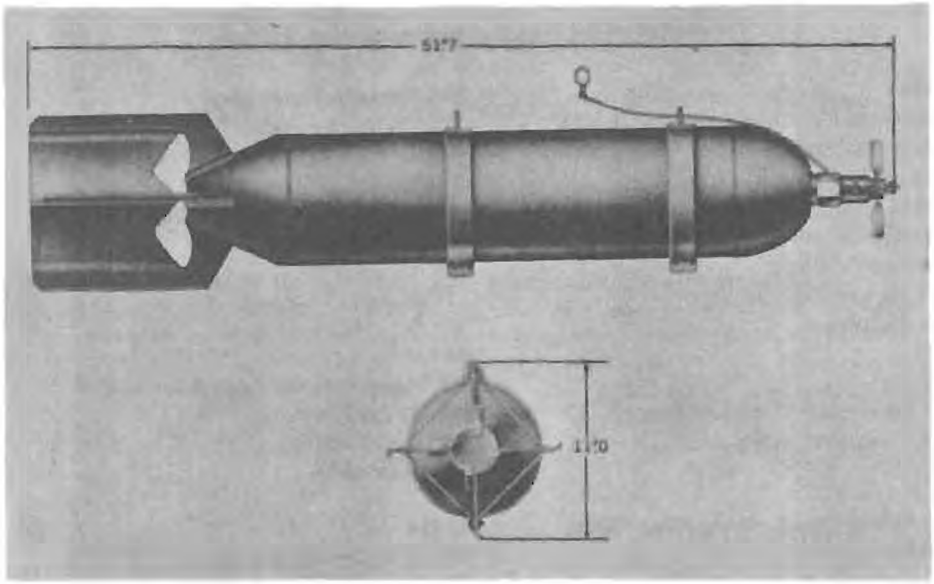


Figure 3-33. 100-lb Smoke or Incendiary Bomb, AN-M47A4

products of combustion, the mode of energy transfer process, and the efficiency with which the energy is absorbed by the fuel. Typical small arms incendiary mixtures are listed in Table 3-19[1]. See Ref. 1 for further details.

3-15.2 INCENDIARIES FOR GROUND APPLICATION

Ground incendiaries include that class of munitions used for damage, mainly by combustion, to ground targets. Various munitions of this type include bombs, grenades, mortar projectiles, and artillery projectiles.

The amount of energy from these incendiaries serves only to initiate combustion of the target in the oxygen of the air. All of these munitions, except those that are spontaneously combustible, must contain an initiator. Three types of incendiary fillings are used in incendiary bombs – PT, IM, and NP[31]. Table 3-20[1] lists the composition of PT mixtures while Table 3-21[1] lists the composition of IM incendiary gels. Filler NP (oil, incendiary, Napalm Type 1) is a mixture of 88.5 percent gasoline and 11.5 percent napalm thickener. Napalm thickener is a granular base aluminum soap of naphthenic, oleic, and coconut fatty acids[1].

Table 3-22[31] lists the characteristics of different sizes of incendiary bombs. A typical incendiary bomb is the AN-M47A4 (see Fig. 3-33[31]), a 100-lb incendiary or smoke bomb. It uses Igniter, AN49 (white phosphorus or sodium filled) with Burster, AN-M13 (TNT or tetryl filled).

Incendiary bombs are deployed from aircraft and are designed for use against combustible land targets such as warehouses, factories, docks, or storage dumps. They are also used over water to ignite oil slicks. When an incendiary bomb, equipped with a sodium igniter, impacts on the water, it bursts and scatters burning gobs of incendiary gel containing particles of sodium. The gobs of gel will float and the sodium will ignite spontaneously with water, thereby insuring the ignition of flammable oil slicks. If a white phosphorus filled igniter is used, the scattering and the ignition of the gel takes place, but

TABLE 3-19

TYPICAL SMALL ARMS INCENDIARY MIXTURES

IM-11
50% Magnesium-Aluminum Alloy (50/50)
50% Barium Nitrate

IM-21A
48% Magnesium-Aluminum Alloy (50/50)
48% Barium Nitrate
3% Calcium Resinate
1% Asphaltum

IM-23
50% Magnesium-Aluminum Alloy (50/50)
50% Potassium Perchlorate

IM-28
50% Magnesium-Aluminum Alloy (50/50)
40% Barium Nitrate
10% Potassium Perchlorate

IM-68
50% Magnesium-Aluminum Alloy (50/50)
25% Ammonium Nitrate
24% Barium Nitrate
1% Zinc Stearate

IM-69
50% Magnesium-Aluminum Alloy (50/50)
40% Barium Nitrate
10% Iron Oxide (Fe_2O_3)

IM-112
45% Magnesium-Aluminum Alloy (50/50)
5% Tungsten Powder
50% Barium Nitrate

IM-136
49% Magnesium-Aluminum Alloy (50/50)
49% Potassium Perchlorate
2% Calcium Resinate

IM-139
10% Magnesium-Aluminum Alloy (50/50)
40% Red Phosphorus
47% Barium Nitrate
3% Aluminum Stearate

IM-142
46% Magnesium-Aluminum Alloy (50/50)
48% Barium Nitrate
5% Asphaltum
1% Graphite

IM-214
50% Zirconium (60/80) (lot 6)
25% Magnesium-Aluminum Alloy
25% Potassium Perchlorate

IM-241
50% Zirconium (20/65)
25% Magnesium-Aluminum Alloy
25% Potassium Perchlorate

IM-385
49% Magnesium-Aluminum Alloy (50/50)
49% Ammonium Perchlorate
2% Calcium Resinate

MOX-2B (*High Explosive Incendiary Fillers*)
52% Aluminum Powder
35% Ammonium Perchlorate
6% RDX/Wax (97/3)
4% TNT (Coated on the Ammonium Perchlorate)
2% Calcium Stearate
1% Graphite

ignition of the gel on water is not assured[31]. Burning gobs of incendiary gel will produce a temperature of 500° to 675°C at a height of 3 in. above the flame over a maximum period of approximately 8 min.

3-15.3 SPECIAL INCENDIARY DEVICES

Special incendiary devices are used for the destruction of various materiel. A typical incendiary grenade (Fig. 3-34[1]) is loaded with thermite. Ignition action is as follows: the fuze spits out a flame that ignites the first fire mixture. This mixture, taking the place of an igniter, is shaped to cover the top of the thermite charge so as to insure reliable ignition of the entire thermite charge.

The main use of special incendiary devices is the destruction of safes and their documents or other contents to prevent their falling into enemy hands. The M1A2 Safe

TABLE 3-20

COMPOSITION OF PT INCENDIARY MIXTURES

Code	PT-1	PT-2	PT-3
Constituent	Composition, Percent		
Goop	49.0	30.0	–
Isobutyl methacrylate polymer AE	3.0	–	–
Magnesium (coarse)	10.0	10.0	30.0
(50/50 Mg-Al alloy)			10.0
Sodium Nitrate	5.0	8.0	6.5
Gasoline	30.0	44.0	37.5
Petroleum Oil Extract	3.0	–	–
(Bright stock)			10.0
GR-S (Buna-S synthetic rubber)	–	8.0	6.0
Sulfur monochloride (S_2Cl_2)	–	0.2 (add)	0.2 (add)

TABLE 3-22

TYPICAL INCENDIARY BOMBS

Assembled Weight, lb	Filler Weight or Volume	Filler Material	Overall Length, in.
4	0.6 lb	TH3	21.3
10	2.8 lb	PT1	19.5
500	174 lb	PT1	59.2
100	42 lb	PT1, IM, or NP	51.7
750 (Fire Bomb)	110 gal	gasoline	138
1000 (Fire Bomb)	112 gal	gasoline, napalm	168

Destroying Incendiary (Fig. 3-35[27]), a modification of the M1A1 TH1, is also used for the sole purpose of destroying cryptographic equipment. It uses the M210 Incendiary Fuze and two floating Smoke Pot Fuzes (M209). The incendiary can be ignited electrically or manually by withdrawing the fuze safety pin.

Incendiary Device, M2A1 TH1 (Fig. 3-36[27]) for destroying equipment is similar in construction to the M1A2 but is smaller and has only two fuzes. It is designed to destroy a single item of classified cryptographic equipment. It is fitted with a M210 Fuze, a M209 Smoke Pot Fuze, loaded with 8.5 lb of

TABLE 3-21

COMPOSITION OF IM INCENDIARY MIXTURES

Code	IM Type 1	IM Type 2	IM Type 3	F-1416	F-1429	F-1431	F-1457
Constituent	Composition, Percent						
Isobutyl methacrylate polymer AE (IM)	5.0	5.0	2.0	3.0	3.0	3.0	3.0
Stearic acid	3.0	–	–	1.0	4.0	3.0	4.5
Fatty acids	–	2.5	3.0	–	–	–	–
Naphthenic acid	–	2.5	3.0	3.0	–	1.0	0.5
Calcium oxide	2.0	–	–	3.1	4.0	3.5	–
Caustic soda (40% solution)	–	3.0	4.5	–	–	–	–
Ammonium hydroxide (27% solution)	–	–	–	–	–	–	2.3
Gasoline	88.75	87.0	87.5	87.6	86.5	87.3	89.3
Water	1.25	–	–	2.3	2.5	2.2	–

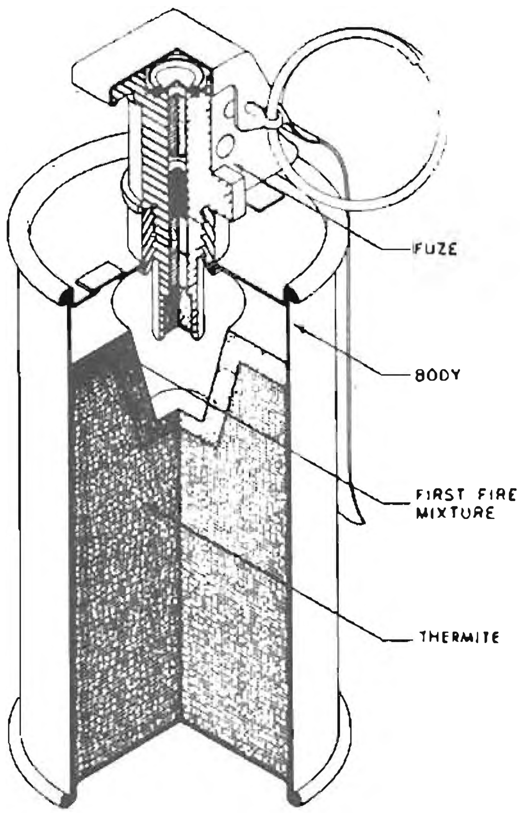


Figure 3-34. Typical Incendiary Grenade

thermite (TH1) and is ignited either electrically or manually.

The M4 File Destroyer is intended primarily to be used to destroy classified material in filing cabinets provided with combination locks. It consists of 44 oxidizer boxes, four igniter boxes, and four racks. Fig. 3-37[27] illustrates this incendiary. The oxidizer is required because a closed file cabinet does not contain sufficient oxygen to sustain combustion. The incendiary is ignited electrically by connecting M1 Squibs in each igniter box in parallel to a power source. The oxidizer boxes are made of celluloid and filled with approximately 26.5 oz of sodium nitrate. The racks are made of interlocking links of heavy wire that allows them to follow the contours of the tops of the papers in the file drawer. This arrangement keeps the papers compressed while they are burning[27].

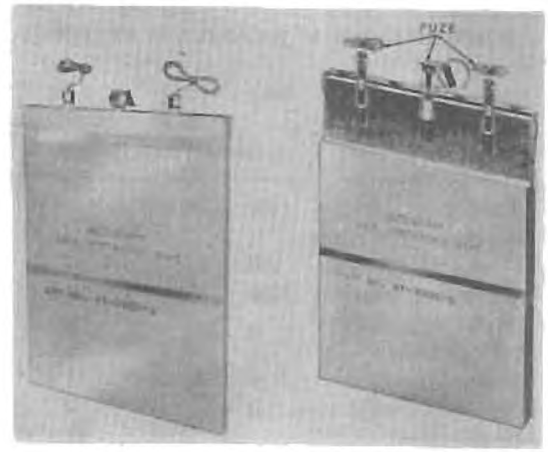


Figure 3-35.
TH1 Safe Destroying Incendiary, M1A2

3-16 BATTERIES

3-16.1 BATTERY TYPES AND REQUIREMENTS

There are three distinct types of battery.

1. Live primary batteries that consist of electrodes and aqueous electrolyte all in place and ready to function when connecting the load to the terminals. The most common type is the dry cell.

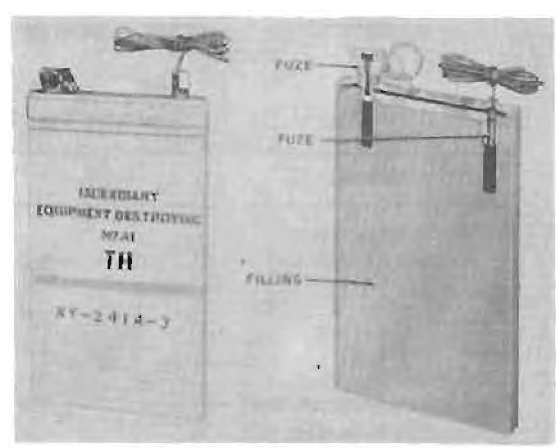


Figure 3-36.
TH1 Equipment Destroying Incendiary, M2A1

Figure 3-37. File Destroyer Incendiary, M4

2. Secondary batteries that have their electrodes immersed in the electrolyte but may not be capable of furnishing instant power to their load. Some types require charging to convert the surfaces of the electrodes electrochemically to the proper composition for power delivery. A common type is the old-style automotive battery.

3. Reserve batteries that have their electrodes in place but the electrolyte is introduced just prior to use. In the thermal type reserve battery, the electrolyte is in the solid, dry state between the electrodes. The thermal battery is made active by applying heat to melt the nonaqueous electrolyte.

While all three types of battery are used by the military, there are inherent difficulties with the first two types. The difficulty of designing live batteries to meet all of the requirements is caused by the incompatibility of the requirements with the properties of electrochemical systems. Those systems characterized by high power density at low temperatures cannot withstand long storage at moderate to high temperatures because of their high chemical reactivity. On the other hand, the systems stable at moderate to high temperatures have inadequate power densities at low temperatures. Without exception, those systems that produce adequate output at −40°F or below deteriorate rapidly at high temperatures. Since adequate output at −40°F at least is required, a highly reactive system must be used, with deterioration controlled by using a reserve or secondary power supply. Although storage life of a live primary cell may be extended markedly by storage at low temperatures, this would create a serious problem in logistics, in maintaining cold-storage facilities at depots and in transit, as well as in routine replacement of overaged batteries[32]. Live batteries, therefore, are not recommended for pyrotechnic ammunition.

Secondary batteries have similar design problems if only to a lesser extent. In addition, they are difficult to activate rapidly and are too large in size. Hence, they are also not recommended for this application.

Reserve batteries, on the other hand, can best fulfill the requirements. They are activated rapidly and capable of withstanding long storage without maintenance. They do have the disadvantages of relatively high cost and one-time use capability.

3-16.2 THERMAL BATTERY

A thermal battery is basically a primary voltaic cell of the reserve type. It consists of a bimetallic electrode system, a fused-salt electrolyte, a heat source to melt the electrolyte, thermal insulation, and an initiating system[33]. During storage, the electrolyte is in an inactive solid state. When heat is applied to the electrolyte (temperature of about 750°F), the electrolyte becomes a liquid ionic conductor.

Although the heat source for activation may be external, a complete thermal battery contains an integral source of heat that is dormant until required for operation. One way of providing heat is to surround the

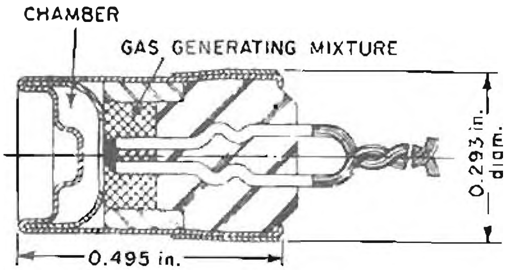


Figure 3-38. Dimple Motor, M4

individual cells with a pyrotechnic material that is ignited by a primer. The activation time (the time for the electrolyte to melt) varies from about 0.5 to 8 sec depending on battery size; the smaller the battery, the faster the activation time. Thermal batteries can be designed with a variety of dimensions and with different voltages and currents. Their active life is about 10 min. They are inherently rugged, withstanding all required shock and vibration tests, and have a shelf life of approximately 15 yr.

The thermal battery is the only power supply giving assured operation over the military temperature range. It is widely used in nonrotating and slowly rotating projectiles. Current development effort is under way to improve its capability in withstanding spin forces, to lengthen its life within a small package, and to further shorten its activation time[32].

3-17 GAS ACTUATED DEVICES

A gas actuated device is one that employs the energy supplied by the gases produced when a pyrotechnic composition burns to accomplish or initiate a mechanical action, other than expelling a projectile. Gas actuated devices are often called propellant actuated devices (PAD) and formerly were referred to as cartridge actuated devices. The mechanical tasks performed by gas actuated devices include switching, stroking, pin pulling and pushing, and cable cutting.

3-17.1 TYPICAL DEVICES

Many gas actuated devices such as switches, dimple motors (see Fig. 3-38[29]), and bellows motors are relatively small and contain the gas producing pyrotechnic mixture as an integral part of the device. Others, such as catapults or thrusters (see Fig. 3-39[34]), employ separate power cartridges. The cartridge contains its own primer and booster charge and has the general appearance of a shot gun shell.

Another category of gas actuated devices includes those actuated by sources of gas that have been generated externally by a gas producing device. The pin puller shown in Fig. 3-40[34] is an example of a gas actuated device with no self-contained gas supply. Details and specifications for existing gas actuated devices are found in Refs. 34 and 35.

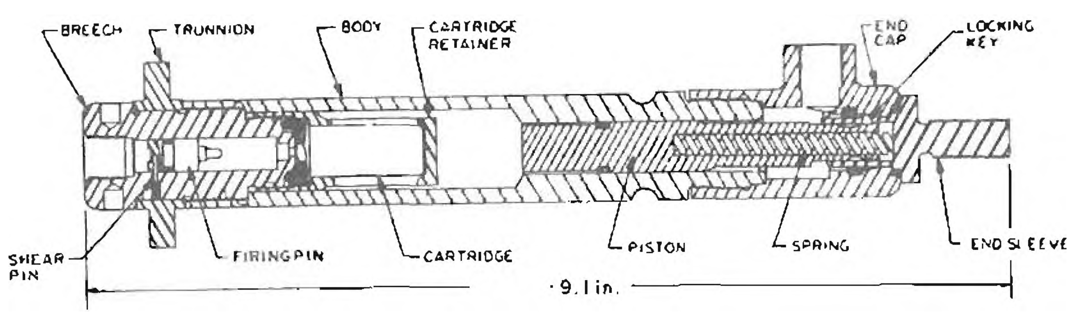


Figure 3-39. Thruster, M3A1

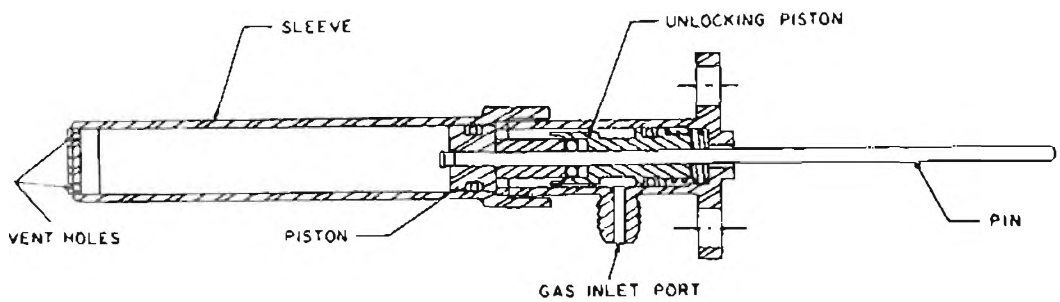


Figure 3-40. Pin Puller

3-17.2 METHOD OF OPERATION

Basically, gas operated devices contain a chamber of semifixed volume which, when filled with a pressurized gas, is able to expand and perform work. The dimple motor, shown in Fig. 3-38 for example, has a small chamber adjacent to a gas generating mixture. Upon application of a sufficient electric current through the resistive bridgewire, the mixture is ignited and the generated gases fill the chamber to such an extent that the chamber itself is forced to expand in order to accommodate the gas. Thus, the dimpled end of the device "pops" out. This motion is commonly used to operate a switch. A bellows motor operates in the same manner except that the gas fills a sealed bellows that is capable of expanding a greater distance than the dimple motor. A 1-in. travel is common.

Larger gas actuated devices operate on the same principle. In some devices the chamber is behind a piston that is thrust outward when the chamber fills with gas (Fig. 3-39). The gas for piston-type actuators is usually supplied by cartridges that are fabricated separately and placed in the actuators before use or by an external source of gas that is piped to the chamber. One advantage of using replaceable cartridges is that the actuator may be reused.

The duration of the power impulse produced by the gas actuated devices varies from milliseconds for dimple and bellows motors to several seconds for large thrusters. Initiation may be electrical, pneumatic, or mechanical. Cartridges are usually initiated mechanically by a stab mechanism that is spring-loaded or pneumatically operated.

Gas actuated devices are simple devices containing a minimum number of parts. They must be light in weight, yet strong enough to withstand the maximum pressure created by burning the propellant they contain. The materials selected for use in these parts must be compatible with the propellant, igniter, and primer at the temperatures and in the functional and storage conditions to which the parts are exposed.

Standard parts should be used wherever possible, and when special parts are necessary they should be designed so that they are manufactured easily. Wherever possible, parts should be made nonreversible (i.e., it should be impossible to assemble a component backwards). Much time is saved by using existing cartridges, details of which are found in Refs. 34 and 35. Information on the thermochemical properties of gas generating pyrotechnics (generally referred to as propellants) is contained in Ref. 36.

3-18 GAS PRODUCING DEVICES

A gas producing device is one that generates gas. Many gas actuated devices (see par. 3-17) employ an external source of gas for operation. This external source is a gas producing device using a pyrotechnic mix. It differs from a gas actuated device only in output. Its container is a chamber of fixed

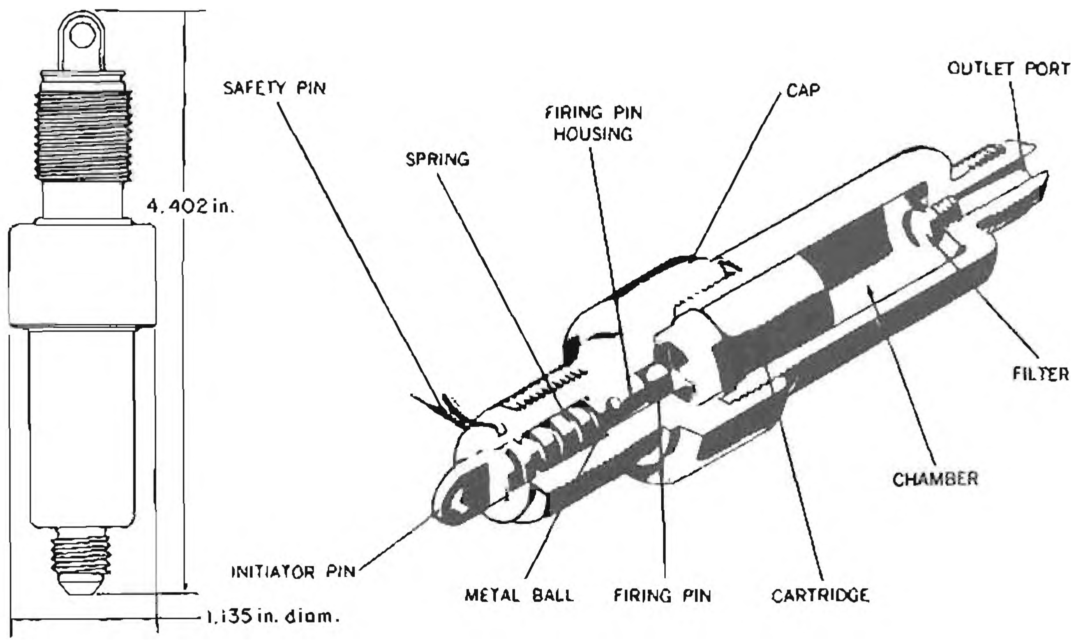


Figure 3-41. Mechanically Operated Initiator, Mk 9 Mod 0

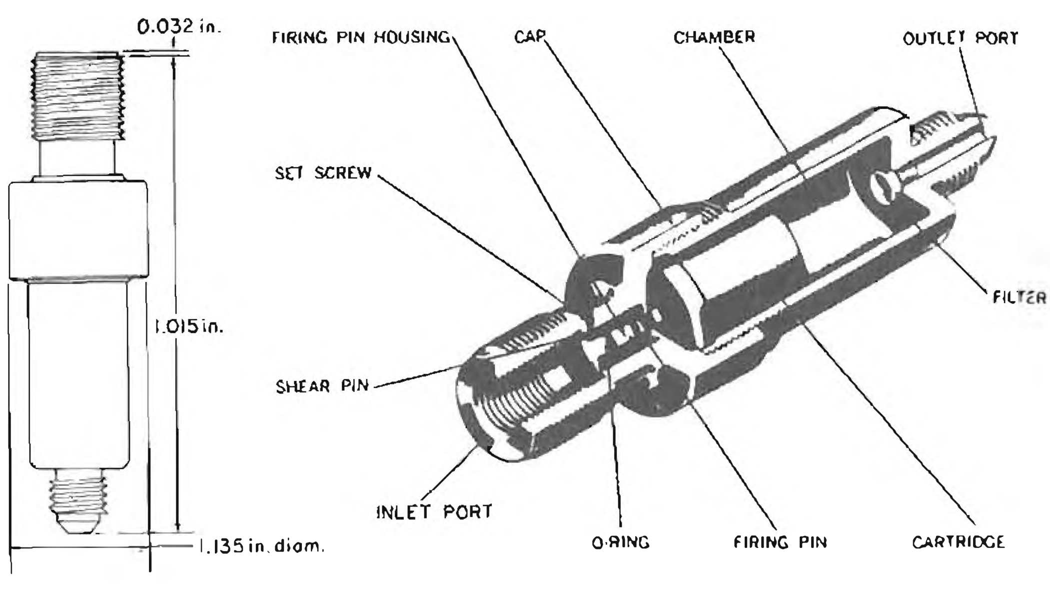


Figure 3-42. Gas Operated Initiator, Mk 10 Mod 0

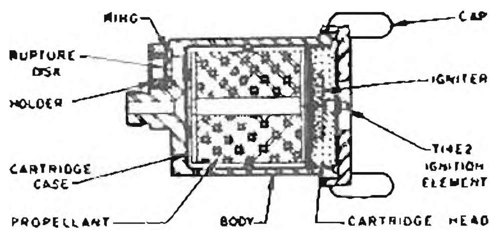


Figure 3-43. Gas Generator

volume that connects to an outlet port which, in turn, is connected via tubing to the gas actuated device.

There are basically two types of gas producing devices: (1) short duration (usually less than 0.5 sec) "initiators" and (2) long duration (more than 0.5 sec) "gas generators". Both devices consist of vented chambers containing cartridges and firing mechanisms. The firing mechanisms may be operated electrically, pneumatically, or mechanically. While gas producers are designed primarily to supply gas pressure to operate the firing mechanisms of gas actuated devices, they may also be used as sources of energy for operating piston-type devices such as safety belt releases, safety-pin extractors, and switches. Initiators are used extensively in aircraft to operate the firing mechanisms of propellant actuated devices. They eliminate cumbersome cable-pulley systems and provide a more reliable method of triggering. Initiators are often used as intermediate boosters in systems where the gas actuated device is remote from the initiator. They are also used to introduce a delay into gas actuated systems where several operations must be properly sequenced. A typical mechanically operated initiator is shown in Fig. 3-41[35] while a gas operated initiator is illustrated in Fig. 3-42[35]. Comparative data for several initiators are given in Table 3-23[34]. Further information is found in Refs. 34 and 35.

TABLE 3-23

COMPARATIVE DATA FOR INITIATORS

Model	Weight, lb	Chamber Volume, in.^{3}	Delay, sec	Peak Pressure*, psi
MECHANICALLY OPERATED				
M4	1.0	2.4	2	600 (12)
M12	1.0	2.4	1	600 (12)
M3	0.9	2.3	–	1000 (15)
M29	1.6	2.3	–	1000 (15)
M27	0.3	0.6	–	1200 (15)
T30E1	0.3	0.6	–	1200 (15)
M30	1.1	2.6	2	1500 (15)
M32	1.1	2.6	1	1500 (16)
M8	2.2	4.3	–	1800 (30)
GAS OPERATED				
M6	1.0	2.4	2	600 (12)
M33	1.0	2.4	1	600 (12)
M5	0.9	2.3	–	1000 (16)
M28	0.3	0.6	–	1200 (15)
T31E1	0.3	0.6	–	1200 (15)
M10	1.1	2.6	2	1500 (15)
M31	1.1	2.6	1	1500 (15)
M9	1.8	4.3	–	1600 (30)

*Peak pressure in 0.062 in.^{3} gage located at the end of a length of MS-28741-4 hose. The number following the pressure indicates the length of hose in feet between the initiator and the gage.

Gas generators differ from initiators in the duration of the pressure impulse that may last several minutes for a gas generator. Typically, gas generators are used for catapults, ejectors, cutters, removers, and thrusters. They have also been used to supply gas flow to spin turbines as well as for supplying pressure to operate pumps that supply hydraulic pressure

TABLE 3-24

COMPARATIVE DATA FOR GAS GENERATORS

Model	Weight, lb	Chamber Volume, in.^{3}	Operating Pressure, psi	Operating Time, sec
T3	25	100	2000	90
T4	30	50	1500	480
XM7	0.75	0.3	500†	0.9

†At the end of 2 ft of MS-28741-4 hose.

to missile controls. Comparative data for gas generators are given in Table 3-24[34]. An example of a gas generator is shown in Fig. 3-43[34]

The heart of the gas producing device is the cartridge that contains the gas producing pyrotechnic composition and an ignition element. The characteristics of the complete gas producing device are determined by the design of the cartridge and the chamber with its vents into which the gas expands. Complete design details are given in Refs. 34 and 35.

SECTION V FUZING AND TIMING

3-19 FUZES

3-19.1 PURPOSE OF A FUZE

The word fuze is used to describe a wide variety of devices used with munitions to provide the basic functions of (1) arming, i.e., sensing the environment(s) associated with actual use including safe separation and thereupon aligning explosive trains, closing switches, and/or establishing other links to enable the munition to function; (2) firing, i.e., sensing the point in space or time at which initiation is to occur and effecting such initiation; and (3) safing, i.e., keeping the munition safe for storing, handling (including accidental mishandling), and launching or emplacing.

Because of the variety of types and the wide range of sizes, weights, yields, and intended usage of ammunition, it is natural that the configuration, size, and complexity of fuzes also vary over a wide range. Fuzes extend all the way from a relatively simple device such as a grenade fuze to a highly sophisticated system or subsystem such as a radar fuze for a missile warhead. In many instances the fuze is a single physical entity—such as a grenade fuze while in other instances two or more interconnected components placed in various locations within or even outside the munition make up the fuze or fuzing system. There is also a wide variety of fuze related components, such as power sources, squibs, initiators, timers, safing and arming (integrating) devices, cables, and control boxes that sometimes are developed, stocked, and issued as individual end items but which in the overall picture constitute a part of the fuzing system.

Inherent to the understanding of the purpose of a fuze is the concept of the progression of action of the explosive train starting with initiation and progressing to the functioning of the main charge. Initiation, as the word implies, starts with an input signal, such as target sensing, impact, or other. This signal must then be amplified by suitable intermediate charges until a proper stimulus is obtained that will set off the main charge, be it photoflash, smoke, or flare. The explosive train is interrupted to provide safety. Present requirements call for at least two independent safing features, wherever possible, either of which is capable of preventing an unintended functioning; at least one of these features must provide delayed arming (safe separation).

The design of fuzes, then, is a complex subject. It is treated in detail in Ref. 37.

3-19.2 TIMERS FOR FUZES

A timer is a programming device; its purpose is to control the time interval between an input signal and an output event or events. There are four essential components in all timers: (1) a start system that initiates the programming action, (2) a power supply that sustains the timing action, (3) a time base or regulator, and (4) an output system that performs the required operation at the end of the desired time interval.

In selecting the components of timing systems, the designer must first determine the purpose for which the system is to be used and the factors influencing the selection of components. Some of the factors to be considered in the choice of the basic mechanism include time range and variation, accuracy and reliability, input and output signals, and cost.

Military timers are categorized into main types depending upon the method used to generate the time base. The main types are:

(1) Precision Reference Timers

(2) Electronic Timers

(3) Mechanical Timers

(4) Pyrotechnic Timers

(5) Flueric Timers

(6) Electrochemical Timers.

General timer characteristics are listed in Table 3-25[38]. As a general rule, there is a direct relationship between the accuracy of a timing device, and its output power and cost. Those timing devices that are most accurate, such as the quartz crystal controlled units and the cesium beam standards, are likely to have the least output power and to be the highest in cost. Those timers that have a lower order of accuracy, such as the pyrotechnic delays and the untuned-escapement mechanical timers, are likely to provide more output power and to be lower in cost.

With the exception of precision timers that are reserved for special applications, all of the timer types are in use in fuzes for pyrotechnic devices. Perhaps the most common timer type is the mechanical clockwork making use of a tuned two-center escapement in combination with a gear train. Electronic timers make use of an RC circuit.

The design of timers is discussed in detail in Ref. 38. For a discussion of pyrotechnic delays, see par. 3-21.4.

3-19.3 ENVIRONMENTAL SENSORS

If the fuze is to provide safing and functioning actions, it must sense when the environment is right for action. Hence, environment sensing is a basic and critical action of every fuze.

3-19.3.1 THE ARMING ENVIRONMENT

The arming environment is a combination of all of the conditions at which the fuze is to change from a safe state to one of readiness for functioning. The interior ballistic environment includes setback and spin (see par. 4-5) and the exterior ballistic environment includes aerodynamic forces (see par. 4-6). Sensing is accomplished by means of sliders, spring-mass combinations, links, and the like. For design details, see Ref. 37.

3-19.3.2 THE FUNCTIONING ENVIRONMENT

Often referred to as target sensing or terminal ballistics, the functioning environment relates to having the pyrotechnic devices accomplish its intended function. The target can be sensed by contact when the device touches the target; it can be sensed by influence as with a proximity fuze; action can be preset in a time fuze so that the fuze will function when a predetermined time interval has expired; or it can be sensed by a combination of these or command triggering. For design details, see Ref. 37.

Occasionally an intermediate action is required of pyrotechnic ammunition, such as ejection of a parachute (see par. 4-8). The intermediate actions are sensed in the same manner as final actions.

3-19.4 INPUT AND OUTPUT

Fuzes are initiated by a source of energy that produces heat. Mechanical initiators are ignited by a firing pin. Electric initiators are ignited by a current that heats a bridgewire;

TABLE 3-25

GENERAL CHARACTERISTICS OF TIMERS

Features	Precision Referance	Electronic	Mechanical	Pyrotechnic	Flueric	Electro-Chemical
Input to start	Voltage pulse	Voltage	Voltage or mechanical	Voltage, flame, or firing pin	Fluid pressure	Voltage, chemical release
Time base	Crystal or atomic	Oscillator	Escapement, motor, tuning fork	Pyrotechnic burning rate	Oscillator	Rate of chemical reaction
Time range	10^{-9} sec to years	10^{-3} to 10^{3} sec	Seconds to days	10^{-3} to 10^{3} sec	1 to 10^{3} sec	Minutes to days
Accuracy	1 part in 10^{6} to 1 part in 10^{12}	±0.1%	±5% to 1 part in 10^{6}	±10%	±1%	±4-10%
Output	Voltage pulse or time interval	Voltage	Mechanical	Flame	Fluid pressure, voltage	Chemical reaction, voltage, chemical

current source is a battery or other power source. See par. 4-4 on ignition

For most pyrotechnic devices the output is a flame that will ignite the main pyrotechnic charge to produce light, smoke, heat, gas, or sound. Occasionally, the output is a detonation wave as in a battle effects simulator or an ejection cartridge. Here the explosive train must include a detonator and possible other components that augment the detonation wave. Design details are covered in Ref. 28.

3-20 FUSES

The safety fuse most commonly used contains black powder that is tightly wrapped with several layers of fabric and waterproofing materials. It is used to transmit a flame along a preselected path to the pyrotechnic charge, where the flame may be used to initiate the charge directly, or it may initiate one or several squibs that are used as charge igniters. Fuse burns slowly at a fairly uniform rate; however, it is likely that the burning rate will vary from roll to roll of the fuse, and it will vary once a segment has been cut and emplaced for a period of time.

Safety fuse is made with several different burning speed ranges; the two most common burning rates are 30 and 40 sec ft^{-1}, both having a tolerance of ± 10%. Some fuse, made for higher altitudes, may burn slightly slower (nominally 43 sec ft^{-1}). The fuse is usually manufactured in 50-ft lengths, then coiled and wrapped in packages containing two coils.

Two types of fuse are in common use by the U.S. Army: (1) blasting time fuse that has a spiral wrapped outer cover usually colored orange, and (2) Safety Fuse M700 that has a smooth green plastic cover with length markers of abrasive material (so they can be felt in the dark). These two types of fuse are shown in Fig. 3-44[39].

Safety fuse can be ignited in several ways:

(1) Matches. Ordinary matches are frequently used to light a single line of fuse. The

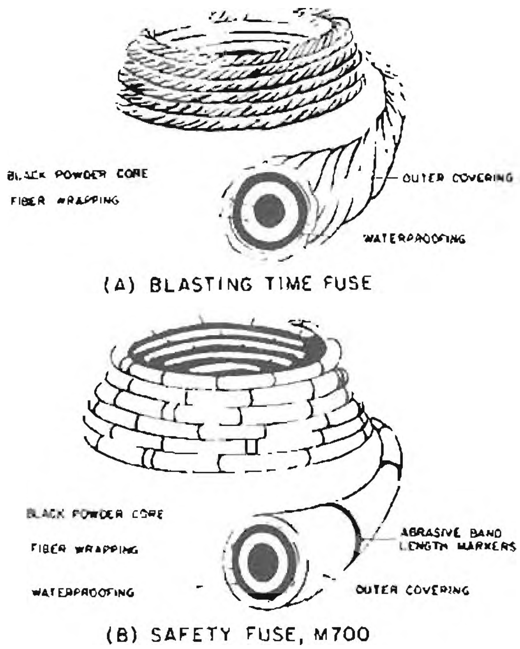


Figure 3-44. Types of Safety Fuse

fuse must be split, taking care not to dislodge the black powder filler. The match is applied so that its initial flare ignites the fuse.

(2) Military fuse lighters. The military lighters provide a method for positive ignition

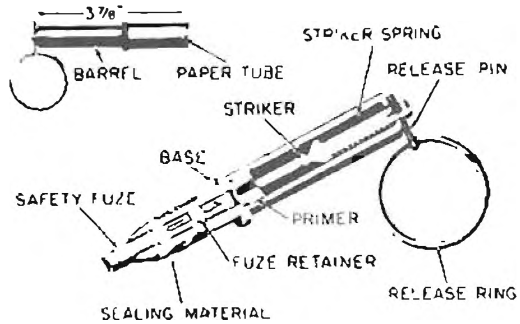


Figure 3-45. Fuse Lighter, M2

of safety fuse even under extreme environmental conditions. Two military fuse lighters in use by the U.S. Army, the M2 and the M60 are shown in Figs. 3-45[37] and 3-46[39]

(3) Pull wire fuse lighter. This lighter for safety fuse is a commercial product commonly used where positive ignition together with weather protection is required. It is a paper tube, closed at one end, from which a wire with a pull tab protrudes. In use, the fuse is inserted into the open end until it bottoms and is securely held in this position by an internal gripper. The fuse is ignited by pulling the wire.

Safety fuse should be used and stored so as

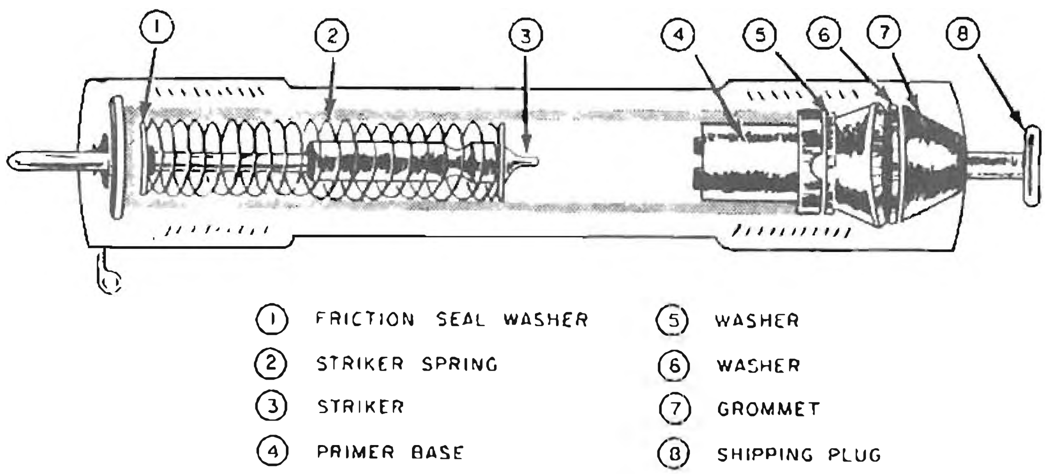


Figure 3-46. Fuse Lighter, M60

to prevent contact of the covering from petroleum distillates that will attack the covering and make the fuse unreliable. Twists, kinks, or sharp bends may crack the covering or cause discontinuities in the powder train. Cold weather causes the covering to be less resistant to mechanical movement and additional care is required to maintain its reliability. When safety fuse is used in applications where it is closely confined, its burning rate is considerably increased, the tighter the confinement, the faster the burning rate.

Warning: It is important to distinguish safety fuse from detonating fuze. Detonating fuze has a high explosive filler with a propagation rate of approximately 21,000 fps. Its intended use is the detonation of high explosives.

3-21 DELAYS

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. Representative delays covering various time ranges have been compiled in a compendium[40]. 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 they must take into account the space limitations imposed.

3-21.1 SPACE LIMITATIONS

The designer of a pyrotechnic device always will be faced with space limitations when trying to fit it 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), wall thickness of the confinement, internal volume, the need for baffles and retainers, and the method of initiation (i.e., mechanical or electrical). For methods of initiation, see par. 3-14.

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. These topics are discussed in detail in Ref. 38.

3-21.2 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 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. 3-47[1].

The burning time of a given quantity of a gas producing material is, in general, nearly directly proportional to pressure. The relationship has been shown to be hyperbolic and can be represented by an empirical equation of the form

$$t = a + \frac{k}{P^n}, \text{ sec} \tag{3-12}$$

where

t = burning time, sec

a = factor depending on mixture, sec

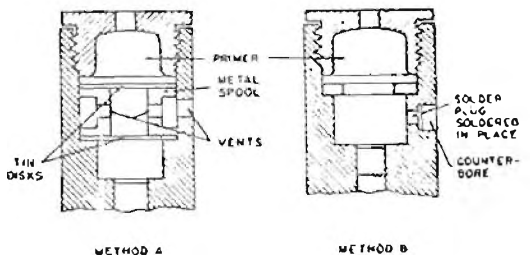


Figure 3-47. Sealing of Vented Delay Element

k = factor depending on mixture, dimensionless

P = pressure, lb in.$^{-2}$

n = factor depending on mixture, dimensionless

The numerical values of the factors are a = 0.26, k = 1.0, and n = 0.13 for the 95.4/4.6 barium chromate boron/composition (DP 480). This equation fits many of the data points, however, it is not accurate below a pressure of 10 cm Hg.

The design of a vented 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. Means of alleviating separation include threading the inner diameter wall 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. 3-48[40]. The baffles are always force fitted into the delay body with approximately 0.002- to 0.005-in. interference fit.

3-21.3 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 charge is ignited, see Fig. 3-49[1].

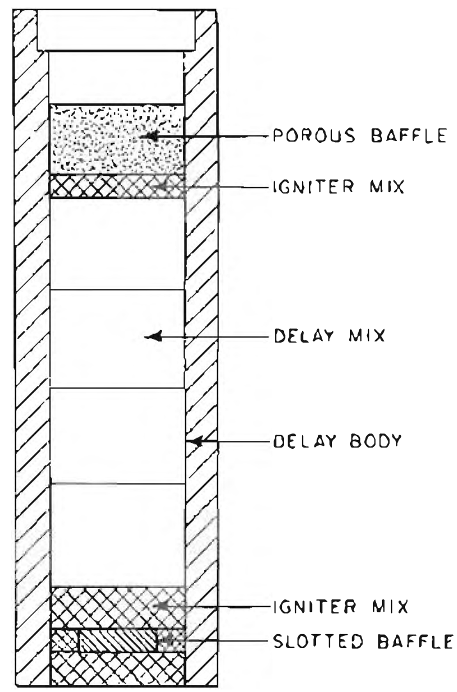


Figure 3-48. Typical Baffled Delay Column

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 is often used because obturation tends to increase the average burning rate of the delay composition.

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. 3-21.2.

The internal free volume is that volume

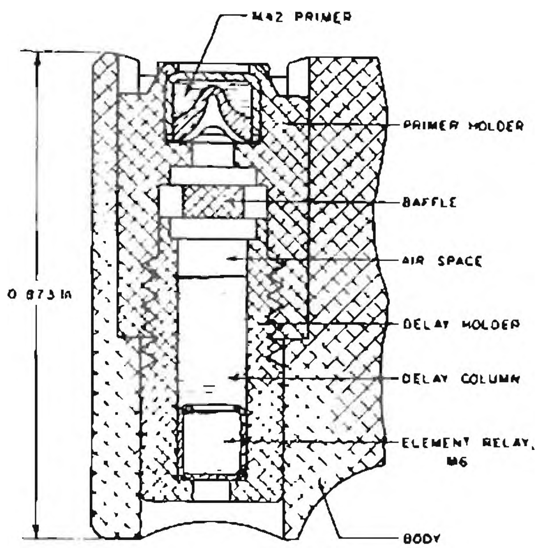


Figure 3-49. Delay Element, Obturated, M9

formed by a cavity in the delay housing which is designed to contain the gases produced by the chemical reaction. Containment of the gases makes the delay independent of the effects of pressure or humidity of the ambient atmosphere and the fumes which might damage 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 equation[28]

$$P = \frac{30\,(W_p + W_d)}{V},\ \text{lb in.}^{-2} \qquad (3\text{-}13)$$

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.

3-21.4 DELAY COMPOSITIONS

The basic ingredients of a delay composition consist of a fuel, an oxidant, a binder, and a lubricant. Delay compositions react when the proper ratio of oxidant and fuel are intimately mixed and ignited. The rate of burning is dependent on the concentrations of the ingredients, their particle size, composition, temperature, and pressure. For a general discussion of the chemistry and technology of primary explosives, see Ref. 41.

3-21.4.1 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, poor burning qualities under diminished pressure, and finally, limited supply.

3-21.4.2 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.

TABLE 3-26

GASLESS DELAY COMPOSITIONS IN CURRENT USE

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

Table 3-26[1] 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. Additional delay mixtures are discussed in Ref. 38.

3-21.5 SYSTEM DESIGN AND PERFORMANCE

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

(1) They should be stable and nonhygroscopic; should have the highest purity consistent with requirements; should be readily avaiable 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 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.

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.

(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.)

SECTION VI OTHER EFFECTS

3-22 SOUND

The production of sound by means of pyrotechnic compositions has found some military applications. These include training of troops and observers, decoy or deception of enemy troops, atmospheric sounding, warning, signaling, and military salutes. In general, two types of sound are produced with pyrotechnics: (1) single burst or report, and (2) whistle.

The single blast effect is usually produced by the rapid expansion of the gaseous and/or solid products of a pyrotechnic reaction. The shock produced by high explosive reactions can also generate burst-like effects. Whistle-like effects are produced by the burning of certain compositions in tubes. The whistle is

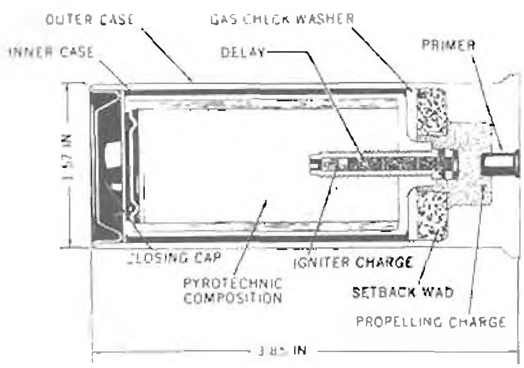


Figure 3-50
Projectile Air Burst Simulator, M74A1

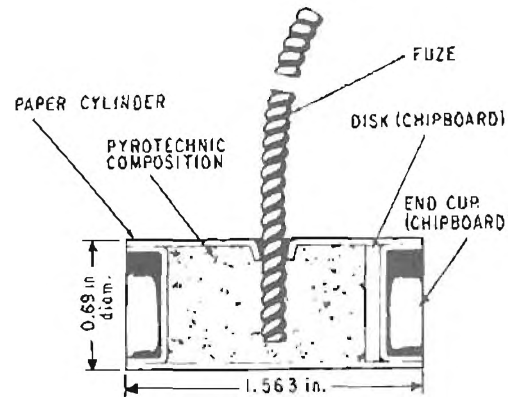


Figure 3-51. Firecracker, M80

produced by the decrepitation and subsequent intermittent burning of the composition[42].

The selection of a pyrotechnic system (composition, container, delivery mode) for producing audible effects depends, of course, on the intended use. A discussion of some of the possible uses will clarify this point. The mechanisms of producing sound are covered in pars. 3-22.2 and 3-22.3.

3-22.1 USE OF SOUND-PRODUCING PYROTECHNICS

3-22.1.1 TRAINING OF TROOPS AND OBSERVERS

Although it would be desirable to simulate the sound of typical military items, the requirements of safety and the restrictions on size, weight, cost, and state-of-the-art often make exact duplication impractical. It is sufficient for most training maneuvers if personnel can associate the simulated sound with the real. Some of the sound simulators presently used in training are:

(1) Air burst simulators. These simulate an artillery projectile burst by producing a puff of smoke and a loud report. An example is the M74A1 Projectile Air Burst Simulators shown in Fig. 3-50[3].

(2) Booby trap simulators. These devices are used during troop training and maneuvers to provide safe simulation of actual booby traps. Either a loud report or a whistle lasting 3 or 4 sec is produced. Training in the installation of actual booby traps as well as the respect for enemy booby traps can thus be accomplished. The M80 Firecracker which simulates an explosive detonation is shown in Fig. 3-51[4]. The M119 Booby Trap Simulator is a whistling device and is shown in Fig. 3-52[3].

(3) Ground burst simulators. These simulate an approaching artillery projectile with a 2 to 4 sec whistling sound followed by a flash and loud report. The M115 Projectile Ground Burst Simulator shown in Fig. 3-53[3] is an example.

(4) Hand grenade simulator. This device is approximately the size of a hand grenade. The fuse burns for 6 to 10 sec after ignition and the simulator explodes with a loud report and mild explosive action. The M116 Hand Grenade Simulator looks very similar to the simulator in Fig. 3-53 except it is only 4.25 in. long.

(5) Nuclear blast simulators. These are training devices that attempt to simulate the flash, sound, and mushroom-shaped smoke cloud of a nuclear blast. The XM142E1 Atomic Explosion Simulator is an example[43].

Figure 3-52. Whistling Booby Trap Simulator, M119

(6) Gun-fired blank cartridge. This type of ammunition is provided in small and medium calibers (75, 76, 90, and 105 mm) for simulated heavy gun fire and military salutes. It consists of partially loaded cartridge cases with no projectile.

3-22.1.2 DECOY AND DECEPTION OF ENEMY TROOPS

Almost all of the devices described in par. 3-22.1.1 can be used to deceive or decoy enemy troops. If gun fire must be simulated under the scrutiny of enemy troops, it is obvious that some degree of realism must be sought in the simulator. However, the psychological effect of a loud report or whistling sound on an enemy infiltrator—as provided by a booby trap which simulates no particular weapon—is apparent. In this instance it should be noted that unconventional devices can be used to improvise noise makers. Blasting caps, acetylene and oxygen ignited by a spark coil to achieve a machine gun effect, and others have been tried. It has been suggested that pyrotechnic whistles might be used underwater to decoy or confuse sonar devices[42]

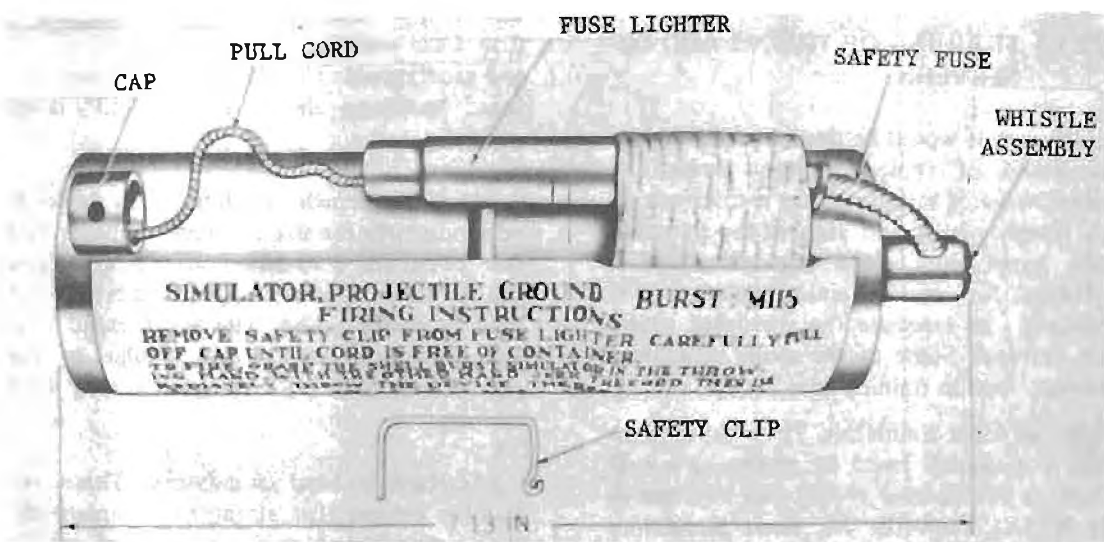


Figure 3-53. Projectile Ground Burst Simulator, M115

3-22.1.3 WARNING AND SIGNALING

The so-called railroad torpedo is used to warn the engineer in an engine cab by means of a loud report that he is approaching an open switch, fork, etc. It is sometimes used by the military for this purpose as well as for simulation. A simulator such as the M117 or M119 Booby Trap Simulator is useful for warning or signaling the approach of the enemy or alerting friendly troops in restricted areas.

3-22.1.4 MILITARY PROTOCOL

The use of blank small and medium caliber ammunition for military salutes is covered in par. 3-22.1.1.

3-22.1.5 SOUNDING

The sound levels afforded by pyrotechnic mixes can be used advantageously for aerial sounding. The properties of air which affect sound transmission (density, temperature, etc.) can thus be studied.

3-22.2 BLAST EFFECT

The production of a blast or single loud report for the purposes mentioned previously is easily accomplished by the use of pyrotechnic compositions which react or burn rapidly, thereby producing a rapid release of gas. The speed of normally slow-burning compositions, such as black powder, may often be increased by confinement thus making them useful for blast effects. In general, flash signals (see par. 3-2.1) may also function as burst simulators if the distance is not excessive[3].

Some typical compositions used in sound producing devices are listed in Table 3-27[7,43]. Note that the compositions are of the extremely rapid burning class. Thus, the production of sound is not necessarily dependent upon confinement.

Black pelletized or loose powder is used in blank cartridges, and the sound is produced by the obturation of the cartridge case with a fiber or plastic closing cap.

TABLE 3-27

SOUND PRODUCING COMPOSITIONS

Ingredients	Weight, %
M115 Projectile Ground Burst Simulator	
Mg	34
Al	26
Potassium perchlorate	40
M117 Booby Trap Simulator	
Mg (Grade A, Type II)	17
Antimony sulfide (Grade I or II, Class C)	33
Potassium perchlorate	50
XM142E1 Atomic Explosion Simulator (Sound Charge)	
Al (pyro black)	20
Potassium perchlorate	64
Sulfur	8
Bran (grain)	8

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3-22.3 WHISTLE EFFECT

Whistle effects are produced by burning compositions containing gallic acid; the potassium salts of benzoic acid, of 2, 4, dinitrophenol, and picric acid; and the sodium salt of salicyclic acid; combined with potassium chlorate, perchlorate, or nitrate in tubes. Some typical formulas are given in Table 3-28[7,42].

The frequency of the whistle compositions is determined to a large extent by the length of the tube into which the compositions are loaded. Fig. 3-54 shows the relationship between frequency and tube length, for two tube diameters loaded with the middle composition of Table 3-28. Frequencies much higher than 5000 Hz have not been encountered.

The burning rate of whistling compositions appears to decrease as the frequency of the

TABLE 3-28

COMPOSITIONS PRODUCING A WHISTLE EFFECT

Ingredients	Weight, %
M119 Whistling Booby Trap Simulator	
Potassium chlorate	73
Gallic acid	24
Red gum	3
Experimental	
Potassium perchlorate	70
Potassium benzoate	30
Experimental	
Potassium nitrate	30
Potassium dinitrophenate	70

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whistle is increased. RMS pressures at 20 ft have ranged from 3.59 dyn cm^{-2} for a 0.34-in. diameter tube up to 72 dyn cm^{-2} for a 3-in. diameter tube. The tube material has little effect on the acoustical output. The acoustical output intensity is dependent upon the relative proportions of the ingredients.

It has been theorized that the whistling phenomenon is due to the rhythmic, intermittent burning of the composition which is enhanced by the resonance of the tube. An alternate but untried method of producing a whistle effect would be to use a gas producing pyrotechnic composition (see par. 3-18) in conjunction with a mechanical type whistle.

3-23 LUMINESCENCE

Luminescence is an emission of light that is not ascribable directly to incandescence and, therefore, may occur at ambient temperatures. It may be produced by physiological (as in the firefly), chemical, frictional, electrical, and radiative action. The uses of luminescent materials as delivered or dispersed or mixed with pyrotechnic compositions are numerous.

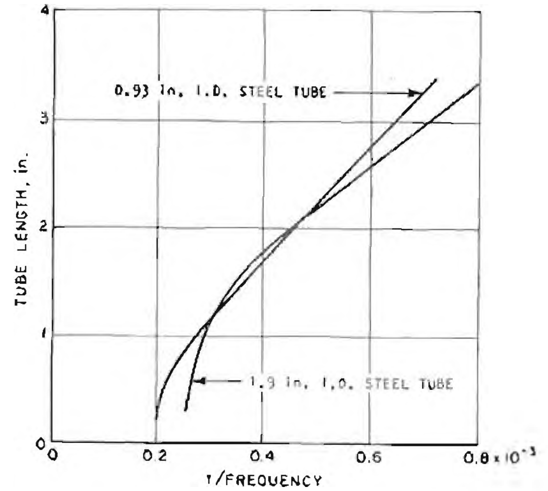

Figure 3-54. Effect of Tube Length on Frequency of Burning Whistle Compositions

The following uses are exemplary:

(1) Marking and Low-level Illumination. Certain organic substances have been used for marking and illuminating trails, airstrips, minefields, and enemy troops at night. One chemiluminescent substance is a liquid aliphatic amine which may be delivered to the target with artillery or other commonly used pyrotechnic vehicles[7]. Upon delivery and dispersion, the chemiluminescent material solidifies with the aid of a waxy material and thereafter reacts with atmospheric oxygen to produce a glow lasting up to 7 hr. For more information about liquid-filled projectile design, see Ref. 44.

(2) Upper Atmosphere Studies. Certain materials, when released above altitudes of 80 km, can combine with the atomic oxygen or nitrogen at these levels, or with previously released materials to produce chemiluminescent reactions[45]. Some of the materials which have been released into the upper atmosphere are sodium[45], ammonia[45], nitric oxide[46], ethylene[47], acetylene[48], and aluminum compounds[46]. Of these, sodium and aluminum have been dispersed pyrotechnically[7]; the other materials are mentioned be-

cause it may be possible to release them with the aid of pyrotechnics.

Chemiluminescents are released into the upper atmosphere to study wind speed and direction, temperature, diffusion coefficients, and N_2 and O_2 concentrations during the night.

The chemistry of the high-altitude chemiluminescent releases is well documented in the literature[45] and laboratory simulation of the various chemiluminescent reactions has preceded the high altitude tests in most cases. In one experiment[46] the pyrotechnic mix consisted of 75% cesium nitrate, 23% aluminum powder, and 3% magnesium powder pressed at 20,000 psi to form a 7.11-cm diameter, 15.5-cm long grain. The pressed grain was then loaded into a steel tube and ignited by a pyrotechnic train. The reaction products were vented through a convergent tungsten nozzle with a 0.5-cm throat. At altitudes above 100 km, such flares burned for periods of 40 to 100 sec producing glowing trails persisting up to 180 sec. The suggested reaction mechanism is

(1) $AlO + O \rightarrow AlO_2^*$
(formation of excited state)

(2) $AlO_2^* + \text{Molecule} \rightarrow AlO_x + \text{Molecule}$
(collisional deactivation)

(3) $AlO_2^* \rightarrow AlO_2 + h\nu$
(radiative decay)

(4) $AlO_2 + O \rightarrow AlO + O_2$
(regeneration of AlO)

where reaction (2) would predominate over reaction (3) below 100 km because of the density of the atmosphere.

The chemistry and delivery modes for chemiluminescent materials used under normal atmospheric conditions are covered in classified literature. Suffice it to say that the presently used compounds are activated (to the glowing state) upon exposure to the air or by mixture with other compounds. In either case, a storage problem occurs because of the reactivity of the compounds. The method of dispersion from an artillery projectile is also a problem because the mere bursting of the projectile has proven unsatisfactory. Since personnel may come in contact with the dispersed material, the toxicity of the chemiluminescent substances also must be considered.

3-24 IONIZATION

Ionization is the process of creating ions—atoms, molecules, or nuclei—that have more or less than the number of electrons needed to balance the opposing internal charges. The unbalance of electrons causes ionized substances to have a positive or negative charge and thus rather reactive properties both electrical and chemical.

The properties of ionized materials as generated pyrotechnically are useful in a few applications, mostly involving upper atmospheric research.

3-24.1 CREATION OF ARTIFICIAL COMET TAIL

It has been discovered that comet tails interact with the solar wind thus revealing information about the latter. Rather than depend upon the uncontrollable nature of existing comets, the production of interplanetary ion clouds has been proposed to simulate the properties of actual comet tails. Barium and strontium have been suggested as useful elements for these endeavors[49]. The dissociation of ammonia (NH_3) into NH_2 and NH radicals has also been suggested for simulating certain comet tail characteristics[45].

3-24.2 STUDY OF INTERPLANETARY MAGNETIC FIELD LINES

It has been shown that the barium ion will diffuse along magnetic field lines at extremely high altitudes. Observation of this phenomenon is done with a camera equipped with the proper filters[49].

3-24.3 PRODUCTION OF ARTIFICIAL ELECTRON CLOUDS

The production of artificial electron clouds may be accomplished by vaporizing some of the alkali metals such as potassium and cesium at altitudes between 70 and 130 km (the region known as the "E layer"). The usefulness of artificial clouds stems from the ability to track the clouds with ground-based radar because the clouds act as a radar "target". The scientific uses of artificial electron clouds include studies of high-altitude winds, diffusion, ionospheric structure, atmospheric parameters, expansion of high-pressure gases, thermochemical reactions, and electromagnetic propagation[50]. Of course, the use of small quantities of alkali metals in rocket exhausts can produce concentrations of ions useful for tracking purposes[7]. In this regard a rocket exhaust also might be simulated with a flare-like device.

3-24.4 REMOVAL OF ELECTRONS FROM THE NORMAL IONOSPHERE

It has been shown that the chemical release of sulfur hexaflouride (an electronic-attacking gas) into the "F layer" region of ionosphere (200-300 km) can substantially reduce the normal electron concentrations. In effect, a "hole" is produced in the ionosphere that distorts radio and radar signals[45].

3-24.5 PRODUCTION OF VAPORIZED METALS

The production of the vaporized metals that are often used in the aforementioned applications is accomplished by burning pyrotechnic mixtures of the oxides or nitrates of the metals with aluminum or magnesium. Factors to be considered in the dispersion of ionized or ionizable materials are photoionization by sunlight, ion life, initial velocity of ion or electron clouds from the source, temperature of released materials, and pressure at release altitude[45,49,50]. The impor-

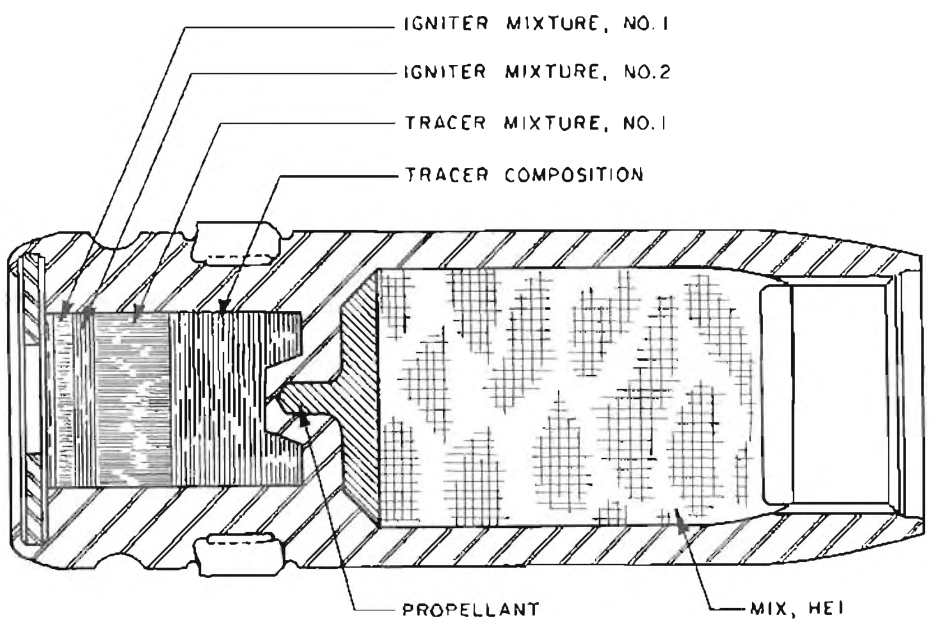

Figure 3-55. 20 mm Charged Body Projectile, HEIT-SD, XM246E5

tance of these factors would depend heavily upon the intended use.

3-25 DESTRUCT ELEMENTS

Self-destruction is required in the design of many munitions such as antiaircraft rounds that may endanger friendly territories by missing and going beyond their intended target. Self-destruct features are also used to deactivate area chemical munitions after a specified period. The destruct action is normally initiated by a fuze or a tracer in the round after a time that allows the projectile to reach its maximum effective burst height.

The charged body 20 mm projectile shown in Fig. 3-55 illustrates the principle. The igniter mixes start the burning of the first tracer composition which in turn ignites the second tracer mix. As the latter burns to completion, it generates sufficient heat to ignite the propellant stored in the recessed cavity which initiates the high explosive incendiary mix.

Pyrotechnic units are also used for destroying classified cryptographic equipment, safes, and files. These units normally consist of an incendiary mix such as thermite or sodium nitrate and wood flour packaged in a metal case of suitable geometry for the application (see par. 3-15.3).

3-26 WEATHER MODIFICATION

Modification or control of the weather has been the subject of many investigations in the past. Aside from the obvious socio-economic advantages to be gained from such control, the military has interest in hurricane modification (Navy Project STORM FURY), dissipation of all types of low stratiform clouds and fog (Air Force), and the suppression of lightning discharges (Army)[51]. Endeavors such as these, if successful, would facilitate or allow tactical operations normally impossible due to weather conditions. The positive control of certain weather conditions also would prove to be a powerful military weapon.

Attempts have been made to control almost all types of meteorological phenomena including winter orographic storms, cumulus clouds, hail, extratropical cyclones, cold and warm fogs, hurricanes and tornadoes, and lightning. Varying degrees of success have been encountered in these attempts. In most cases the statistical verification of success or failure is difficult due to the lack of proper control specimens. In small scale experiments, especially in fog control at airports, demonstrable results have been produced.

3-26.1 TECHNIQUES OF PRODUCING NUCLEI

A large variety of techniques and substances have been used in weather control attempts. Historically, one of the first cloud seeding experiments was performed in 1946 which succeeded in precipitating ice crystals from a supercooled "cloud" of water vapor by the injection of dry ice (solid CO_2) pellets. Chilled metal rods also induced precipitation in this experiment. The mechanism of inducing precipitation was found to be the production of nuclei of 1 to 2 micron diameter upon which the water vapor could condense.

The most frequently used substance for producing ice nuclei in cloud formations is silver iodide (AgI). At temperatures of $-6°C$ and below, AgI will form ice nuclei in supersaturated atmospheres thereby inducing the formation of ice crystals that may precipitate as rain or snow or that may affect cloud formation or directions. Sodium iodide, lead iodide, certain steroids, amino-acids, phloroglucinol, α-phenazine, and metaldehyde have all been tried as nucleating agents. Advantages sought by the use of agents other than AgI are lower cost, higher nucleating temperatures, less sensitivity to photolytic inactivation, and greater nucleating ability. Successful reduction of the photolytic decay of the nucleating properties of AgI has been shown with the addition of β-naphthol, bsi-(2-amino phenyl) disulfide, diphenylthiourea, 8-hydroxyquinoline, and Kodak Anti-Fog No. 2. The efficiency of the nucleating process of AgI has

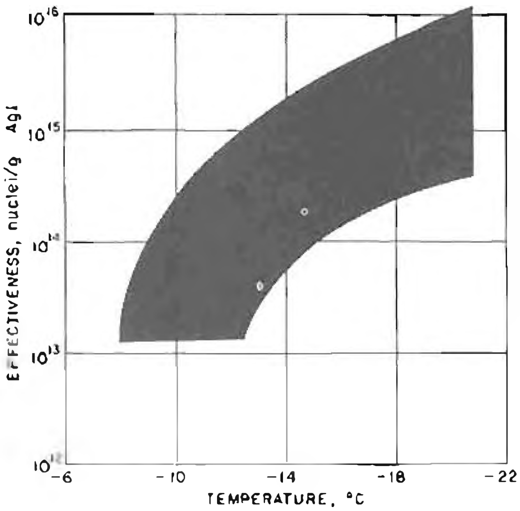

Figure 3-56. Area of Effectiveness-temperature Relationship for Fuel-supported AgI Generators

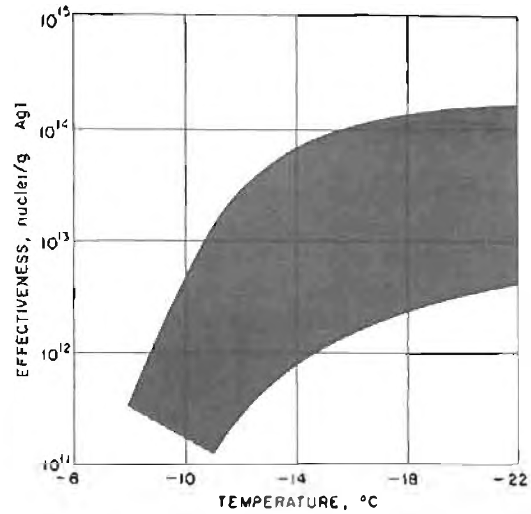

Figure 3-57. Area of Effectiveness-temperature Relationship for Pyrotechnic AgI Generators

been increased by the deliberate addition of contaminants such as ammonium hydroxide, hydrogen sulfide, and sulfur dioxide.

When dealing with warm water-laden clouds or fogs, different techniques must be used for control or modification. Substances which exhibit hygroscopicity are thought to be useful. Calcium chloride and sodium chloride have been tried; and a pyrotechnic mixture of aluminum powder and hexachloroethane, burned to yield aluminum chloride, has been suggested. Other methods for use in warm fogs and clouds include evaporation by heat from jet engines, asphalt paving, and spraying suspended carbon black[51].

In general the seeding agent is dispersed in the form of an aerosol or a smoke, depending on the method of generation; the generator may be ground stationed or air borne. Delivery from the ground is necessarily limited. The major techniques that have been used to disperse nucleating agents are:

(1) Evaporation from an electrically heated wire

(2) Burning a complex of AgI and acetone or isopropylamine with the aid of a fuel such as propane or fuel oil

(3) Burning a wick impregnated with AgI in a liquid petroleum gas flame

(4) Detonating a mixture containing high explosive and AgI

(5) Burning a pyrotechnic mixture containing AgI or substances which will form AgI upon reaction.

It has been found that the nucleating ability and the susceptibility to photolytic deactivation vary with the method of dispersion. The dispersion techniques that are important from the pyrotechnic standpoint are discussed in pars. 3-26.2 through 3-26.4.

3-26.2 BURNING AgI COMPLEX WITH A FUEL

Typically, the complex consists of 2 or 3% AgI with 0 to 1% NaI in a solution of acetone, isopropylamine, or ammonia[52]. This complex is fed to a nozzle which forms an aerosol. The aerosol is burned with the aid of a fuel such as propane or fuel oil. In the case of the isopropylamine no fuel is used. The burning rates for fuel supported complexes range from 0.1 to 4.5 g min.$^{-1}$ The range of effectiveness as measured in nuclei per gram of AgI is shown in Fig. 3-56[52], as a function of temperature, for a variety of fuel-supported generators.

3-26.3 IMPREGNATED WICK GENERATOR

In this type of generator, a wick is impregnated with AgI and burned in a propane or butane flame. Typical burners generate from 0.006 to 0.04 g min^{-1} of AgI and are as effective (in nuclei per gram of AgI) as fuel supported types[52]. Wick generators are usually limited to ground-based operation.

3-26.4 PYROTECHNIC TYPE AgI GENERATORS

AgI and similar nucleating agents may be conveniently produced by pyrotechnic compositions in which the product or products consist of said substances. Compositions are various and AgI content varies from 10 to 70%. AgI burn rates range from 1.5 to 150 g min^{-1}. Fig. 3-57[52] shows the range of effectiveness of pyrotechnic generators measured in nuclei per gram of AgI over a range of useful temperatures. Note that the pyrotechnic generators are about a magnitude of order less effective than fuel-supported and wick-type generators. However, this is offset by the fact that more nuclei can be dispersed in a shorter period of time with pyrotechnic generators thus adding to their usefulness.

A detonating type of generator which uses detonating cord impregnated with AgI is even more rapid in dispersing AgI.

Three typical seeding mixtures are shown

TABLE 3-29

TYPICAL PYROTECHNIC SEEDING MIXTURES

Ingredients	Weight, % No. 1	
Silver Iodide or Lead Iodide	40-60	
Ammonium Perchlorate	25-45	
Iditol (synthetic resin)	10-25	
Graphite or Oil	1.5-2	
	No. 2	No. 3
Silver Iodate	75	—
Lead Iodate	—	75
Magnesium (25μ)	15	10
Laminac (with no hardener)	10	15

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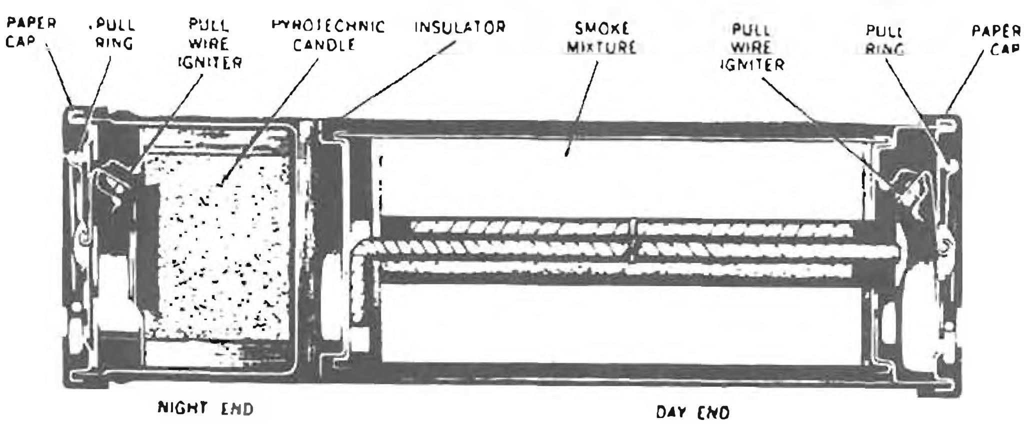

Figure 3-58. Marine Smoke and Illumination Signal, Mk 13

in Table 3-29[7]. Photoflash cartridges have been used successfully for packaging pyrotechnic seeding generators, and special dispensers capable of delivering up to 60 lb of AgI smoke also have been employed.

3-27 COMBINATION OF EFFECTS

It is often desirable to have more than one effect (light, smoke, etc.) available in a single pyrotechnic device. The combination of a smoke and illuminant signal, for instance, is often used in signaling and marking devices that might be employed either in day or nighttime operations. Fig. 3-58[4] illustrates the Mk13 Marine Smoke and Illumination Signal which is hand-launched and produces either an orange smoke for day use or a red flame for night use.

Other devices incorporating combinations of effects are those used for simulation of battlefield effects. The M115 Projectile Ground Burst Simulator (described in par. 3-22.1.1) is an example of a combinational device.

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CHAPTER 4

DESIGN CONSIDERATIONS

4-1 INTRODUCTION

4-1.1 GENERAL

Before pyrotechnic ammunition can be designed, it is first necessary to define all of its requirements. A certain terminal effect is desired that must be delineated in detail, including the correct amount of pyrotechnic composition that will achieve the desired effect. To have the ammunition arrive at the target, the delivery mode must be selected and all of its constraints must be taken into account. Next, methods of packaging the pyrotechnic mix in the delivery weapon must be selected including containers, restraints, and ejection method.

Following the design, all components and finally the complete assembly must be thoroughly tested to assure reliable performance. Particular emphasis must be given to make certain that the pyrotechnic mix will perform as intended over the military temperature range and that the entire pyrotechnic package will survive the stresses imposed by the delivery system.

Designing ammunition for the delivery mode is further complicated by the fact that design constraints of other payloads must be taken into account. As a result, ammunition may be optimum for, say, both high explosive and pyrotechnic fillers but not for each of these separately. Nonetheless, both kinds of ammunition must perform reliably. The consideration of multiple ammunition is termed ballistic matching.

4-1.2 BALLISTIC MATCHING

Projectiles are ballistically matched if the impact or burst distribution have the same mean and equal standard deviations when fired under common conditions[1]. The conditions stated in this definition can never be completely achieved There will always be some tolerance, the magnitude of which depends on the cost and effort required to achieve a near perfect ballistic match.

The ballistic match is expected to improve accuracy of fire and the responsiveness of fire requests. Improved accuracy can reduce significantly the amount of ammunition required to defeat targets. Ballistic matching also reduces the number and complexity of firing tables required as well as data stored in fire direction computers. Matching greatly speeds delivery of ammunition to the target when surprise fire is desirable. Each projectile type not matched ballistically would have to be registered individually, requiring about 20 min and 15 rounds.

To illustrate the design problem, let us examine how other projectiles in a family might influence the design of a high explosive projectile. Fig. 4-1(A)[1] shows what the HE projectile might look like if there were no requirement for ballistic matching. It is a low drag, high capacity projectile that is easy to manufacture. The top half of Fig. 4-1(B) shows how the design is influenced by the requirement that the HE projectile be ballistically matched with a rocket-assisted projectile shown on the lower half. The recess required in the base of the projectile slightly increases the manufacturing costs.

A match with a base-ejection projectile is shown in Fig. 4-1(C). For proper ejection, the payload of the base-ejection projectile must be cylindrical and to maximize effectiveness, the volume must be maximized. Therefore, the optimized base-ejection projectile is longer than the other configurations. To provide aerodynamic stability, the extremities of the projectile must be relatively light. Hence, the base and ogive are made of aluminum, and the steel ogival portion of the steel projectile is thinned out. The effect on the HE projectile is a significant increase in production costs and degraded terminal effectiveness because of less fragmentation metal.

The selection of a final design can be made only by means of a rigorous cost effectiveness analysis confirmed by ballistic firings[2]. Whatever configuration is finally chosen, some penalty must be accepted to achieve the desired results.

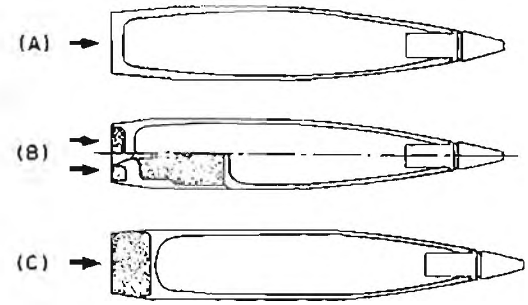


Figure 4-1. Candidate Projectile Configurations for Ballistic Matching

SECTION I DELIVERY MODES AND DESIGN CONSTRAINTS

4-2 DELIVERY MODES

Several modes of delivery are available to the designer of pyrotechnic devices, including tubes and launchers. For each, the interior, exterior, and terminal ballistic conditions must be known. Methods for computing the forces associated with these conditions are given in pars. 4-5, 4-6, and 4-7, respectively.

The designer must examine the effects of the ballistics of the delivery system on the pyrotechnic device so as to insure that the pyrotechnic will not be degraded by the delivery mode, that it will be delivered to the target selected, and that it will be deployed properly when its function is required. The pyrotechnic device may be degraded in one of two ways: (1) the delivery vehicle may not be structurally sound and therefore may collapse or disintegrate, and (2) the pyrotechnic device may be damaged by acceleration or rotational forces imposed by the delivery mode. This paragraph discusses the characteristics of the delivery system that must be taken into account when designing pyrotechnic devices.

4-2.1 TUBES

Pyrotechnic devices may be projected from one of the tube type weapons discussed in the paragraphs that follow. Design procedures are essentially the same for all fired projectiles, only the values of the forces differ in the various weapons. Note that the quantities given are merely typical values that do not take into account model to model differences. While they can serve for first-cut calculations, the exact values of the actual weapon must be obtained for meaningful design.

4-2.1.1 MORTAR

A mortar is a short weapon designed to be fired at high elevation (up to 65 deg). It is muzzle loaded. The bore may be smooth or rifled. When rifled, a cup-shaped disk of soft metal at the base of the projectile is forced outward by the propellant pressure to act as rotating band. Mortar characteristics are summarized in Table 4-1[3]; complete values are tabulated in Ref. 4. Setback force may be as high as 8000 g but is usually about 600 g lasting for about 3 msec. Spin rate for rotated ammunition is up to 2000 rpm.

4-2.1.2 RECOILLESS RIFLE

As the name implies, recoilless rifles do not recoil. The recoilless feature is achieved by

TABLE 4-1

SUMMARY OF MORTAR CHARACTERISTICS

Caliber	Projectile Wt, lb	Pyro Filler Wt, lb	Range, yd	Velocity, fps	Chamber Press, psi
60 mm	4	0.7	2000	450	6000
81 mm	11	4.0	2500	700	6000
4.2 in.	27	8.1	5000	900	6000

having nozzles at the breech end that permit propellant gases to escape rearward to balance the momentum of the forward motion of the projectile. Recoilless rifles are light and mounted on shoulder or tripod. Recoilless rifle characteristics are summarized in Table 4-2[3]; complete values are tabulated in Ref. 4. Setback force is on the order of 10,000 g and spin rate, 9000 rpm.

4-2.1.3 GUN AND HOWITZER

The classification of gun and howitzer no longer conveys the precise meaning it once did. As formerly defined, a gun was a high-velocity weapon firing at low elevation while a howitzer was a shorter and lighter weapon firing at higher elevation with less velocity. The distinction is now less marked. Antiaircraft guns fire at high elevations, and increased ranges demanded of howitzers have necessitated longer, heavier weapons. In general considering equal caliber, the gun will have the higher velocity, longer range, and less mobility.

TABLE 4-2

SUMMARY OF RECOILLESS RIFLE CHARACTERISTICS

Caliber	Projectile Wt, lb	Pyro Filler Wt, lb	Range, yd	Velocity, fps	Chamber Press, psi
57 mm	5	0.5	4900	1200	8,000
75 mm	21	1.0	7000	1000	9,000
90 mm	13	2.0	2300	700	9,000
105 mm	46	4.5	9000	1200	10,000
106 mm	41	7.7	3000	1600	10,000

Characteristics of guns and howitzers are summarized in Table 4-3[3]; complete values are listed in Ref. 4. Values of setback and spin

TABLE 4-3

SUMMARY OF GUN AND HOWITZER CHARACTERISTICS

Caliber	Weapon	Projectile Wt, lb	Pyro Filler Wt, lb	Range, yd	Velocity, fps	Chamber Press, psi
37 mm	Gun	2	0.7	9,000	2600	50,000
40 mm	Gun	2	0.2	9,600	2900	40,000
75 mm	Gun	19	1.5	14,000	2000	36,000
	Howitzer	18	1 0	9,600	1250	29,000
76 mm	Gun	25	1.5	16,000	3200	43,000
90 mm	Gun	42	2.0	20,000	2700	38,000
105 mm	Gun	45	7.0	10,000	2400	30,000
	Howitzer	42	5.0	12,000	1500	25,000
120 mm	Gun	50	7 5	25,000	3500	38,000
152 mm	Gun	49	6.0	9,800	2300	40,000
155 mm	Gun	100	15.0	26,000	2800	40,000
	Howitzer	100	15.0	16,000	1800	30,000
165 mm	Gun	68	20.0	(information is classified)		
175 mm	Gun	147	30.0	35,500	3000	35,000
8 in.	Howitzer	200	36.0	16,000	2000	38,000
240 mm	Howitzer	360	53.0	25,000	2300	36,000
280 mm	Gun	600	102.0	31,500	2500	35,000

TABLE 4-4

SUMMARY OF SMALL ARMS CHARACTERISTICS

Type	Caliber	Weapon	Projectile Weight, gr	Pyro Filler Weight, gr	Velocity, fps	Chamber Press, psi
M27, Tracer	cal .30	Carbine	103	7.0	1800	40,000
M1, Tracer	cal .30	Rifle	152	16	2700	52,000
M196, Tracer	5.56 mm	Rifle	54	4.2	3200	52,000
M62, Tracer	7.62 mm	Rifle	142	8.5	2750	50,000
M26, Tracer	cal .45	Pistol	208	5.5	885	19,000
M17, Tracer	cal .50	Mach. gun	643	55	2860	54,000
M23, Incendiary	cal .50	Mach. gun	512	90	3400	58,000
M220, Tracer	20 mm	Mach. gun	1470	31	3380	51,000
M53, Incendiary	20 mm	Mach. gun	1546	70	3380	55,000

vary considerably with caliber. In general, the smaller calibers have the higher values of these forces. Setback can be as high as 100,000 g and spin rate as high as 120,000 rpm.

4-2.1.4 SMALL ARMS

The small arms family includes a series of rifles, pistols, and machine guns. It includes in addition, by a convention established for convenience, 20 mm ammunition. The main use of small arms for pyrotechnic application is tracer ammunition. Small arms characteristics are summarized in Table 4-4[5]. In general setback and spin are lower than corresponding values for guns and howitzers although the values for 20 mm ammunition are among the highest to be found. Details about pyrotechnics for small arms ammunition are contained in Ref. 6.

4-2.2 LAUNCHERS

Launchers are tubes from which ammunition is propelled—such as rockets, guided missiles, and special pyrotechnic devices. As a class, launched devices are subjected to much lower forces and have much lower velocities than tube-fired projectiles. As in projectiles, design procedures are very similar for all of the devices in the launched class. Note that the quantities given in the paragraphs that follow are merely typical values that do not take into account model to model differences. While they can serve for first-cut calculations, the exact values of the parameters of the actual launcher must be obtained for meaningful design.

4-2.2.1 ROCKET

Rockets are propelled from smooth-bore rocket launchers. A launcher may be a single tube or a number of tubes fastened together in one mount to permit salvo firing. Rockets are fin-stabilized. For some rockets the fins fold to allow firing from the tubes but extend into the air stream for stability after launching. Acceleration and setback forces are generally much less than those of gun-fired ammunition, resulting in lower velocity. Typical values are: setback, 550 g, and spin rate 350 rpm. Even though the rockets are fin-stabilized, they usually spin slightly so that a small spin component must be allowed for. Rocket characteristics are summarized in Table 4-5[7,8].

As an example of rockets applied to pyrotechnics, the 24-tube XM3 Rocket Launcher (2.75 in.) has been modified for smoke use when mounted on a helicopter. The adapter permits laying of a smoke screen up to 1000 m long for periods of 10 min by firing AN-M8 Smoke Grenades[9].

4-2.2.2 OTHER

There is a wide variety of small, launched

TABLE 4-5

SUMMARY OF ROCKET CHARACTERISTICS

Size	Type	Rocket Wt, lb	Pyro Filler Wt, lb	Velocity, fps
66 mm		2	0.7	
2.75 in.	Folding Fin	19	1.5	1800
3.5 in.	—	10	2	500
4.5 in.		42	6	1300
5 in.	Folding Fin	107	15	1800
5 in.	High Vel	138	8	2800

pyrotechnic devices including signals, flares, and markers. Most of these are hand manipulated. Characteristics of the hand-manipulated pyrotechnic devices are summarized in Table 4-6[7,10]. Four launching methods are common:

(1) Firing from rifle launcher, revolver, or a special pistol designed to fire pyrotechnic devices.

(2) Firing from a mortar type launcher that consists of a vertical steel tube fastened to a steel base plate.

(3) Hand thrown (for grenades) and or hand-held combination devices (for single-use launch devices where the case acts as launcher).

(4) Ejection, primarily for aircraft launched pyrotechnics.

The devices may or may not have delays, depending on their intended use. All hand-manipulated devices are light enough to be handled easily; they are subjected to small if any forces. The forces for ejected and

TABLE 4-6

SUMMARY OF HAND-MANIPULATED PYROTECHNIC DEVICE CHARACTERISTICS

Item	Launched from	Display	Total Wt, oz	Diameter, in.	Burning Time, sec
Illum. signal	Pyro. pistol	colored stars	6	1.5	7
Smoke signal	Pyro. pistol	parachute-suspended colored smoke	16	1.5	30
Smoke grenade	Rifle launcher	colored smoke	12	1.9	18
Smoke grenade	Hand thrown	colored smoke	23	2.5	100
Illum. signal	Hand. Outer case is projector	colored stars	21	1.8	5
Signal cartridge	cal .38 revolver	colored streak	0.4	0.4	8
Aircraft flare	Aircraft	colored light 10^6 candle-power	400	5	180
Aircraft smoke signal	Aircraft	colored smoke	50	5	3500
Marine location marker	Aircraft	colored smoke	50	3	3500

launched devices, less than those of mortar ammunition, are on the order of 10 g.

Marine location markers have been adapted successfully for use in such terrain as jungles and flooded rice paddies[11].

An interesting example of a small launched pyrotechnic device is the indoor-outdoor warning system developed for civil defense use[12]. It was designed as an inexpensive outdoor-mounted alert system that can provide instant audible and visual warning, day or night. The device consists of a small (3-lb) fin-stabilized rocket sealed in a 5 in. metal tube that serves as its launcher. The assembly is mounted atop a pole or building. On signal, the rocket is expelled and rises to 2000 ft. The warning components are an explosive charge, a red smoke cloud, and an intensive red flare, the latter being lowered by parachute. The requirements established for this civil defense signal are extremely rigorous. The units must withstand temperatures ranging from −65° to 200°F for a minimum of 10 yr and remain operable without maintenance. No other pyrotechnic device has been required to meet standards this high. Design of the device has been completed. It operates by electronic controls from 115-V house current.

4-2.3 AIRCRAFT LAUNCHED

Aircraft launched pyrotechnic devices have the lowest velocities and are subjected to the lowest forces of any delivery mode. This class includes primarily bombs dropped from aircraft. Bombs do not spin. They are not subjected to any setback when merely released from the aircraft but must sustain a small setback force when ejected from a launching tube. Because submarine-launched, stationary, and manual pyrotechnic devices are subjected to similar small forces, it is convenient to consider them in this class as well.

Design procedures are very similar for all pyrotechnic devices in this delivery mode class. Note that the quantities given in the paragraphs that follow are merely typical values that do not take into account model to model differences. While they serve for first-cut calculations, the exact values of the parameters actual device must be obtained for meaningful design.

The pyrotechnic devices in this delivery class do have some unique problems requiring special design features. Bombs are affected by aircraft travel and aerodynamic heating, and submarine-launched devices must contend with hydrodynamic forces. These topics are covered in the appropriate paragraphs.

The main pyrotechnic device dropped from an aircraft is a bomb. Bombs may be carried inside a bomb bay or suspended from a bomb rack under a wing position. The bombadier releases the bomb by means of an electric signal so that it will drop on the target area. Bombs may be released singly or in clusters depending on the application.

4-2.3.1 BOMB RELEASE

Because the bomb follows the aircraft closely for a short time, a risk is involved to personnel and materiel in the delivery of bombs. Fig. 4-2[13] shows the trajectories of a bomb after release from an aircraft in horizontal flight. The figure labels the following important parameters:

(1) Safe Vertical Drop (SVD). SVD is the vertical distance below release altitude in which the bomb must be safe. Hence it is the distance during which the fuze is not armed. The horizontal component of this distance is called the Minimum Safe Air Travel (MSAT).

(2) Maximum Drop to Arm (MDA). MDA is the vertical distance below release altitude at which the bomb must be ready to function. Hence it is the distance at which the fuze must be armed. This distance is also the minimum altitude at which a bomb may be released and still have an armed fuze upon arrival at the target.

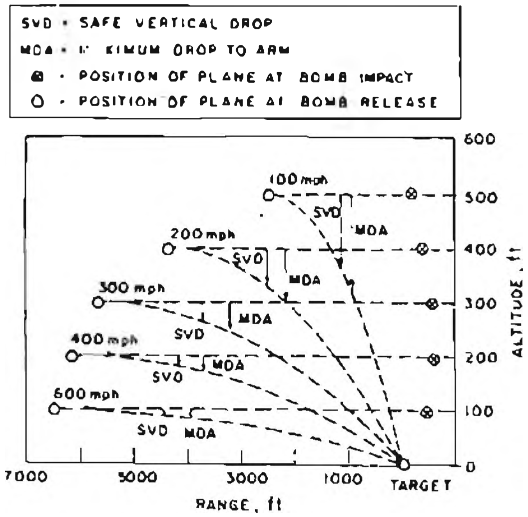


Figure 4-2. Bomb Trajectories

The trajectories shown in Fig. 4-2 present the simple case of horizontal flight in which the drop time is independent of aircraft velocity. In dive bombing, the situation becomes exceedingly complex. Bomb velocity then becomes a function of release altitude, release angle, and aircraft speed. Aircraft pull-out altitude and velocity are also of concern. Not only do these quantities differ for the operational conditions just cited but they are also a function of different aircraft models and loading. Bomb releases curves for the aircraft considered must be consulted to obtain specific values.

Bomb fuzes generally are armed by a propeller that spins in the air stream. A safety pin prevents the propeller from rotating prior to releasing the bomb. The pin is attached to an arming wire that is fastened to the bomb rack so that the pin is pulled free when the bomb is released.

4-2.3.2 AERODYNAMIC HEATING

The determination of temperature profiles within ammunition items affected by aerodynamic heating is difficult, complex, and quite beyond the scope of the present discussion. It is, however, frequently possible for a designer, by means of a few quick calculations using a simplified model of his system, to obtain a gross answer regarding the need for more detailed calculations, the substitution of pyrotechnics, or their insulation. The discussion that follows is intended as an aid in making such approximate calculations.

The flow conditions about an object moving through the atmosphere are most simple if they are considered in terms of a coordinate system moving with the object. In such a system, the undisturbed air is an infinite stream moving at a velocity of magnitude equal to that of the object in a system of fixed coordinates. Quite clearly, the object impedes this flow of air. By Bernoulli's principle (conservation of momentum) any reduction of the velocity of part of the stream must be accompanied by an increase in pressure. Rapid compression of a gas causes its temperature to rise. The highest temperature which may be anticipated in any point in such a system, called the stagnation temperature, is that of air which has been brought to rest with respect to the object. The formula for the calculation of the stagnation temperature is

$$T_s = T_o(1 + 0.2M^2), ^\circ K \qquad (4\text{-}1)$$

where

T_s = stagnation temperature, °K

T_o = temperature of the undisturbed atmosphere, °K

M = Mach number

If the stagnation temperature is below that at which the pyrotechnic charge will suffer any ill effects, there is no problem of aerodynamic heating.

A stagnation temperature high enough to have deleterious effects upon the pyrotechnic is not necessarily reason to take special measures. Only a small fraction of the surface of a moving object is exposed to air at the stagnation temperature. The boundary layer of air in contact with the surface at points where there is an appreciable tangential flow component approaches a recovery temperature that is well below the stagnation temperature. Typical relationships of recovery temperatures to stagnation temperatures are

$$0.8 \leqslant \frac{T_r - T_o}{T_s - T_o} \leqslant 0.9 \tag{4-2}$$

where

T_r = recovery temperature, °K

The value of this ratio varies with velocity, position, and shape of the object.

In most instances, projectiles are subjected only for a short period of time to high velocities during their flight at which the stagnation temperature of the air would have an undesirable effect upon the explosives. The question as to whether the pyrotechnic materials will reach undesirably high temperature during such an interval can be answered only by considering in detail the heat flow into and within each component.

As the stagnation temperatures rise relative to those at which pyrotechnics are stable and as designs become more intricate, the means of resolving doubts regarding whether the charges will survive aerodynamic heating become more laborious and less positive. The introduction of a heat barrier may be the only way in which these doubts may be removed.

4-2.3.3 CHARACTERISTICS OF PYROTECHNIC DEVICES

The characteristics of pyrotechnic bombs are summarized in Table 4-7[14]. These bombs neither spin nor are subjected to setback forces. Minimum release altitude for smoke bombs is 250 ft.

4-2.4 OTHER DELIVERY MODES

4-2.4.1 EJECTOR

Rather than merely being released, some bombs are pushed out of a tube by an ejector cartridge. Ejector firing simulates a rocket launcher. Both single shot firing and salvo firing are possible. Setback forces are less than those in a rocket because ejection speed is only about 5-10 fps. Ejected pyrotechnic devices must have a delay (minimum of 5 sec) to clear the aircraft before firing.

4-2.4.2 SUBMARINE LAUNCHED

Pyrotechnic devices are launched from submarines for signaling and marking purposes. The devices are fired from an ejector tube at 250 psi above sea pressure. All of these devices have a safety pin that prevents a trip lever from opening. The pin is pulled before inserting the device into the ejector tube and the lever operates after the device leaves the tube. Water pressure is used to arm percussion-initiated devices or to activate the

TABLE 4-7

SUMMARY OF PYROTECHNIC BOMB CHARACTERISTICS

Size, lb	Type	Pyro. Filler Wt, lb	Color	Burning Time	Candlepower
250	Identification	66	Red	3 min	25,000
			Yellow	3 min	12,000
			Green	3 min	5,000
175	Photoflash	82	White	0.04 sec	1.3×10^9
100	Smoke	72	Red		—
100	Pyrotechnic	42	—	—	—

TABLE 4-8.

SUMMARY OF SUBMARINE-LAUNCHED PYROTECHNIC DEVICE CHARACTERISTICS

Item	Display	Total Wt, lb	Burning Time	Delay, sec
Marine signal	Colored smoke on surface	4	15 sec	100
Marine signal	Parachute-suspended stars	4	25 sec	50
Location Marker	Colored smoke on surface	3	300 sec	150
Location marker	Fluorescent slick on surface	8	Slick persists 90 min	0

battery of electrically-intiated devices. The mechanical devices are operated by spring pressure with a spring force so set that the spring pressure overcomes the hydrostatic pressure at a depth of about 10 ft. Characteristics of submarine launched devices are summarized in Table 4-8[10].

4-2.4.3 MANUAL

There is a large variety of manual pyrotechnic devices in the main categories of illumination, signaling, and battle effects simulation. Their characteristics are summarized in Table 4-9[7].

Each device has, for arming safety, a manual pull pin. The head-held devices are small so as to be conveniently carried and held. Larger devices are emplaced either on the ground or aboard an aircraft and fastened to a simple rig designed to hold the device in the right attitude for functioning. The family of battle effect simulators provides the sound, light, or smoke of ammunition. The devices are similar to the ammunition they simulate except they are often simpler and contain a minimum charge. They are initiated remotely.

4-3 DESIGN CONSTRAINTS

Pyrotechnic ammunition is one component of a military system. It therefore must conform to all of the constraints imposed by the system and by the other components of the system. Ammunition must function reliably and safely in the military environment, must fit the geometry and weight imposed by the other components, and must be compatible with them.

4-3.1 PERFORMANCE REQUIREMENTS

4-3.1.1 TARGET AND TERMINAL BALLISTIC NEEDS

Pyrotechnic ammunition accomplishes its function when it performs as intended at the target. There are essentially two types of target: (1) remote, and (2) at hand. To reach remote targets, the ammunition must be fired, launched, or dropped from aircraft—often over appreciable distances—while being subjected to various forces, environments, and conditions. Requirements for nearby targets are not as severe. The pyrotechnic devices are hand held or attached to stationary mounts. The devices must still survive the military environment.

Both maximum velocities and ranges continue to increase with improvements in propellants and other design features. The values for tube-delivered ammunition are listed in Tables 4-1 to 4-5. Four aspects of ammunition motion must be considered by the designer of pyrotechnic charges, namely:

(1) Range and accuracy of fired and launched ammunition depend upon its aerodynamic characteristics. The external contours dictated by aerodynamic considerations are a limitation upon the size and shape of the pyrotechnic system. See par. 4-6 for external ballistic considerations and par. 4-3.2 on configuration limitations.

(2) It is sometimes necessary to modify

TABLE 4-9

SUMMARY OF MANUAL PYROTECHNIC DEVICE CHARACTERISTICS

Item	Total Wt, lb	Illuminant Wt, lb	Delay Time, sec	Burning Time, sec	Candle-power
Photoflash cartridge	4	2	4	0.04	4×10^6
Aircraft guide flare	12	4	7	60	700,000
Aircraft flare	65	31	5-90	180	3×10^6
Towed aircraft flare	21	15	0	360	80,000
GM tracking flare	2	1	–	90	70,000
Surface trip flare	5	0.7	3	70	100,000
Illum. aircraft signal	0.4	0.2	5	13	50,000
Smoke and illum. aircraft signal	15	4	90	3600	650
Marine illum. signal	3	0.4	50	35	15,000
Ground illum. signal	1	0.4	5	10	18,000
Ground smoke signal	1	0.2	5	8	5,000
Burst simulator	0.3	0.1	0	3	–

the design of pyrotechnic charges in order to distribute the weight properly for flight stability (see par. 4-3.2).

(3) Velocities and flight times of many modern bombs and missiles are such that aerodynamic heating has introduced additional design problems (see par. 4-2.3.1).

(4) Acceleration forces during firing or launching, flight, and impact are the main sources of the structural loading of the ammunition (see par. 4-3.1.3).

4-3.1.2 ENVIRONMENTAL ASPECTS

Pyrotechnic devices are subjected to rigorous environments. For a discussion of the environmental forces caused by the ballistic system, see par. 4-5. The general surroundings are termed the military environment. The military environment influences the design choices, type of materials, design of component parts, and methods of packaging. The main environmental characteristics are:

(1) Operating Temperature. The pyrotechnic device must withstand temperatures ranging from an air temperature of 125°F (ground temperature of 145°F) in hot-day climates to an air temperature of −50°F (ground temperature of −65°F) in cold climates. Temperatures can drop to −80°F in bomb bays of high-flying aircraft, and aero-

dynamic heating can raise the temperature above 145°F for missiles launched from high speed aircraft[15].

(2) Storage Temperature. −70° to 160°F, operable after removal from storage

(3) Relative Humidity. 0 to 100%

(4) Water Immersion. For certain applications the pyrotechnic device may be required to be waterproof. In this instance, it must be operable after immersion in water at 70° ± 10°F under a pressure of 15 ± 5 psi for 1 hr.

(5) Rough Treatment. Operable after withstanding the rigors of transportation and rough handling

(6) Fungus. The pyrotechnic device must not support fungus growth.

(7) Surveillance. Operable after 10-20 yr storage.

4-3.1.3 ACCELERATION

Ammunition, when fired, launched, or dropped, is accelerated. In some instances, the magnitudes of the accelerations are great. To the designer of pyrotechnic charges, these accelerations produce structural loading that applies inherently to all masses including the pyrotechnic composition itself. Accelerations associated with changes of momentum along the line of flight are always variable, usually impulsive, while centrifugal accelerations of spin-stabilized projectiles remain nearly steady during the time of flight.

When considering the effects of acceleration on ammunition, its variability must also be considered. On the one hand, it is often possible to reduce peaks by use of shock absorber principles. On the other hand, the rapid changes can result in impact forces of much greater magnitude than those due to the direct effects of gross acceleration. When considering these effects, the designer should obtain the best estimates available of the time-acceleration function to which his device will be subjected. Table 4-10[16] lists the magnitudes of some typical accelerations that ammunition is subjected to. The main types of acceleration in ammunitions are:

TABLE 4-10

VALUES OF ACCELERATION IN AMMUNITION

Ammunition and Condition of Exposure	Typical Peak Acceleration, g	Direction
Projectile setback when fired in gun	50,000	Axial
Projectile piercing armor	−150,000	Axial or Oblique
Rocket or missile, gun launch	100	Axial
Rocket or missile, gun launched	30,000	Axial
Missile steering	40	Transverse
Missile flight vibration	10	Random
Mine water entry	−2,500	Axial

(1) *Setback*

Setback is the relative rearward movement of component parts in ammunition undergoing forward acceleration during firing or launching. Setback is conventionally assigned a positive value. Setback can be quite large in tube-fired ammunition but is less so in launched ammunition. Values for specific delivery modes are given in par. 4-2.

(2) *Setforward*

Setforward is negative setback. It occurs when ammunition is decelerated in its forward motion. The largest value of setforward is that associated with impact of hard targets such as armor plate. However, pyrotechnic ammunition is not usually called upon to defeat armor. Setforward also occurs when projectiles are rammed into an automatic weapon. While weapon designers would like to increase ram velocities, they are presently limited to 1000 g, the maximum that present fuzes can withstand.

(3) *Sideways Acceleration*

Sideways acceleration occurs as a result of changes in velocity at right angles to the line of travel. Sideways acceleration is caused in modem automatic weapons due to seating. In practice, perfect alignment of a projectile and the gun axis prior to firing is not consistently achieved. Therefore, upon firing, a sideways force results as the projectile aligns itself with the gun tube. For example, the 175 mm field gun and the 120 mm tank gun have such high lateral forces that fuze ogives have broken off. These forces have not been measured or calculated to date. In air-gun and drop tests, damage was simulated by accelerations larger than 10.000 g.

Because the accelerations can be large, special care must be taken by the designer to make certain that the ammunition will not fail structurally, an event that would result in failure to perform at the target as intended. Structural failures can result in the failure of metal parts, in unstable flight, or both. Metal part security and flight stability tests are commonly performed to test the adequacy of the design. For example, such a test was performed with the 155 mm Projectile, Illuminating, XM459[17]. The projectile with fuze is 34 in. long and weighs 96 lb. In a previous test, the load bearing area of the body base joint was loaded in a 450-ton hydraulic press to simulate the setback load resulting from the 16,500-g firing acceleration. The projectile passed this test. Firing tests were then conducted at the excess pressure of 51,000 psi both at ambient and −65°F temperatures. The projectiles passed the metal parts security test but a flight instability was noted. A bulge was produced at the intersection of projectile body and ogive that was believed to be caused by the shifting of the dummy illuminating charge which was loose.

4-3.1.4 TIMING AND SEQUENCING

The designer of pyrotechnic ammunition must consider all aspects that involve placing the device in the desired location with respect to its target, safeguarding against its operation until it gets there, and initiating the action at the desired place and time. The sequencing of these various actions is critical. In general, the first action is arming; in multistage devices, stage separation is next; finally the device must function.

(1) *Arming*

All ammunition must be safe during the entire stockpile to target sequence. It must also be capable of being armed in order to function as intended. Safing and arming devices must have two independent safing features, whenever possible, either of which is capable of preventing an unintended functioning before the ammunition is projected or emplaced[18]. The philosophy is based on the low probability that two features will fail simultaneously. Details of fuze arming features are discussed in Ref. 13. In all ammunition that is fired, launched, or dropped, an arming delay is provided so that the ammunition will safely clear the delivery system. Hand-held or emplaced devices are always provided with a pull pin, and delay is provided whenever feasible.

(2) *Staging*

Staging refers to an intermediate action required before functioning. The term originated with the stage separation of missiles but is also used for such actions as the operation of dissemination containers or the opening of parachutes. The time delay required is a function of the specific application and cannot be generalized.

(3) *Functioning*

Functioning delays vary from microseconds to minutes depending on the particular application. Mechanical, electronic, pyrotechnic, flueric, or electrochemical timers are used to provide time delays as discussed in Ref. 19. For some pyrotechnic applications, the functioning must be sequenced, such as when laying a smoke screen. Here successive smoke charges are set off at regular intervals that depend on the type of screen desired and the speed of the applying vehicle.

4-3.2 PAYLOAD CONFIGURATION

The pyrotechnic payload must fit into the ammunition for which it was designed, neither impairing the performance of the ammunition nor the operation of the payload. Hence, the payload is limited in weight, size, and geometry. Specific filler weights and sizes for different ammunitions are listed for the various delivery modes in Tables 4-1 through 4-9.

4-3.2.1 WEIGHT

The weight available for the pyrotechnic filler depends on the ammunition into which it is to be assembled and on the delivery mode. In general, smaller munitions have proportionally less space than larger ones because the metal parts take up a certain minimum space. Thus, 70% of the volume of a 100-lb bomb is available for a smoke filler but only 15% of the volume of an M16 Rifle Cartridge for the tracer bullet is available. Weights for hand-held devices are limited to about 10 lb, beyond which they are difficult to manipulate.

4-3.2.2 SIZE

Like weight, size is a function of the specific ammunition and delivery mode. All tube-fired and launched ammunition have a definite outside diameter that cannot be exceeded for the ammunition to fit. The diameter available for the pyrotechnic composition is further reduced by the wall thickness of the metal housing. Since most ammunition is longer than its diameter, more space is generally available in the axial direction. However, other needed components, such as a parachute pack, take up some of this space; hence no generalized statement can be made regarding the available space.

4-3.2.3 GEOMETRY

The rule for hand-held and stationary devices is that any convenient geometry will serve. The pyrotechnic composition can be made to fit or the container can be modified when required; however in propelled ammunition, geometry is absolutely fixed. Not only must dimensions be adhered to, but the center of gravity must also remain unaltered. This limitation is necessary to permit the ballistic matching (see par. 4-1.2). Hence, the design constraints of the particular ammunition are imposed on the design.

4-3.3 MATERIAL CHOICES

Many materials go into the manufacture of pyrotechnic ammunition. Each must be selected to optimize the entire military system under consideration. For example, it is not optimum to have an "ideal" flare mix if it is incompatible with the housing material or if it is obscured by smoke under the planned conditions of use. Hence, materials must be selected carefully.

Specific pyrotechnic material are covered in the same paragraphs as their design. Topics of general concern–compatibility and sealants–are treated in the paragraphs that follow.

4-3.3.1 COMPATIBILITY

Compatibility implies that two materials, such as a pyrotechnic charge and its container, do not react chemically when in contact with or in proximity to each other, particularly over long periods of storage. Incompatibilities may produce either more sensitive or less sensitive compounds, or affect the parts they touch. If the metal container is incompatible with the pyrotechnic charge, coating or plating it with a compatible material will often resolve the difficulty. The compatibility of two materials may be determined by storing them together for a long time under both ordinary and extreme conditions of temperature and humidity. Table 4-11[12] lists compatibility relations among various metals and common explosive materials. The blank spaces indicate no conclusive results to date.

Of the reactions of explosives with metals, that of lead azide with copper deserves special comment. Although this reaction is relatively slow, even in the presence of moisture, some

TABLE 4-11

COMPATIBILITY OF COMMON EXPLOSIVES AND METALS

	Lead Azide	Lead Styphnate	PETN	RDX	Tetryl
Magnesium	N		B N S		
Aluminum	A N	A N	A N VS	A N VS	A N
Zinc	C N			A	B VS
Iron	N			A	B S
Steel	C N		B N VS	A VS S	C H
Tin	A N			A	A N
Cadmium	C				A
Copper	D N	A	B N VS	A S S	A N
Nickel	C			A	A N
Lead	N			A	A N
Cadmium plated steel			B N S	VS VS	A N
Copper plated steel	N		B N VS	B VS VS	A VS
Nickel plated steel	N		B N VS	A N S	A N
Zinc plated steel	N		B N VS	A N S	A N
Tin plated steel	N			A	B VS
Magnesium aluminum	VS		B N S		
Monel Metal	C N				
Brass	D N		B N S	A S S	B VS
Bronze	N			A	A VS
18-8 stainless steel	A N	A	A N N	A N N	A N
Titanium	N			N	N
Silver	N			N	N

CODE

A no reaction
B slight reaction
C reacts readily
D reacts to form sensitive materials

H heavy corrosion of metals
VS very slight corrosion of metals
S slight corrosion of metals
N no corrosion

forms of copper azide are so sensitive as to create a serious hazard even in minute quantities, particularly when in contact with lead azide. For this reason, it is desirable to use only containers of aluminum and stainless steel.

The compatibility of explosives with a large number of plastics has also been studied[20]. It was shown that the following types of plastic have negligible effect on explosives and are themselves unaffected: acrylates, cellulosics, ethylenes, fluorocarbons, nylon, properly cured unmodified phenolics, and silicones.

An important class of explosive materials is that of mixtures of fuels and oxidants. Many of the oxidants used are nitrates, chlorates, and perchlorates. Water solutions containing these ions are highly corrosive to metals. The alkaline metal salts, with the help of a little moisture, will pit aluminum quickly. The trend away from potassium chlorate in priming mixes is part of the effort to reduce corrosion. Where explosives are used that contain metallic nitrates, chlorates, or perchlorates in contact with metals, particular attention should be given the exclusion of moisture.

In delay compositions, these corrosion problems have resulted in widespread use of chromates that, in addition to being insoluble, tend to inhibit corrosion.

Mixtures containing chlorates and perchlorates in combination with organic materials tend to be quite sensitive. There has been a general reluctance to use such mixtures except as primary explosives. An exception has been ammonium perchlorate.

4-3.3.2 SEALANTS

A sealant is a liquid or paste that is applied to a joint to prevent or reduce the penetration of gases, liquids, dust, or all of these. Two types of joint on which sealants are often used in ammunition construction are the butt or crimped joint, and the threaded joint. A sealant used on threads must not act as a cement for the threaded joint, but must be easily broken to permit inspection or repair of enclosed components. A sealant for a butt or crimped joint has greater latitude because this type of joint is usually a permanent one and cementing is desired.

The term sealing materials is also one that refers to the sheet stock and molded shapes of resilient character that form the gasket type seals. The materials most often used for this purpose include natural rubber, synthetic rubber, and plastics. Whenever possible, the designer should use this kind of mechanical seal rather than liquid or paste because production quality more readily is assured.

The following factors must be carefully weighed when selecting a sealant or sealing material:

(1) Physical properties. The sealant or sealing material physical properties- such as tensile strength, compression set, elongation, and hardness—must be considered.

(2) Chemical compatibility. The seal must be chemically compatible with the metals, fuels, lubricants, explosives, acids, or other materials to which it may be exposed (see also item 4 following).

(3) Storage characteristics. The seal must withstand exposure to a wide range of environments over a long period of time in storage.

(4) Outgassing. Any products of outgassing, especially during the curing process of the sealing material, must not cause particle or organic contamination of electrical contacts nor fouling or corrosion of other parts.

(5) Temperature. The seal must not

degredate at the extremes of the military temperature range.

No sealant or sealing material has all the qualities required. The problem, then, is to choose the best combination of characteristics. Choice is usually based primarily on the overall physical and chemical properties of the materials and secondarily on its aging properties. Other things to be considered before a final decision is made are availability of materials, cost, ease of application, toxicity, useful pot life, and service life[21].

The materials commonly used as sealants include various rubber, neoprene, polyesters, alkyds, phenolics, vinyls, and flexible epoxy resins[22]. No sealant has been found that will produce a joint as tight as a well-soldered joint.

The designer should investigate the present effort made to apply one component sealers in order to avoid pot life problems.

SECTION II IGNITION AND BALLISTIC CONSIDERATIONS

4-4 IGNITION

The overall process of ignition involves heating a portion of a combustible material—such as a propellant or a pyrotechnic mixture—to its ignition temperature, i.e., the minimum temperature required for a self-sustaining reaction. An ignition stimulus that can be reduced to effect heat absorption starts a sequence of preignition reactions involving crystalline reactions, phase changes, or thermal decomposition of one or more of the ingredients. In many instances, a gaseous phase is formed and combustion starts in the gaseous phase. For more detailed information on ignition of pyrotechnic mixtures see Ref. 23.

4-4.1 IGNITION TRAIN

The ignition train consists of an assembly of explosive elements arranged in order of decreasing sensitivity. The function of the train is to accomplish the controlled augmentation of a small impulse into one of suitable energy to reliably initiate the main pyrotechnic composition. Such a train can be considered as divided into three parts. The first part contains a sensitive initiating composition that can be ignited by a relatively small, mechanical, electrical, or chemical stimulus. This initiating composition, on burning, produces sufficient heat to ignite an intermediate pyrotechnic composition in the second part of the ignition train. Its output will then initiate the main charge. Often a delay train is included in the second part of the explosive train. See par. 3-21 for details on delays.

Certain chemical reactions have been used for ignition trains. An example is white phosphorus exposed in air. Others include diethyl zinc or triethyl aluminum in a glass vial, alkali metals reacting with water, and sodium. The mixture of iron powder, potassium permanganate, and sulphuric acid results in a vigorous chemical reaction. See Ref. 23 for details on heat effects from chemical reactions.

4-4.2 METHODS OF INITIATION

Pyrotechnic ammunition is initiated with (1) stab, (2) percussion, or (3) electric primers. Stab primers are initiated by a pointed firing pin that punctures the cup. In contrast, the percussion primer is fired without puncturing its container. A blunt firing pin crushes the priming mix against an anvil. Electric initiators differ from stab and percussion primers in that they contain the initiation mechanism as an integral part. A plastic plug holding the initiation mechanism makes up one end of the cylindrical housing. As a group, electric initiators are more 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. For detailed design information of initiators and for a discussion on methods of initiation see Ref. 16. Priming compositions are tabulated in Appendix B.

4-5 INTERIOR BALLISTICS

4-5.1 GENERAL

Projectiles containing pyrotechnics, like all gun-fired ammunition, are subjected to interior ballistic forces while traveling within the weapon barrel. A brief review of classical interior ballistics will make clear the forces resulting from firing a gun[24].

A series of pressure waves is produced within the gun chamber by the burning propellant. The pressure acts on the rear of the projectile to force it out of the weapon. A typical pressure-travel curve is shown in Fig. 4-3[24]. The important facts to note from this figure are:

(1) Curve A cannot be tolerated because the allowable barrel stress would be exceeded.

(2) The area under any P-u curve is the work done on the projectile per unit cross-sectional area.

(3) To obtain a higher muzzle velocity, a greater area is required under this curve. Pressure C gives a higher velocity than pressure B.

(4) Force due to the pressure on the round at every instant is given by $F = PA$, where P is the instantaneous pressure, and A is the bore area.

Thus the internal force (from setback, etc.) is governed by the shape of the pressure-travel curve, that in turn can be altered by a different choice of propellant and gun barrel length. Since barrel length has a practical limit, the propellant properties are generally manipulated to obtain a desired muzzle velocity. The propellant variables basic

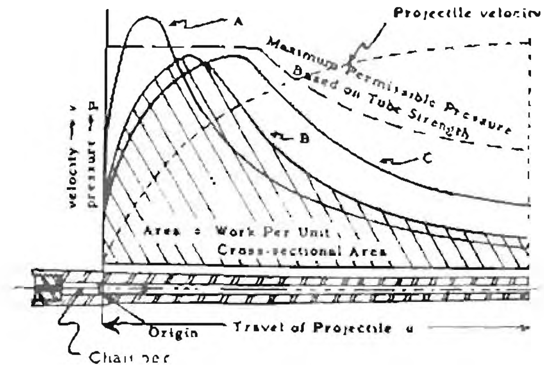


Figure 4-3. Pressure-travel (solid lines) and Velocity-travel (dotted lines) Curves

to the control of interior ballistics include:

(1) Variation in propellant chemical composition

(2) Variation in reaction rates

(3) Variation in ignition characteristics

(4) Variation in shape of grains (grain geometry)

(5) Variation in charge weight (density of loading)

(6) Environmental factors

(7) Physical density and mechanical properties of grains

(8) Effects of retardant coating composition and thickness.

The internal parts of a projectile (payload) must be able to withstand without failure any effects of setback and spin forces that may occur within the chamber.

Two methods commonly used for interior ballistic calculations of small arms are given, with examples, in Appendix C. These can serve in estimating the ballistic performance required of small arm pyrotechnic ammunition.

4-5.2 SETBACK FORCES

4-5.2.1 SETBACK IN THE WEAPON

Setback results from the relative motion between parts on or in the projectile body as the projectile accelerates. When the projectile accelerates, unequal forces are applied to its components. The projectile is normally thought of as being a solid, uniform body, but this is not the case. Most ammunition comprises a number of internal components that are accelerated only because the projectile in which they are contained is accelerated.

In most weapons there is an axial component of acceleration and in some instances a spin component. Typical accelerations are shown as a function of projectile travel within the bore (see Fig. 4-4). The maximum axial acceleration is experienced as the projectile moves down the bore, usually within a few milliseconds after propellant ignition. The axial acceleration force is

$$F_a = M_p a = M_p \left(\frac{PA}{M}\right), \text{ lb} \qquad (4\text{-}3)$$

where

F_a = axial force, lb

a = axial acceleration, ft sec^{-2}

P = pressure in the gun, psi

A = area over which the pressure acts, in.^{2}

M_p = mass of the part, slug

M = projectile mass, slug

Note in Eq. 4-3 that F_a is directly related to a and varies with the acceleration time curve shown in Fig. 4-4. F_a is a force vector directed opposite to the direction of motion applied at the mass center of the part being considered.

Axial acceleration may range from hundreds of g's for some projectiles to tens of thousands of g's for high-performance weapons (see par. 4-3.1.3). It is important to define acceleration levels that must be met by a pyrotechnic device and then to assure, by design or experiment, that the components used and their supporting structures remain intact.

Structural consideration of the effects of high-acceleration loading requires the application of conventional mechanics and strength of material analysis. The product of the mass of each pyrotechnic component and the number of g's experienced results in the force to which the component will be subjected. Mechanical failure of components of pyrotechnic ammunition may result in premature firing or in disruption of the pyrotechnic components.

Much has been learned in fuze developments concerning the treatment of high acceleration; some of this experience is pertinent to pyrotechnic applications that require delivery by high acceleration means[13].

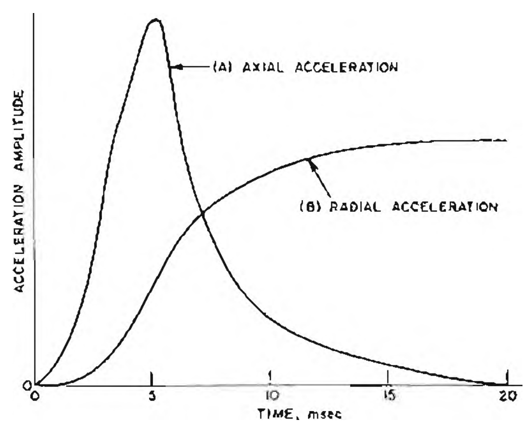


Figure 4-4. Typical Acceleration Functions vs Time (Artillery Projectile)

Analytical methods of predicting performance have limitations. Among these are incomplete information on the materials being used, particularly their ultimate strength under the conditions of high setback. Hence, designs are completed to the point where prototypes are built and tested, often in air guns or centrifuges to recover the components, to assess their performance under accelerations approaching those of setback. Similar procedures may be used for pyrotechnic payloads.

Quite often it is found that components survive setback more readily in one orientation than they do in another. The orientation in the payload should be adjusted to provide the proper resistance to setback if orientation is found to be critical.

4-5.2.2 EFFECTS OF ACCELERATION ON DELAY ELEMENTS

Delay compositions are consolidated with pressures between 30,000 and 40,000 psi in order to withstand the forces to which they are subjected in use[23].

Delay elements are often subjected to very high accelerations while the delay composition is burning. If the structure of the material at or behind the reaction front is too weak, the acceleration may cause the hot reacting materials to lose contact with the unreacted composition or a subsequent charge and extinguish the reaction. Quantitative data regarding the resistance of delay compositions to this type of failure are not available. However, "slag retention", i.e., the fraction of the weight of the original charge remaining in an open-ended delay column after functioning, has been used as a possible indication of the resistance of a delay element to acceleration forces. The higher the slag retention the greater the setback resistance. Slag retention for some delay compositions is: manganese, 95%; red lead, 90-95%; tungsten, 95%; nickel-zirconium, 80-90%; boron, 59-90%.

Introduction of a binder into the mixtures will improve performance under high acceleration conditions; however, binders tend to produce large amounts of gaseous products so that the system can no longer be considered gasless. Mechanical support of the delay column at both ends tends to reduce variation in burning times by minimizing slag flow.

4-5.3 SPIN FORCES

Some gun bores have helical grooves that act on the rotating band of a projectile and force the projectile to spin, producing the acceleration shown in Fig. 4-4. Spin is important in maintaining projectile stability. Too little spin will cause wobbling and a large deviation from the intended trajectory, while too much spin will tend to keep the projectile nose up during the flight. The spin velocity of the projectile as it leaves the muzzle is related directly to the twist of rifling (measured in calibers per turn) and the speed with which the projectile leaves the gun. Spin velocity reaches a maximum at the muzzle where the spin velocity ω is expressed as

$$\omega = \frac{24\pi\nu}{nd}, \text{ rad sec}^{-1} \tag{4-4}$$

$$\omega = \frac{12\nu}{nd}, \text{ rev sec}^{-1} \tag{4-5}$$

where

n = twist, cal rev^{-1}

ν = instantaneous projectile velocity, ft sec^{-1}

d = bore diameter, in. (the caliber)

Twist varies from weapon to weapon and is specified as "1-50" which is read as "one revolution of the projectile for 50 calibers (diameters) of travel along the gun barrel" – which is $1/n$ when applied to Eqs. 4-4 and 4-5. Twist can also be expressed directly as the number of calibers per turn (cal/turn).

While twist is commonly uniform throughout the travel of the projectile, a few guns use a variable or gain twist. Here the rifling is straight in the breech section of the bore with the twist increasing progressively to its highest value at the muzzle. Uniform and variable twist can be represented graphically as shown in Fig. 4-5. This type of presentation allows visualization of the relationships among the travel along the bore, the circumference of the bore, and the angle of twist. Examples of uniform twist and increasing twist are shown in Fig. 4-5(A) and 4-5(B), respectively. The angle of twist ϕ is the angle between a tangent to the rifling grooves and a line parallel to the center of the bore. For weapons with uniform twist, this angle is a constant. For variable twist the angle is constantly changing. The relation between the angle and twist is

$$\tan\phi = \frac{dy}{dx} = \frac{\pi}{n} \qquad (4\text{-}6)$$

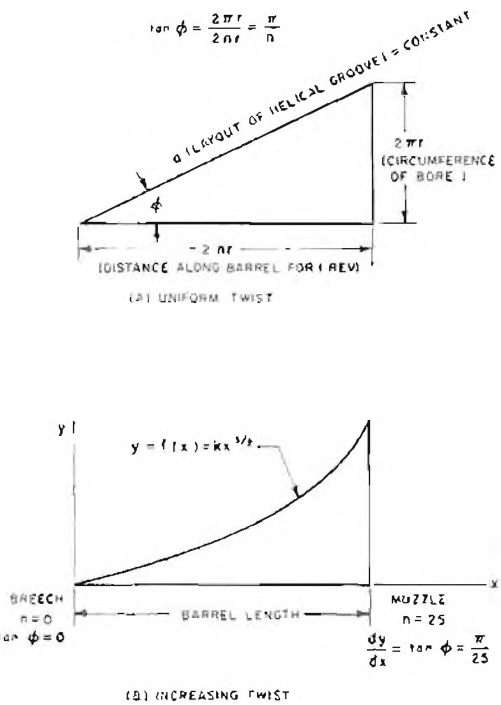


Figure 4-5. Uniform and Increasing Rifling Twist Rates

When using Eqs. 4-4 and 4-5 for determining spin rates, the instantaneous values of velocity v and π/n always must be used.

With uniform twist, engraving of the rotating band occurs only until such time that the entire rotating band enters the rifling and the grooves of the rifling have been formed in the band. With increasing twist, however, portions of the band are constantly being engraved.

Spin rates of projectiles vary from 0 to 200,000 rev sec^{-1} with no definite relation between caliber and twist. Data for weapons from 20 mm to 250 mm are presented in Fig. 4-6[13]. This nomogram permits determination of spin velocity given the muzzle velocity, twist, and caliber. While the nomograph is intended for existing weapons, there is no reason why it cannot be used for determining spin velocity for other weapons if the same characteristics are known.

Spin introduces a radial force vector in addition to the force generated as a result of setback (par. 4-5.2). The centrifugal force vector varies directly with the radial distance from the spin axis. This force F_r is determined from

$$F_r = M_p a_r = M_p \omega^2 r, \text{ lb} \qquad (4\text{-}7)$$

where

F_r = centrifugal force, lb

M_p = mass of the part, slug

a_r = radial acceleration, ft sec^{-2}

ω = angular velocity, rad sec^{-2}

r = radial distance from the spin axis to the CG of the part, ft

4-5.4 COMBINED SETBACK AND SPIN

It can be easily seen that both axial forces (from setback) and radial forces (from spin) will occur at the same time in the interior of

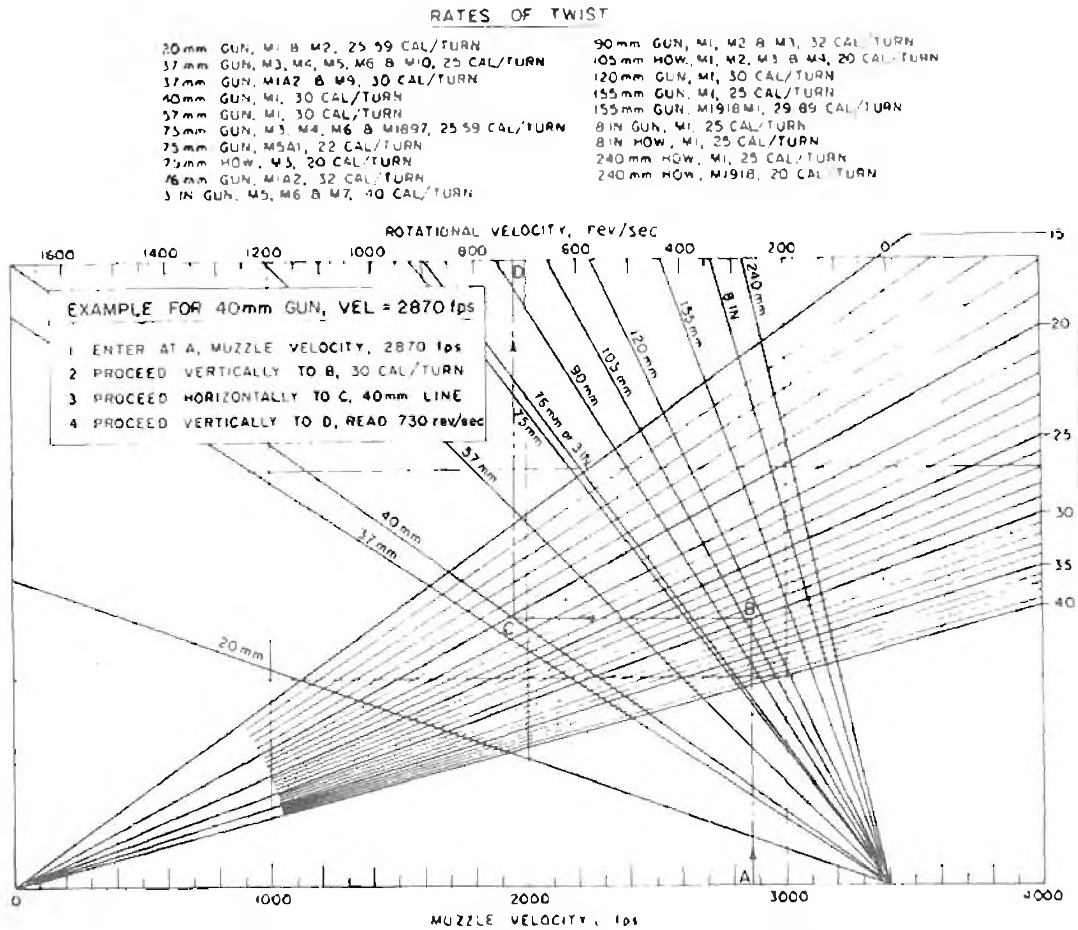


Figure 4-6. Nomogram for Determining Spin Velocity of a Projectile

the barrel. Each of these forces contributes to the overall stress in any one part of the pyrotechnic payload.

The magnitude of the total force F_t due to combined setback force F_a and spin force F_r is

$$F_t = \sqrt{F_a^2 + F_r^2}\ , \text{lb} \qquad (4\text{-}8)$$

Fig. 4-7 shows the direction of the force acting as a result of these two components. In addition the resultant force vector and the direction of this vector are shown.

At some location, the magnitude of the total force F_t will be a maximum. This location will most probably be near the point of maximum setback acceleration where F_a is dominant. Maximum particle stress occurs when the total force F_t is a maximum. However, in order to be thorough, maximum stresses in tension, compression, and shear should be computed and these compared with the safe allowable stresses for the materials.

4-5.5 EXAMPLE OF DESIGN PROCEDURES

The following design procedure is applicable for an illuminating round to be fired from a howitzer. The designer will make

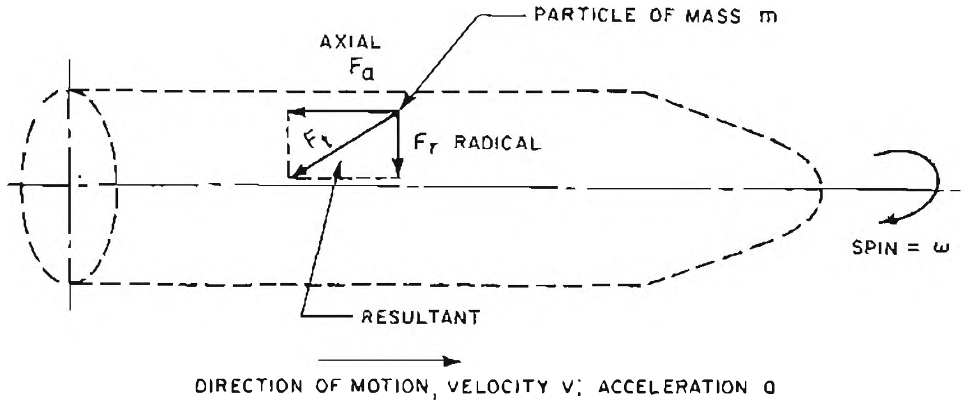


Figure 4-7. Internal Restoring Forces on Particle Within a Projectile

preliminary calculations to determine the soundness of his design approach and refine them as the design progresses. The dimensions used were not taken from a specific projectile design, but are of the order of magnitude of those found in a medium caliber (105 mm) base ejection projectile (see Fig. 3-6 for projectile configuration).

Bearing stress of the projectile body on the base plate is determined in order to assure that the projectile (carrier) is not subject to collapse in compression by the driving force of the propellant gas pressure in the bore during firing. A subsequent estimate of the combined stress on the rear section of the projectile determines the effect of the bore pressure and setback forces. These forces tend to cause failure of the projectile body by separation during firing. An additional initial calculation should be made to determine the force which must be generated inside the projectile by the expelling charge in order to properly eject the payload upon fuze functioning.

4-5.5.1 BEARING STRESS BETWEEN BASE PLUG AND PROJECTILE BODY

The weight of the projectile body is determined by approximation from a detail drawing. For this example the body is of steel having a basic outside diameter of 3.9 in. and a basic inside diameter of 3.6 in. with a cavity 12 in. long to accommodate the candle and parachute.

Weight estimates (lb) for projectile components are:

Fuze	2.2
Cylindrical shell	9.0
Other, including base plug, illuminant, expellant parachute, and holder	23.8
Total projectile	35.0

In determining the bearing stress, weight of candle, parachute, and expelling charge are ignored because they bear on a much larger surface of the base plate which is not considered a critical area. Because of the machined mating surface at the base plate-body junction, the ID at this location is considered to be 3.64 in. A bore pressure of 11,200 psi is used in calculating the stress. The groove diameter of the barrel is 4.19 in. A more exact estimate of bore pressure may be obtained by the Le Duc equations[24]. These empirical equations express projectile velocity and propellant gas pressure as functions of time or distance in the bore.

The acceleration a applied to the projectile when fired is

$$a = \frac{\pi d_g^2 P_m}{4 W}, \text{g} \tag{4-9}$$

where

a = acceleration, g

d_g = groove diameter, in.

P_m = peak pressure, psi

W = weight of projectile, lb

$$a = \frac{3.14 \times (4.19)^2 \times 11{,}200}{4 \times 35} = 4410 \text{ g}$$

The force F_a necessary to accelerate all mass forward of the base plug is

$$F_a = a W_b, \text{lb} \tag{4-10}$$

where

F_a = accelerating force, lb

a = acceleration, g

W_b = weight of fuze and body, lb

$$F_a = 4410 \times 11.2 = 49{,}400 \text{ lb}$$

The source of this accelerating force is the propellant gas acting on all surfaces aft of the rotating band including the rear band surface. The force is applied to the bearing surface of the base plug and body. The bearing stress S_b in this area is

$$S_b = \frac{F_a}{A}, \text{psi} \tag{4-11}$$

where

S_b = bearing stress, psi

A = area of the bearing surface, in.^{2}

$$S_b = \frac{49{,}400}{\frac{3.14}{4}\left[(3.9)^2 - (3.64)^2\right]} = 31{,}500 \text{ psi}$$

The values of bearing stress calculated in this manner are conservative because we assumed that the driving force of the propellant gas is applied only through the base plug. In practice, however, some of the driving force is applied through the rotating band to the projectile body, thus lowering the stress at the base plug bearing surface.

4-5.5.2 COMBINED STRESS IN THE PROJECTILE BODY

In making this calculation, the conditions and location chosen are those considered most critical, namely, the stress on the wall just aft of the rotating band. Projectile ID and OD are, respectively, 3.6 and 4.04 in. The analysis is based on the behavior of a thin-walled cylinder. The hoop stress S_h due to the bore pressure is

$$S_h = P_m \left(\frac{2r_1^2}{r_1^2 - r_2^2}\right), \text{psi} \tag{4-12}$$

where

S_h = hoop stress, psi

P_m = peak pressure, psi

r_1 = outside radius of projectile body, in.

r_2 = inside radius of projectile body, in.

$$S_h = 11{,}200\left[\frac{2\,(2.02)^2}{(2.02)^2 - (1.8)^2}\right] = 110{,}000 \text{ psi}$$

The longitudinal stress S_ℓ is

$$S_\ell = \frac{F}{A} \tag{4-13}$$

where

S_ℓ = longitudinal stress, psi

F = longitudinal force, lb

A = area under stress, in.^{2}

There are two forces acting in the projectile body in the longitudinal direction, the setback force of the contents applied to the base plate and the driving force applied to the rotating band. Examination indicates these forces are applied so as to oppose each other. We shall arbitrarily designate the setback force as being positive. Assuming the contents of the projectile weigh 25 lb

$$S_\ell = \frac{(4410 \times 25) - \frac{11{,}200 \times 3.14}{4}\left[(4.19)^2 - (4.04)^2\right]}{\frac{3.14}{4}\left[(4.04)^2 - (3.6)^2\right]}$$

$$= 37{,}000 \text{ psi}$$

The combined stress S_c in the projectile wall during firing can then be estimated

$$S_c = \sqrt{S_h^2 + S_\ell^2}\text{, psi} \qquad (4\text{-}14)$$

where

S_c = combined stress, psi

S_h = hoop stress, psi

S_ℓ = longitudinal stress, psi

$$S_c = \sqrt{(110{,}000)^2 + (37{,}700)^2} = 119{,}000 \text{ psi}$$

The results of this design analysis indicate that the critical stress is the combined stress aft of the rotating band. The magnitude of stress indicates that this design may be safely executed in carbon steel, but in iron, only pearlitic malleable iron is usable; and careful design and manufacturing procedures are required.

4-5.5.3 FORCE REQUIRED OF THE EJECTION SYSTEM TO RELEASE THE BASE PLUG

The base plug is held tightly in place by shear pins that must be broken by forces produced by the ejection charge (see Fig. 4-8). The design problem at this stage can be solved by several approaches; the diameter and number of the shear pins can be specified and the pressure required from the ejection charge calculated, or the pressure developed by the ejection charge can be specified and the cross-sectional area of the shear pins calculated.

As an example, the following procedure may be used to determine the size and number of shear pins required. Assuming a gas pressure of 3000 psi from the ejection charge, the shear force F_s on the pins is calculated by

$$F_s = P\left(\frac{d_p^2\,\pi}{4}\right)\text{, lb} \qquad (4\text{-}15)$$

where

F_s = total shear force, lb

P = gas pressure, psi

d_p = diameter of the base plate, in.

$$F_s = \frac{3000 \times 3.14\,(3.6)^2}{4} = 30{,}500 \text{ lb}$$

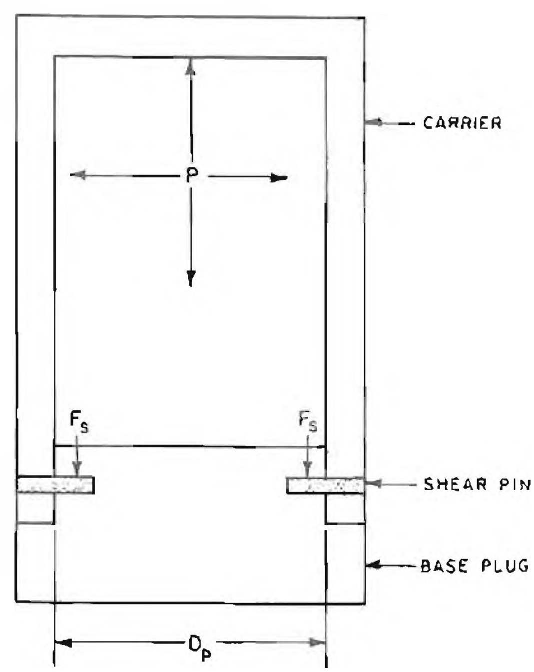


Figure 4-8. Forces on Base Plate of Illuminating Round

Then the cross-sectional area A of the shear pins is calculated

$$A = \frac{F_s}{S_s}, \text{ psi} \tag{4-16}$$

where

A = cross-sectional area of the shear pins, in.^{2}

S_s = ultimate shear strength of the pins, psi

In making this calculation for a design in which steel shear pins are used, the usual practice is to use the factor (0.75) times the ultimate tensile strength of the material as the value for the ultimate shear strength. In this case S_s is estimated at 40,000 psi. Then

$$A = \frac{30{,}500}{40{,}000} = 0.763 \text{ in.}^2$$

If three shear pins are to be used, their diameter d, in., is

$$d = 2\sqrt{\frac{A}{3\pi}}, \text{ in.} \tag{4-17}$$

$$d = 2\sqrt{\frac{0.763}{3 \times 3.14}} = 0.56 \text{ in.}$$

4-5.6 HYDRODYNAMIC FORCES

Often explosive materials are considered to behave as fluids[13]. If this is the case, the pressure P at the bottom of a cavity containing an explosive charge is given by

$$P = 0.036\, \rho L a, \text{ psi} \tag{4-18}$$

where

P = pressure, psi

ρ = density of explosive, g cm^{-3}

a = acceleration, g

L = column length, in.

The action of this pressure is comparable in time with the acceleration introduced by setback. The time period is long with respect to the transit time for a shock wave to progress through the explosive column, but short for the transfer of heat from the explosive material to the surroundings. The process, therefore, may be considered essentially adiabatic.

It is for this reason that long columns and loosely packed explosive materials are undesirable. Voids in cast explosives and interstices in powders experience dramatic rises in temperature during setback.

Furthermore, many explosive materials will fail structurally under high setback forces. The answer to minimizing these effects is to provide adequate support for explosive columns, to precompress materials with high consolidation pressure, and eliminate voids in explosive charges.

Consider a flare composition of initial density ρ_o = 1.7 g cm^{-3}. 10 in. long. At an acceleration of 30,000 g, the pressure at the base of this column would be about 18,300 psi. Many flare compositions would fail in compression under these circumstances and fluid-like flow would occur. Adequate support of the composition is imperative under these conditions.

4-5.7 PROPELLANT CHARACTERISTICS

For a given gun system—i.e., projectile mass, diameter, and barrel length—the shape of the pressure-travel curve can be altered by the characteristics of the propellant[25]. In considering the characteristics of the propellant we should know the effects of grain size, composition, geometry, and the density of loading. Although in a final design all factors may be involved, it is of basic importance to note first the independent effects of each variable. Much work has been done in the past to record these effects independently. They are summarized in the paragraphs that follow.

4-5.7.1 GRAIN COMPOSITION

Grain composition will fix the burning rate at various pressures and temperatures, and can be related to other propellant compositions by a term known as the "quickness" of the propellant. This is a relative term. The most commonly used propellant (single-based, gelatinized nitrocellulose) has a burning rate of 0.1 to 18 cm sec^{-1} from ambient to 60,000 psi, respectively. A quick propellant will burn more rapidly and in general produce a higher pressure in a given gun than a slow one.

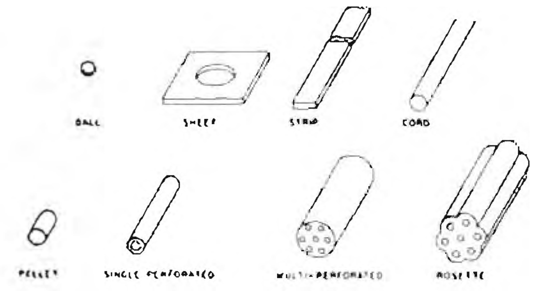


Figure 4-10. Typical Shapes of Propellant Grains

4-5.7.2 GRAIN SIZE

The effect of grain size (surface area variable) for a fixed weight of a given propellant is as shown on Fig. 4-9[26]. Small grain size can be related to large surface area, medium grain size to medium surface area, and large grain size to small surface area.

4-5.7.3 GRAIN CONFIGURATION

Propellant grains can be made of various sizes and shapes as illustrated in Fig. 4-10[26]. The effect of some of these on the pressure-travel curve for a given weight of charge is illustrated in Fig. 4-11[26], where the terms degressive, neutral, and progressive are indicated. These terms refer to the fact that the area exposed to burning is decreasing, remaining the same, or increasing, respectively, as the charge is burned. Fig. 4-12[26] shows the exposed area as a function of "percent grain consumed" for some of the grain shapes illustrated on Fig. 4-11. One should also note that the area under each curve in Fig. 4-12 is about the same because equal charge weights were fully consumed, thus exit muzzle velocity should be about the same in each instance.

4-5.7.4 DENSITY OF LOADING

Increased loading density increases the amount of energy available, increases the maximum pressure attained, and causes peak pressure to occur sooner in the travel of the projectile.

The force on the projectile at each instant is the instantaneous pressure at the projectile position in the gun barrel (pressure may be taken from the pressure-travel curve, see Fig. 4-3) multiplied by the bore area of the gun. Thus the force exerted on the back face of the round follows the pressure-travel contour. This is also the force that gives the projectile mass its acceleration. Experiments have

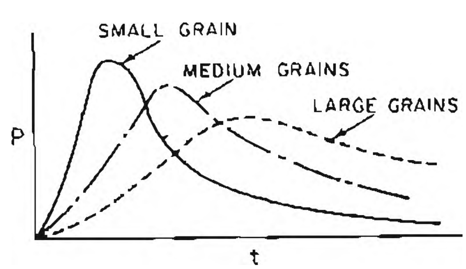


Figure 4-9. Effects of Varying Grain Size for Equal Charge Weights

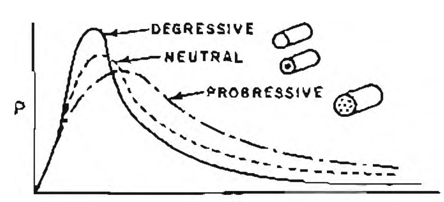


Figure 4-11. Effects of Grain Configuration on Pressure-travel Curves for Equal Charge Weights

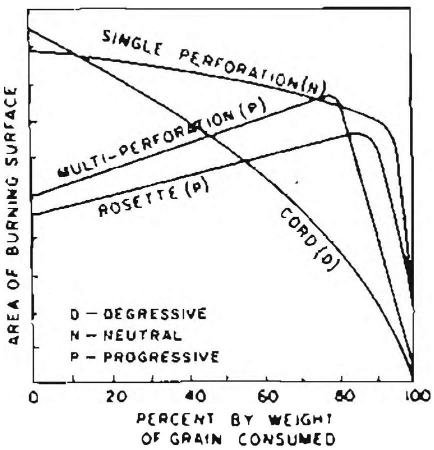


Figure 4-12. Relative Areas of Burning as a Function of Percent of Individual Grain Consumed for Several Typical Grain Shapes

shown that the resisting force due to engraving is large initially as the entire band is engraved, then falls off rapidly after engraving is complete.

4-6 EXTERIOR BALLISTICS

4-6.1 GENERAL

Exterior ballistics is the science of the motion of projectiles in flight. Whereas the times of interior and terminal ballistics are short, projectiles spend most of their active life in the exterior ballistic phase. Hence, this phase is the main cause for inaccuracy in the ballistic weapons, artillery, recoilless rifles, and small arms. Some of these inaccuracies may reflect faults in the original construction of the projectile.

Exterior ballistics draws greatly on statistical parameters based on physical phenomena that are best defined by experimental results. A vast amount of information has been developed on both theory and practice of exterior ballistics. The phenomena affecting the flight of projectiles are well understood and developed in detail in military texts[24,27].

Ammunition containing pyrotechnics may make use of conventional ammunition as carriers. Firing tables exist for conventional weapons and ammunition, describing fully the flight characteristics of projectiles. At times it will be necessary for the pyrotechnic designers to deal with problems of trajectory, stability, and subprojectile deployment.

4-6.2 TRAJECTORIES

The trajectory of a projectile may be computed rather easily when eliminating (1) drag forces, (2) forces due to the rotation of the earth, and (3) effects due to the curvature of the earth. In present pyrotechnic practice the latter two assumptions may be made without serious errors being introduced into the final result. For great altitudes and long ranges, however—such as with intercontinental ballistic missiles and long range artillery—these factors must be considered[28].

The basic differential equation of exterior ballistics is

$$M\ddot{\bar{R}} = F_d + M\bar{g} \tag{4-19}$$

where

M = projectile mass, slug

$\bar{R}$ = vector distance from muzzle to projectile, ft

$\bar{g}$ = vector of the acceleration due to gravity, ft sec^{-2}

F_d = drag force, slug-ft/sec^2 (lb)

If the vector relations are reduced to their respective magnitudes, equations for the vector projection on x- and y-axes are

$$M\ddot{x} = -F_d \cos\phi \tag{4-20}$$

$$M\ddot{y} = -F_d \sin\phi - Mg \tag{4-21}$$

where

ϕ = angle of elevation, rad

x = distance from the muzzle to the x-projection of the projectile, ft

y = distance from the muzzle to the y-projection of the projectile, ft

The drag force F_d is expressed as

$$F_d = K_D \rho d^2 v^2, \text{lb} \quad (4\text{-}22)$$

where

K_D = normalized drag, dimensionless

ρ = air density, slug ft^{-3}

d = projectile caliber, ft

v = projectile velocity, ft sec^{-1}

Solving Eq. 4-22 for K_D

$$K_D = \frac{F_d}{\rho d^2 v^2} \quad (4\text{-}23)$$

The normalized drag was determined experimentally by several investigators, notably Gavre and Kent as shown in Fig. 4-13[25]. The value of K_D varies from about 7 to 10 for M values up to 0.8. (M is the Mach number, the ratio of projectile velocity to sound velocity.) Most pyrotechnic devices travel in the range below Mach 0.8.

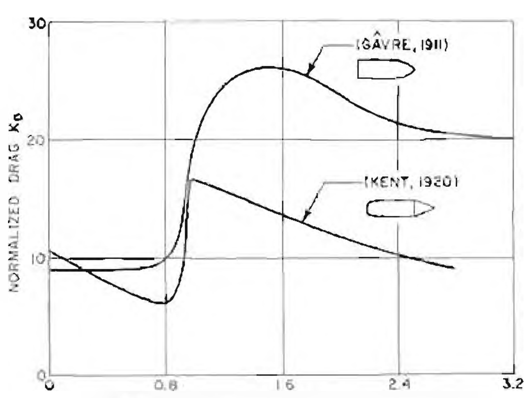


Figure 4-13. Effects of Projectile Velocity on Drag

Using the drag function of Eq. 4-22 and the fact that sin $\phi = y/v$ and cos $\phi = x/v$, the traditional form of the ballistic equation is achieved. The equations must be modified to accommodate yaw, wind, and earth curvature and rotation for practical applications as follows:

$$\ddot{x} = -K_D \rho(d^2/M)v\dot{x} \quad (4\text{-}24)$$

$$\ddot{y} = -K_D \rho(d^2/M)v\dot{y} - g \quad (4\text{-}25)$$

From the differential equations, Eqs. 4-24 and 4-25, it can be seen that two projectiles of different size and weight may have the same trajectory provided (1) the factor d^2/M is identical, (2) they have the same shape (this means K_D will be the same), and (3) the initial condition of velocity and elevation are the same. Thus, the ratio of d^2/M becomes an important consideration. Its reciprocal, M/d^2 is given the name ballistic coefficient. This coefficient describes the properties of a projectile in better terms than the caliber alone. For homologous (have the same shape) projectiles, M is proportional to d^3 and the ballistic coefficient is most often approximately proportional to caliber d; but the ballistic coefficient contains information on mass and shape as well as implied information on drag.

A chart that estimates the range of subsonic projectiles, shown in Fig. 4-14[25], is useful for most pyrotechnic projectiles. This chart allows for determinations of range as a function of maximum vacuum range, given the muzzle velocity v (ft sec^{-1}) and a deceleration factor c (ft^{-1}). The range chart is based on the principal results of the Otto-Lardillon theory of square law drag. The abscissa is the range in terms of the maximum vacuum range. The ordinate, plotted on such scale that the ordinate is proportional to muzzle velocity, indicates the importance of drag. The base line of the figure represents the vacuum trajectory.

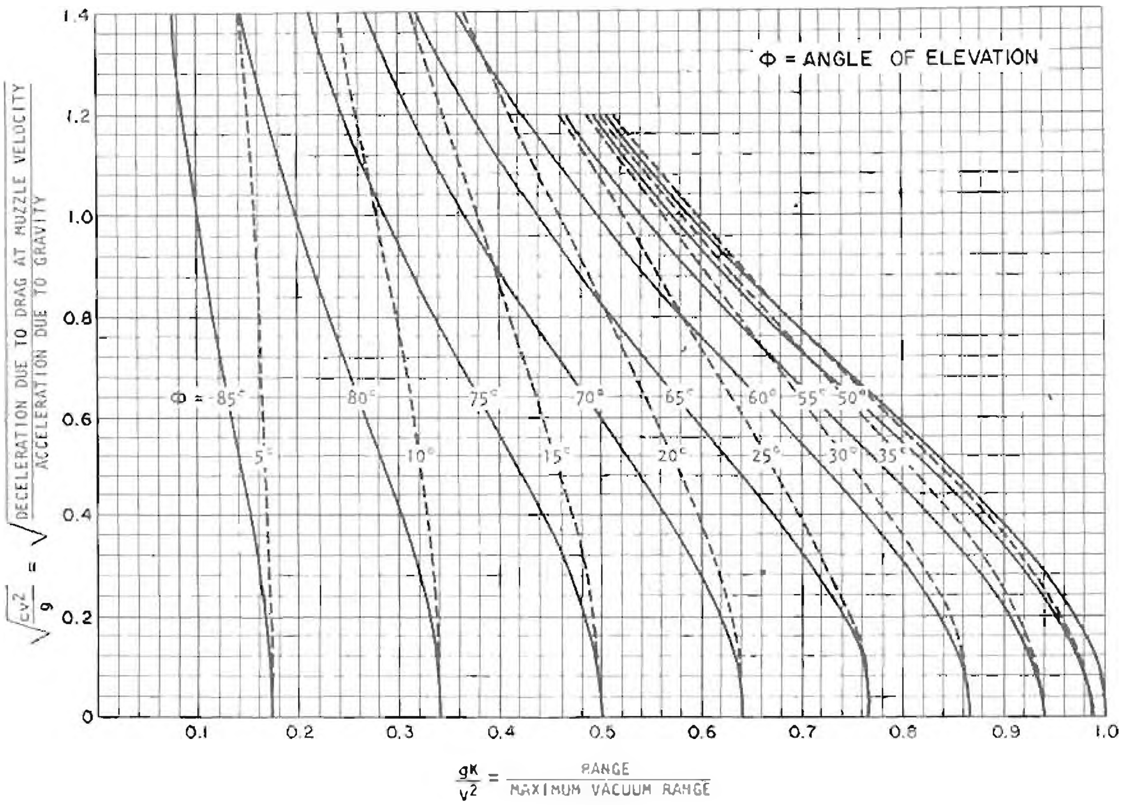


Figure 4-14. Range Chart for Subsonic Projectiles

4-6.3 STABILITY

Stability as applied to projectiles means that the projectile maintains its positional integrity along the line of flight. Stabilization is accomplished either by spinning the projectile or by placing fins on it. This subject is discussed in detail in Ref. 24.

In practice, stabilization is accomplished by applying a restoring force to any external force tending to misalign the projectile from the line of flight; either of the two methods—fins or spinning—can accomplish this task. The main forces tending to deviate the projectile from a vacuum flight are cross-wind forces and drag forces. It must be pointed out that the cross-wind forces are also a function of air density and Mach number both of which vary to some degree with altitude.

A so-called *standard structure* is often assumed in the design of ammunition in which (1) the cross-wind forces are assumed to be zero, (2) the sound velocity is assumed to be 1120 ft sec^{-1}, and (3) the air density varies according to the relation

$$\rho = \rho_o e^{-hy} \qquad (4\text{-}26)$$

where

ρ = weight air density at height, y, lb ft^{-3}

ρ_o = initial weight air density, 0.07513 lb ft^{-3}

y = height, ft

h = a constant, 0.0000316, ft^{-1}

Fin stabilization is accomplished by locating the center of pressure behind the center of gravity of the projectile (as illustrated in Fig. 4-15). At the center of pressure, a force R, the component of cross-wind force F_c perpendicular to the direction of motion, and the drag force F_d act to restore the fin-stablized round to alignment with the motion of the center of gravity. Cross-wind forces are the result of unequal pressure on the fins. The drag force is small and is often disregarded.

The structure of the fins is critical in producing good stability. The problem is that any asymmetrical differences in fins may produce a rudder effect causing the projectile to veer off course. This effect is minimized by introducing a roll to the projectile (nominally 5 to 15 rad sec^{-1}), thus distributing any asymmetry. This action allows for wider tolerances in the fin construction and to some extent reduces errors due to production, handling, and launching.

Spin-stabilized projectiles, in contrast to fin-stabilized projectiles, have their center of pressure forward of the center of gravity as is illustrated in Fig. 4-16. Note that the same forces exist here through the center of pressure as they did in fin-stabilized projectiles.

A stability factor SF may be calculated for a projectile to predict the degree of stability of a relatively untried projectile

$$SF = \frac{I_a^2 N^2}{4IM} \tag{4-27}$$

where

I_a = axial moment of inertia of the projectile, lb sec^2 ft

I = moment of inertia about a transverse axis through the center of gravity, lb sec^2 ft

N = rate of spin of the projectile, rad sec^{-1}

M = overturning moment factor, lb ft

The overturning moment factor is defined by

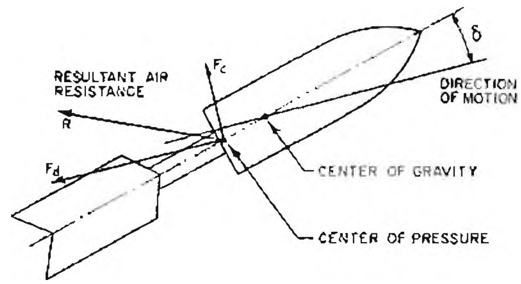


Figure 4-15. Center of Pressure Trails Center of Gravity — Fin-stabilized Projectile

$$M = b(F_d + F_c \cot \delta), \text{ lb ft} \tag{4-28}$$

where

b = distance from center of gravity to center of pressure, ft

F_d = drag force, lb

F_c = cross-wind force, lb

δ = angle of yaw, rad

For small angles of attack, F_d and cot δ usually are ignored.

A stability factor from unity to 2.5 generally indicates that the projectile will perform well with the center of pressure leading the center of the gravity. If the factor is less than one, the projectile will tumble, lose range and is inaccurate. Factors greater than approximately 2.5 produce over stabilization which may result in the projectile landing base first.

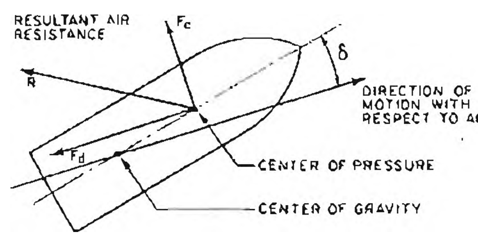


Figure 4-16. Center of Pressure Leads Center of Gravity — Spin-stabilized Projectile

4-6.4 SUBPROJECTILE DEPLOYMENT

Pyrotechnic devices are often delivered to the target by subprojectiles. Hence, it is necessary to activate the pyrotechnic device or the subprojectile at some predetermined time or position. This is done by removing the device from its container which could be a bomb, projectile, or rocket. This action is accomplished in a number of different ways that depend upon the delivery mode, the nature of the pyrotechnic device, and the terminal effects desired.

The design of a pyrotechnic package for an artillery projectile is shown in Fig. 3-6 and described in par. 4-5.5.3, where an ejection charge provides the stimulus to shear pins and the energy necessary to eject the cartridge, including parachute and flare into the atmosphere. This example serves to describe the process of ejection and deployment.

Deployment is sometimes accomplished by drag forces experienced after ejection of the subprojectile. For example, a ribbon is allowed to trail the subprojectile. It creates enough drag force to rip a parachute from the subprojectile package. Details of parachute design and opening devices are covered in par. 4-8.

Ejection charges and their requirements are determined in much the same manner as are charges for other propellant applications as discussed in par. 4-5.7.

The strength of the containers of the pyrotechnic charge is important. However, unlike in the case of gun tubes, only one application of propellant gas pressure is required. General design formulas for thin-wall tubes may be applied to the solution of stresses in the tube walls. Experimental procedures usually follow the design stages of pyrotechnic subprojectiles. Experimental techniques may benefit from measurement of strains in the tube as outlined in par. 5-8.1.

4-7 TERMINAL BALLISTIC CONSIDERATIONS

4-7.1 PAYLOAD DEPLOYMENT

The deployment of the payload is the ultimate objective of ammunition. The methods of deployment are as diverse as the ammunition itself. For this reason, much of the subject matter in this handbook deals indirectly with the deployment of pyrotechnic payloads. This paragraph, however, discusses deployment specifically. In any design where deployment of a pyrotechnic payload is being considered, see also the paragraphs on the specific effects desired, such as exterior ballistics (par. 4-6), fuzing and timing (pars. 3-9 to 3-21), and parachutes and other decelerators (par. 4-8).

4-7.1.1 LIGHT PRODUCING PAYLOADS

Deployment of light sources having a fixed time delay must be analyzed in advance. In projected devices, if the trajectory and the delay are known, an angle of elevation can be specified that will cause illumination to begin at the desired height. Alternatives for projected illuminating devices are variable-time fuzes, variations in the elevation angle, or changes in the launch velocity. All of these complicate the design or increase the cost.

An example of a projected device that makes use of a fixed time delay is the marine signal shown in Fig. 4-17[29]. This signal is a hand-held night distress signal for use by aircraft personnel if forced down over water. When held at a specified angle, it ejects two red stars, successively, to a height of about 175 ft, which may be seen for 2.5 to 3 mi on a clear day and 12 to 15 mi on a clear night.

When the firer pulls the retainer fork, the firing pin is released under the force of the firing pin spring. This initiates the primer which in turn ignites the igniter that projects the igniter holder assembly about 10 ft from the signal. This projecting charge also ignites the first delay charge which burns 2 to 4 sec before igniting the ignition charge, the quickmatch, and the first ejecting charge. That charge ejects and ignites the first star charge

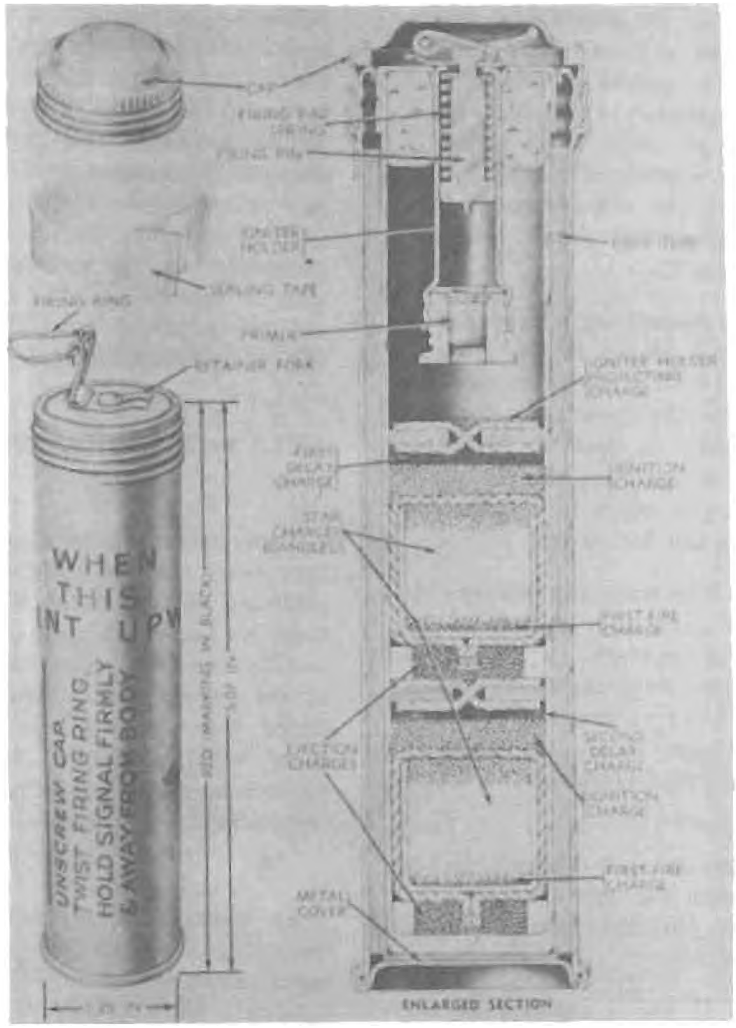


Figure 4-17. Signal, Illuminating Marine, AN-M75

and ignites the second delay charge. The second delay also burns for 2 to 4 sec and then ignites a similar series of elements to eject the second star charge. Each star burns for 4 to 6 sec.

Other light producers, such as bombs and aircraft flares, make use of fuze mechanisms to provide variable delay times[29]. These times normally are indicated in terms of the drop distance to the deployment of the flare. The aircraft parachute flare shown in Fig. 3-5 is an example of such a device. Setting is accomplished by means of a setting ring. Drop distances are variable from a minimum of 300 ft to a maximum 12,000 ft. Trip of the fuze is accomplished by means of a lanyard attached to the aircraft and the flare. Upon drop, the lanyard pull begins the time sequence in the fuze.

Photoflash bombs are deployed in much the same manner as other bombs, i.e., they are dropped from bomb racks[23]. They are timed by fuzing mechanisms set to react at various heights above the ground, but their reaction is different from most pyrotechnic devices. The bomb payload is a consolidated flash powder that must be dispersed rapidly to produce a flash of intense light. For this reason dispersal and reaction of the powder is accomplished by a high explosive core. These devices are treated as high explosive bombs in normal supply, storage, and handling processes.

4-7.1.2 SMOKE PRODUCING PAYLOADS

Smoke producing devices are similar in many respects to light producers except that the time delay need not be as tightly controlled. Devices that produce smoke normally do so for much longer periods than those producing light. If the delay times are contrasted with those of photoflash units, it is clear that the delay times for smoke producers are far less critical than those for photoflash applications.

Most smoke producers are either hand held or emplaced. Few are air dropped for marking purposes. Some pyrotechnic devices are designed to produce both light and smoke so that a dual, day-night function can be served by a single device[30].

4-7.1.3 CHEMICAL AGENT AND SMOKE PRODUCING PAYLOADS

Chemical agents and smokes are usually deployed by mixing the smoke or agent producers with pyrotechnics. The pyrotechnic serves to vaporize the smoke or agent and to expell it into the atmosphere whereupon recondensation occurs. The result of this combination of agent and pyrotechnic is a small package having good dispersal, capable of easy handling, and permitting long-term storage.

Employment normally consists of igniting the pyrotechnic mixture. In the case of smokes and chemical agents, it is desirable to have them disperse over a long period of time. Burning rates are controlled for this purpose and to maintain the temperature of the mixture at an optimum value during delivery. These factors are further discussed in pars. 3-11 and 3-13.

4-7.2 FLOTATION

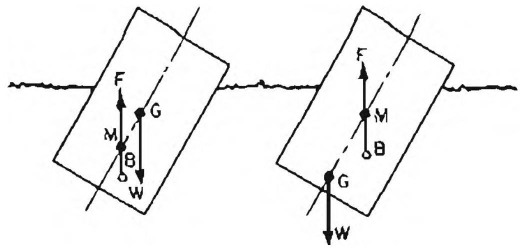
In applications where pyrotechnic devices are to be used in the water, consideration must be given to the process of flotation in addition to the other considerations of preparation for the water environment; i.e., adequate protection of the device from the effects of water pressure, corrosion, and leakage.

Archimedes' principle states that a body partially or wholly submerged in a liquid is buoyed up by a force equal to the weight of the fluid displaced[31]. Thus, an object will float if the weight of the liquid displaced is equal to or greater than the weight of the object. Conversely, it will sink if the object weighs more than the liquid displaced. A floating object, therefore, must be less dense than the water in which it is placed. Nominally, fresh water has a density of 62.4 lb ft^{-3} and sea water has a slightly greater density (64 lb ft^{-3}).

Stability of a floating object depends upon the relationship of three centers of the floating object as depicted in Fig. 4-18, i.e., (1) the center of gravity G is the point at which the resultant downward force (the weight) acts, (2) the center of buoyancy B is the center of the volume of the displaced water, and (3) the metacenter M is the point at which the line of action of the buoyant force intersects the center line of the floating object.

Two conditions of stability are indicated in the figure. In Fig. 4-18(A) the object is unstable and will tip over because the flotation force F and the weight force W acting at M and G, respectively, represent an overturning moment tending to rotate the object in the direction already taken. In this state of instability, the center of gravity is above the metacenter.

The second condition in Fig. 4-18(B) shows the center of gravity below the metacenter. The torque caused by the forces F and W, and the acting arm of these forces indicate a



(A) Unstable Configuration (B) Stable Configuration

Figure 4-18. Conditions of Stability and Instability of a Floating Object

righting force tending to bring the floating object back to its vertical position.

In practice, flotation considerations can be considerably more complicated than is indicated by these basic principles in that the dynamics of the actions are more difficult to describe and analyze. More detailed information is available in literature on ship design[32]. However, these basic discussions make certain of the desirable conditions evident. It is desirable to have the center of gravity located as low as is practicable on the floating object. Similarly, it is desirable to have the metacenter very high on the floating object. It is further important to have a relatively large distance between these two points on the object. Such structures have been practically achieved in what are known as "flip" ships. These are long slender ships that are sailed to their station. They are then partially flooded to give them a vertical attitude. By having a large distance from the center of gravity to the metacenter, they are extremely free of motion induced by wave action.

Deployment of pyrotechnic devices may take place from boats including submarines, surfaces ships, and life rafts; or it may take place from aircraft. The device may experience immersion during deployment or upon exposure to wave action. It is therefore well to include a restart feature that will reignite the pyrotechnic, such as is inherent in the design of the Marine Location Marker, Mk 2, Fig. 3-11. Alternatively, the pyrotechnic may be designed for continuous functioning under water.

4-8 PARACHUTES AND OTHER DECELERATORS

Control of the terminal velocity or descent time of pyrotechnic candles and signals over targets can be obtained by proper use of parachutes or other decelerators. The type of decelerator chosen for given application is usually based upon consideration of the following interrelated factors:

(1) Drag force required to slow descent

(2) Stability required for the payload

(3) Peak force experienced in deployment

(4) Bulk and weight of the decelerator

(5) Environmental conditions

(6) Manufacturing cost

(7) Reliability.

For most applications with a deployment velocity less than Mach 3, parachute systems can provide stability, variation in descent parameters, and a minimum of storage volume. From Mach 3 to Mach 7, deployable rotors, spheres, cones, and flared skirts can be made stronger than parachutes and are more suitable to provide the drag forces. Generally, more storage volume is required for the latter types. The complexity of parachute and decelerator design limits the presentation in this handbook to general considerations. A comprehensive reference should be consulted for details[33,34].

4-8.1 PARACHUTES

4-8.1.1 PARACHUTE TYPES AND NOMENCLATURE

Fig. 4-19 illustrates a simple, flat, circular parachute commonly used to decelerate illu-

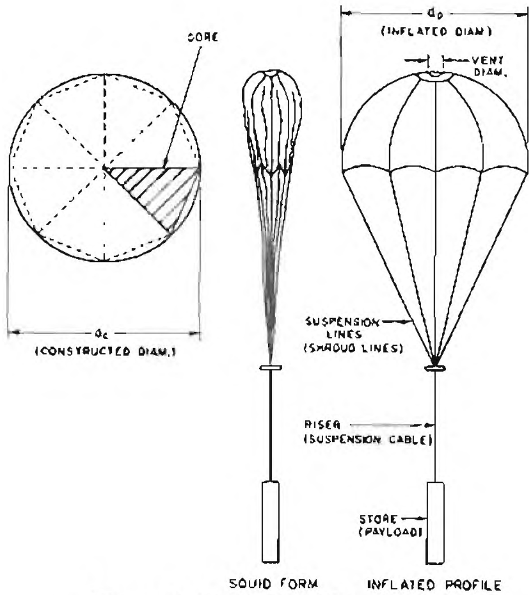


Figure 4-19. Solid, Flat, Circular Parachute

minating candles. Definitions of some terms associated with parachutes follows:

(1) Canopy. The drag producing surface (cloth area or sail).

Deployment. The portion of the operational sequence of a parachute occurring from the initiation of ejection to the instant the lines are fully stretched.

(2) Diameter, constructed, d_c. The design diameter along the radial (main) seam of a parachute or the maximum diagonal of a parasheet.

(3) Diameter, nominal, d_o. The calculated diameter of a canopy equivalent to the diameter of a circle whose total area equals that of the drag producing surface. Vent area larger than 1% of the total area is deducted from the total area.

(4) Diameter, projected, d_p. The mean diameter of the inflated canopy measured in the plane of maximum cross-sectional area.

(5) Gore. Portion of the drag producing surface between the radial seams (triangular segments in the solid, flat, circular canopy).

(6) Permeability. The measured volume of air that will flow through one square foot of cloth in one minute at a given pressure (in United States a pressure of 0.5 in. of water is used; in Great Britain, 10 in. of water).

(7) Porosity. The ratio of open space to total cloth (including slots and vents) area of the drag producing surface. Also known as geometric porosity.

(8) Riser. That portion of the suspension system between the lower end of a group of shroud lines and the point of attachment to the store. It must be as strong as the total strength of all the shroud lines attached to it. It is also known as the suspension cable.

(9) Squid. A partially opened canopy that is fully deployed and whose pear shape makes it resemble a squid with tentacles. This term is also used as a verb. Squidding occurs if the canopy is deployed above critical opening velocity.

(10) Store. A payload, other than human.

(11) Velocity, critical closing. The instantaneous velocity above which the parachute will collapse into the squid shape. Also known as the upper critical velocity.

(12) Velocity, critical opening. The velocity at or under which a parachute will fully inflate from a squid shape. Also known as the lower critical velocity.

(13) Velocity, equilibrium. The velocity that a falling body can attain when the drag is equal to the weight, i.e., when the acceleration for all practical purpose equals zero.

Flat parachutes have a canopy made with triangular gores joined to form a regular polygon. The canopy will be flat when spread out. Parasheets consist of parallel fabric sections that form a flat canopy in the shape of a

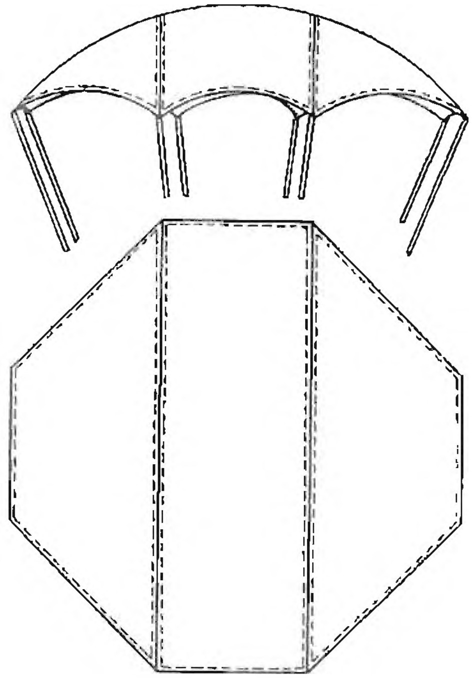


Figure 4-20. Parasheet

regular polygon as shown in Fig. 4-20. The parasheet is somewhat simpler, less expensive than the parachute, and is widely used to decelerate signals and illuminating candles. Shaped parachutes are formed with triangular gores, Fig. 4-21, in which two of the sides are slightly curved to give a pear shaped appearance to the canopy. Other more complex parachute types differ mainly in the canopy configuration to provide more stability, better control of drag forces and line stresses, or both.

A preliminary design of a parachute system requires a simultaneous evaluation of parachute factors and interrelated payload variables (weight, allowable descent rate, and descent time). The shape of the parachute is determined by the specific requirements. Broadly, parachutes may be divided into two classes, (1) those that open at approximately their release speed, and (2) those that slow down their load appreciably before becoming fully inflated[35]. Release mechanisms and forces acting to inflate the parachute to its

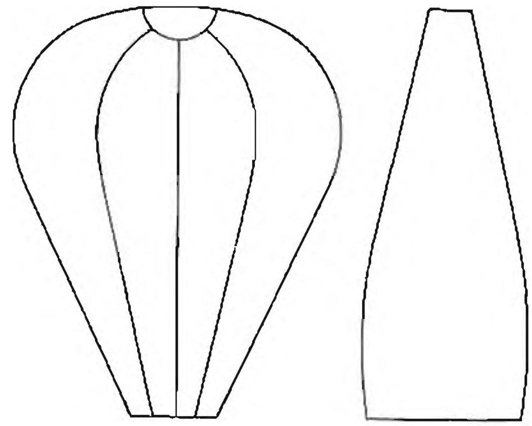


Figure 4-21. Shaped Parachute

full size can also influence performance. Design estimates are normally made with specific data plus information from similar parachute systems and these estimates are refined with successive iterations. It is generally accepted by design engineers that a practical, effective, parachute system for a specific application will involve several trade-offs. Good stability implies a relatively low drag coefficient; higher strength requires greater weight and bulk; high performance systems require high cost canopies, staging of two or more drag areas, or both; fast opening canopies are subject to large opening forces. The most important aspects are discussed in the paragraphs that follow.

4-8.1.2 DRAG

Drag is a force opposite to the downward force of the parachute system and its payload. When these two forces are equal, the parachute descends at a constant speed called its equilibrium descent velocity. There will be both transient and steady state stresses due to aerodynamic, spring, damping, and gravity forces during the descent of a parachute. The governing steady-state equation for a parachute system descending through the atmosphere is

$$F_d = K_D d_o^2 \rho \frac{v^2}{2}, \text{ lb}$$

where

F_d = drag force directed upward, lb

K_D = average drag coefficient, dimensionless

d_o = calculated diameter of parachute canopy, ft

ρ = local air density, slug ft^{-3}

v = descent velocity, ft sec^{-1}

Note that this is the classic equation for drag forces, the same as used for exterior ballistics (see Eq. 4-22, par. 4-6.2). The drag force produced by a parachute depends primarily on the average drag coefficient K_D, the acting dynamic pressure $\rho v^2/2$, and the canopy area d_o^2.

The average drag coefficient K_D is a function of the inflated shape and porosity of the canopy. The inflated canopy shape depends upon the gore shape, the length of the suspension lines, and the decelerated mass[34]. Drag coefficients for most common single canopy type parachutes vary between 0.45 and 1.0. The average drag coefficient for the solid flat circular type canopy shown in Fig. 4-19 is about 0.75.

The drag coefficient for the solid flat circular canopy frequently used in pyrotechnic applications is not constant but varies with d_o, the nominal diameter, and the vertical descent rate v. This variation occurs because the permeability and the inflated shape vary with the pressure differential across the canopy. Test data indicate that the drag coefficient will change with descent velocity for solid flat circular parachutes with different diameters as indicated in Fig. 4-22. The drag coefficient for other canopy shapes may or may not change significantly over the deployment range, and a suitable reference should be consulted as needed[33].

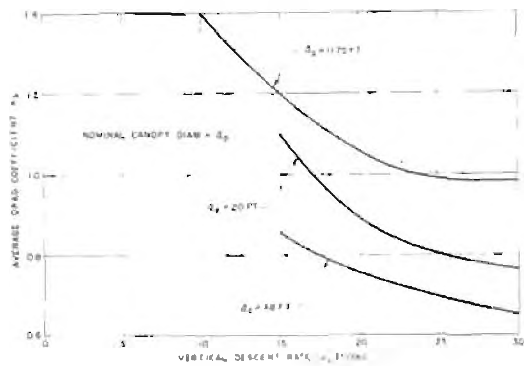


Figure 4-22. Variation in Drag Coefficient With Vertical Descent Rate for Solid Flat Circular Canopy

4-8.1.3 CANOPY LOADING

The loading of the canopy can be obtained if either the descent velocity v or the drag area is known. If v is known

$$P = \frac{\rho v^2}{2} \tag{4-29}$$

If $K_D d_o^2$ is known

$$P = \frac{W}{K_D d_o^2}, \text{ lb ft}^{-2} \tag{4-30}$$

where

P = canopy loading, lb ft^{-2}

ρ = local air density, slug ft^{-3}

v = velocity at the given altitude, ft sec^{-1}

W = total weight of store and parachute, lb

$K_D d_o^2$ = drag area, ft^2

4-8.1.4 CANOPY SIZE

The size of a parachute is most frequently established by the equilibrium descent rate. Equilibrium conditions exist when the drag force developed is equivalent to the suspended weight. Fig. 4-23 is a descent chart

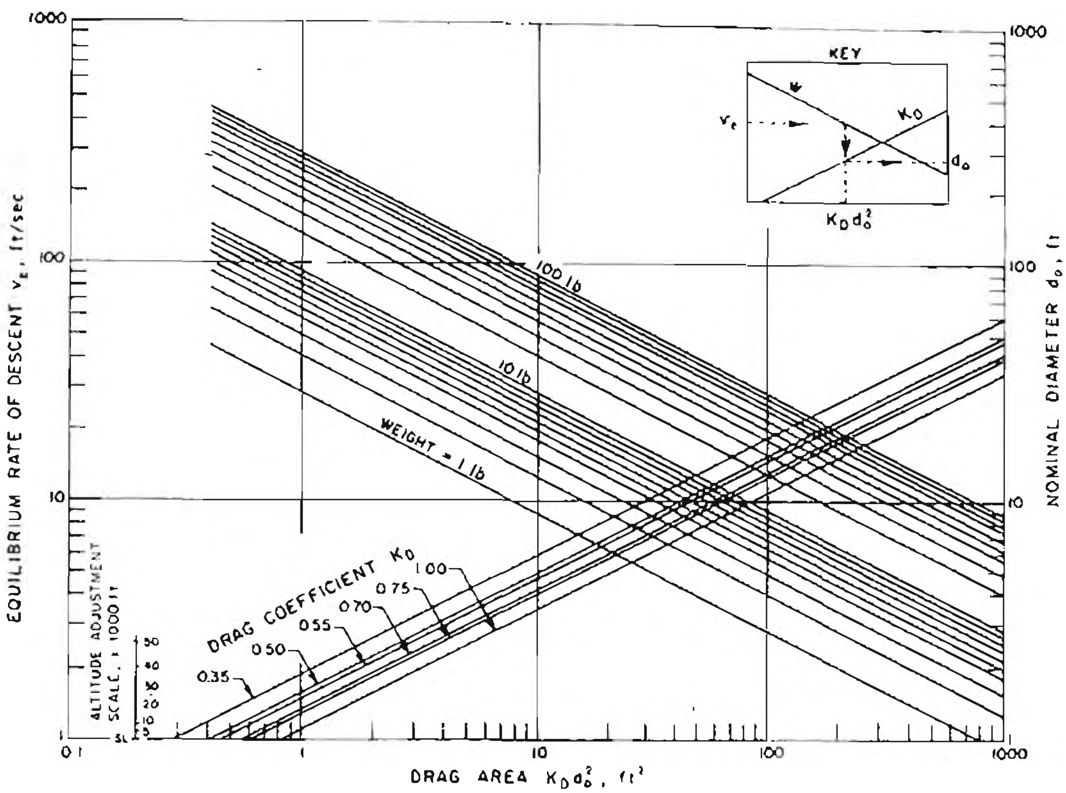


Figure 4-23. Parachute Descent Chart

showing variation of equilibrium descent rate v_e with drag area $K_D d_o^2$ for a given weight. Variation of drag area with nominal diameter d_o is also shown for particular values of the drag coefficients K_D at standard sea level conditions.

Example

Given: Store or payload weight, 10 lb
Equilibrium descent rate, 30 ft sec^{-1}
Type of canopy, flat circular (K_D = 0.75)

Find: (1) The drag area required

(2) The nominal diameter of the canopy to provide the desired descent rate

(3) The equilibrium descent rate at 30,000 ft above sea level.

Solution

A graphical solution is provided by the parachute descent chart shown in Fig. 4-23. Start with the left ordinate equal to a descent rate of 30 ft sec^{-1} and find the point of intersection with the curve representing a weight of 10 lb. A vertical line from this point to the abscissa determinines the drag area, 9 ft^2. The intersection of the vertical line with the drag coefficient curve K_D = 0.75 projected horizontally to the left ordinate determines the nominal parachute diameter d_o equal to 3.9 ft. An altitude correction in the equilibrium descent rate can be made by measuring the linear distance on the altitude adjustment scale between sea level and 30,000 ft and adding it to the ordinate at 30 ft sec^{-1} to obtain a true air speed of 50 ft sec^{-1}.

4-8.1.5 VARIABLE PAYLOAD WEIGHT

In the case of parachute supported flares, the payload weight decreases as the flare is consumed. For a given chute design, the flare will descend a smaller distance in a given time than if the load remained constant. With constant load the distance y descended in time t can be expressed as

$$y = t\sqrt{\frac{2W}{d_o^2 \rho K_D}} \qquad (4\text{-}31)$$

where

- y = distance descended, ft
- W = weight of parachute and load, lb
- d_o^2 = parachute area, ft^2
- ρ = air density, slug ft^{-3} (assumed constant)
- K_D = drag coefficient, dimensionless
- t = descent time, sec

As the pyrotechnic device is consumed, the weight W must be known as a function of time. If the burning rate is linear with time, the following expression can be used.

$$W = f(t) = (W_c + W_p) - \frac{W_p t}{t_p}, \text{ lb} \qquad (4\text{-}32)$$

where

- W_c = parachute canopy and hardware weight, lb
- W_p = consumable pyrotechnic weight, lb
- t_p = time to consume W_p, sec
- t = descent time, sec (valid for $t \leqslant t_p$ only)

Example

A parachute system contains a pyrotechnic flare with 35 lb of combustible material which burns at a linear rate and is totally consumed in 180 sec. The parachute and associated hardware weigh 15 lb and the canopy area is 400 ft^2. The air density is 0.0024 slug ft^{-3} and the drag coefficient K_D = 0.75. Find the distance descended in 180 sec.

Solution

The total weight as a function of time from Eq. 4-32

$$W = f(t) = 15 + 35 - \frac{35}{180}t$$

The function is substituted into Eq. 4-31 and integrated between 0 and 180 sec to obtain

$$y = \int_0^{180} \left\{ \frac{2\left[50 - \left(\frac{35}{180}\right)t\right]}{(400)(0.0024)(0.75)} \right\}^{1/2} dt$$

$$= -1.667 \times \frac{180}{35} \left\{ \frac{2}{3}\left[50 - \left(\frac{35}{180}\right)t\right]^{3/2} \right\}_0^{180}$$

$$= 1690 \text{ ft}$$

If the load had remained constant the parachute would have descended 2125 ft in 180 sec.

4-8.1.6 STABILITY

Stability is a measure of how well a parachute system can maintain a descent course without either lateral oscillations or drift. It is always measured in still air. Stability is also a measure of the damping of oscillations, i.e., the most stable parachute has the largest damping factors.

The main factors influencing stability are canopy loading and total canopy porosity. High canopy loading parachute applications are in general considered more stable. Low canopy loading may produce a gliding type of instability. However, lateral oscillation usually occurs with high canopy loading. For both solid cloth and geometrically porous parachutes, an increase in porosity will lower the maximum angle of lateral oscillation. Frequency of oscillations also will decrease as the porosity of woven fabric parachutes is effectively reduced. This may explain the increase in both the angle of oscillation and the increase in frequency of oscillation commonly experienced at high altitudes. In supersonic operation, a design must be of high geometrical porosity such as provided by ribbon type parachutes to avoid extreme fluctuation and inflation instability of the canopy.

Stability is desirable to prevent large drifts and oscillations for pyrotechnic candles but it is not sought at the expense of ability to withstand opening shock, low cost, and high drag per unit volume. Flat circular parachutes usually give average oscillations of ±15 deg to ±30 deg, which are tolerated as being the current state-of-the-art in most pyrotechnic applications. Parasheets can be expected to produce average oscillations of ±20 deg to ±35 deg.

4-8.1.7 PEAK FORCE LIMITATIONS

In the deployment and inflation of a parachute system, there occurs a snatch force peak and an opening force peak. The allowable forces on the canopy, shroud lines, and store must be considered. The snatch force peak occurs shortly before the opening shock when the deployed canopy is accelerated to the velocity of the store. Its magnitude depends mainly on the mass of the deployed canopy, the length of the suspension lines, and the difference in velocity between the store and canopy. The magnitude of the force is determined by equating the kinetic energy of the separating masses (canopy and store) to the energy the elastic lines must absorb to bring the masses to zero relative velocity. A detailed reference should be consulted for making snatch force and opening shock calculation[33]. A typical plot of these forces for aircraft flares is shown in Fig. 4-24.

The peak forces developed can be appreciably large. A T-10 aircraft flare, which contains a 40-lb candle and an 18-ft diameter flat circular parachute, developed an opening shock force of 11,980 lb when it was released at an altitude of 10,000 ft at 390 kt and allowed to fall 5500 ft before ejecting the parachute at a velocity of 530 ft sec^{-1}. The peak stress on the canopy at opening was 55.4 psi.

These forces are relatively mild for applications such as hand-launched devices in which the parachute is ejected near the apex of the ballistic trajectory.

4-8.1.8 REEFING

In some cases it may be necessary to limit the opening force to meet both canopy strength and payload strength limits. A technique that may be used for this purpose is known as reefing, in which the inflated shape of the canopy is restricted. Disreefing will allow the canopy to assume its full inflated shape. A typical reef-disreef sequence is shown in Fig. 4-25. The reefing line maintains the skirt of the canopy to a fixed size that is smaller than the fully inflated diameter. The reefing line can be cut by mechanically initiated devices containing pyrotechnic delays.

Center line and control line reefing, illustrated in Fig. 4-26[33], have also been used in some military applications. In center line reefing, the center of the canopy is held below the rim (Fig. 4-26(A)). In control line reefing the reefing line is guided through rings inside the canopy similar to the scheme shown in Fig. 4-25. But now a control line is added that connects with two lines from point B to points A (Fig. 4-26(B)). Retraction of the control line reefs the canopy while extension disreefs it.

4-8.1.9 DEPLOYMENT TECHNIQUES

Various approaches are used to expose the canopy to the airstreams from its storage container. Two frequently used types—the

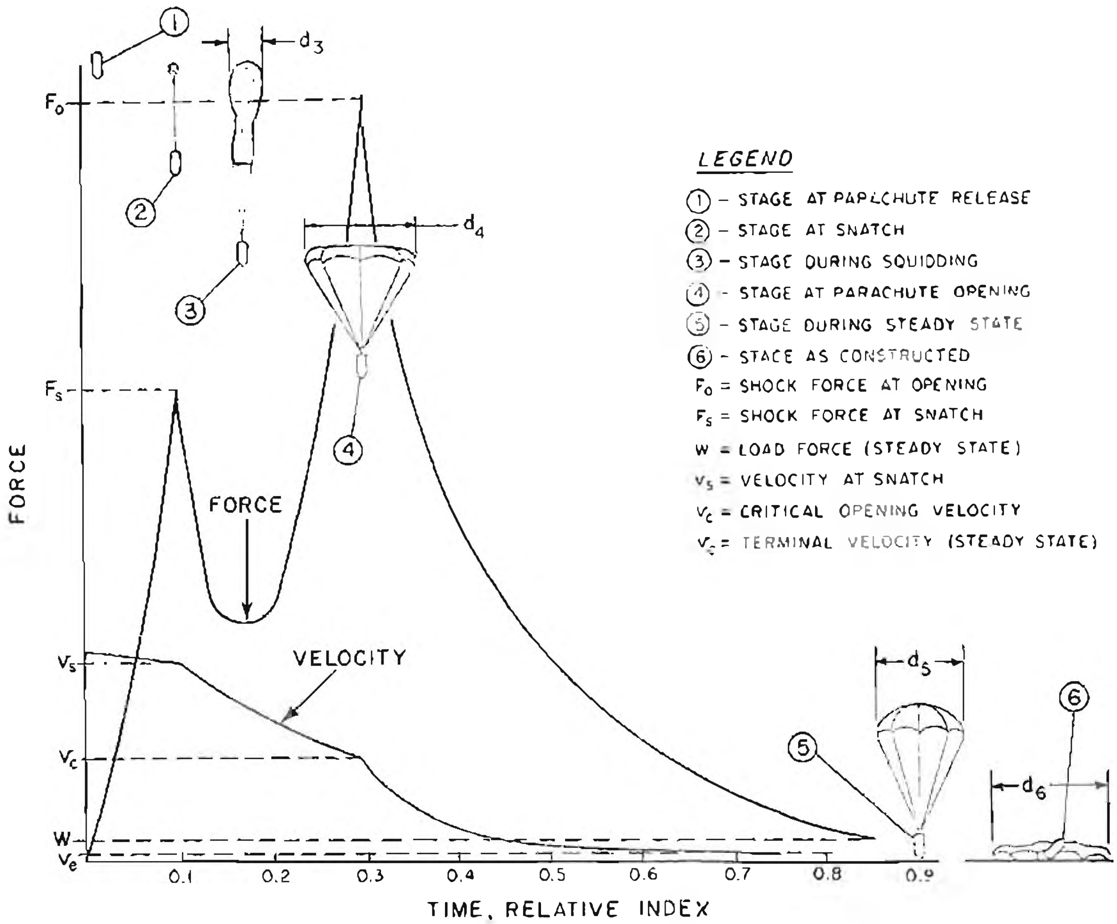


Figure 4-24. Parachute Suspension System Showing Effects of Force, Velocity, and Diameter at Various Stages of Development

free type and the full bag—are illustrated in Fig. 4-27.

The free type deployment often is used in military applications involving single or double ejection of the parachute away from the projectile. In this type of deployment there is a rapid deceleration of the canopy sail and the base plug, pilot chute, or wind sock combination (enclosed by dotted lines in Fig. 4-27(A)) because these components have low ballistic coefficients (high drag due to shape) compared to the payload. Inflation begins during the deployment process, which increases the mass of the combined sail, and deployment aids by the amount of air entrapped in the canopy. The free type deployment therefore produces high snatch loads.

Full bag deployment is used to reduce the snatch force. The dotted lines in Fig. 4-27(B) enclose the mass whose velocity closely approximates that of the pilot drogue chute that provides the deploying force. Solid lines enclose the mass of lines and sail which attains a velocity equal to that of the payload before the snatch load occurs. Full bag deployment offers greatly reduced snatch loads since the canopy is accelerated in increments.

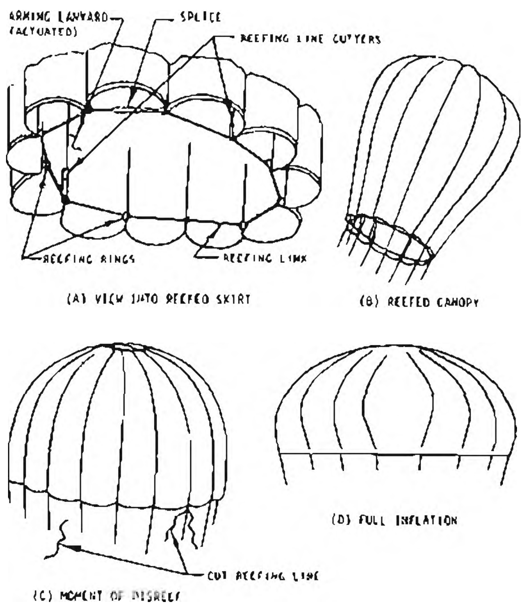


Figure 4-25. Typical Reef-disreef Sequence

4-8.1.10 BULK AND WEIGHT

The weight of a parachute generally must be heavier for faster rates of descent and for greater canopy loading because a canopy and shrouds of higher strength are required. To compare the efficiency of various parachute designs, specific drag—the ratio of drag area to weight—is used. The flat, circular design excels in this efficiency measure with specific drags of 45 to 120 $ft^2\ lb^{-1}$. The parasheet ranks next with values of 35 to 110 $ft^2\ lb^{-1}$.

The bulk (density) is controlled to a degree by the pressure applied during packing. The packed density, in pounds of parachute weight per cubic inch of parachute volume, is used to determine the parachute compartment volume required. Parachute pack densities range from 0.010 to 0.028 lb $in.^{-3}$; however, densities below 0.012 lb $in.^{-3}$ are loose, tend to lose their shape, and are difficult to handle. Densities above 0.024 lb $in.^{-3}$ can create severe packing difficulties[36].

Hand packing methods can be used to obtain densities up to 0.018 lb $in.^{-3}$ and

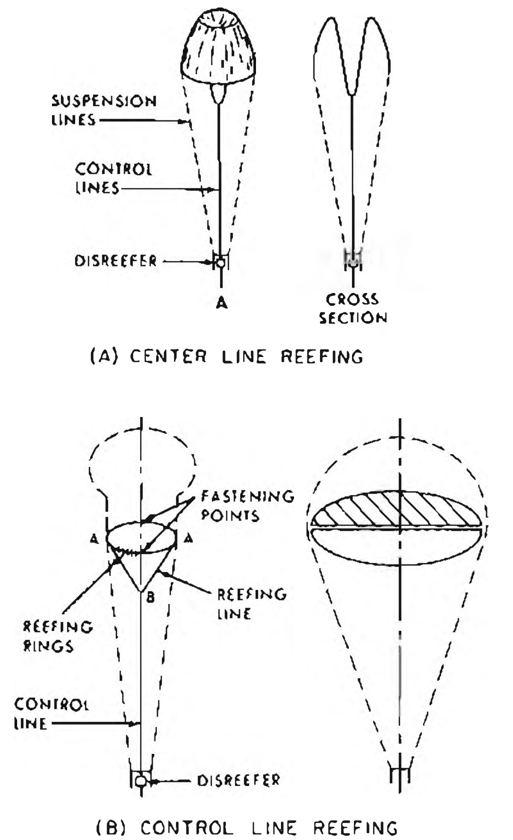


Figure 4-26. Other Reefing Methods

methods such as bag lacing, hydraulic pressing, and removing air with vacuum techniques can be used to achieve densities of 0.024 lb $in.^{-3}$.

4-8.1.11 TYPICAL APPLICATIONS

An aircraft parachute flare is shown in Fig. 3-5. Flares released from aircraft usually have delayed ignition so that they will clear the aircraft and function at a desired altitude below it. The operation of an aircraft parachute flare is shown in Fig. 4-28[23]. Note that much of the original weight (cartridge case) is dropped before the flare is ignited. The characteristics of some typical parachute supported flares released from aircraft are shown in Table 4-12[23]. For characteristics of other pyrotechnic devices, see Tables 4-1 to 4-9.

TABLE 4-12

CHARACTERISTICS OF SOME PARACHUTE SUPPORTED FLARES (AIRCRAFT RELEASED)

Item	Weight, lb	Burning Time, sec	Fall Velocity, fps	Max Speed of Airplane at Time of Release, mph
M8A1	17.6	165 – 195	9.0	200
M26	52.5	195 ± 15	11.6	150
M26A1	52.5	195 ± 15	11.6	350.
M138 (T10E4)	62	360	10	440
M139 (T10E6)	62	180	10	440
Mk 5 and Mods	18	180	–	–
Mk 6 Mods 5 and 6	30	180	–	–
AN-Mk 8 Mods 1 and 2	18	180	8.0	250
Mk24	27	185	7.5	460
XM170	11.5	150	15	–

4-8.2 BALLOONS

A balloon decelerator is a high-drag object fabricated from material with very low porosity. After deployment it is either self-inflated or force-inflated behind the payload that is to be decelerated. Balloon-type decelerators should be considered for deployment vehicle velocities up to Mach 10. At supersonic velocities above Mach 2 most parachute decelerators start to exhibit erratic inflation and stability characteristics.

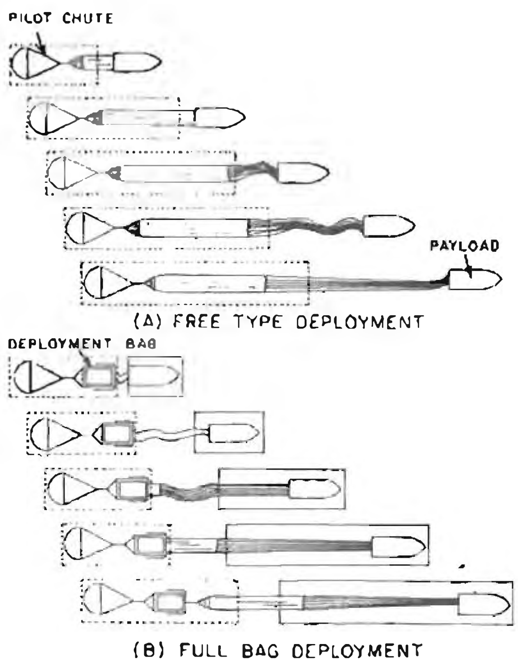


Figure 4-27. Free Type and Full Bag Deployment Techniques

A spherical balloon decelerator is shown in Fig. 4-29[33]. The toroidal-shaped ring is known as a "burble fence" and is used to provide stability at subsonic speeds.

4-8.3 RIGID DECELERATORS

Rigid decelerators are drag producing shapes made from nonflexible material that are suitable in the supersonic speed range. A special category of rigid decelerators called nonpowered rotors may be useful for applications in which the descent is controlled and a soft (near zero velocity) landing is required. Nonpowered rotors can be constructed employing helicopter-type rotor blades. Drag coefficients can approach those encountered with parachutes and, in addition, a long gliding range may be obtained[37].

4-8.4 DYNAMIC DECELERATORS

Several advanced concepts have been

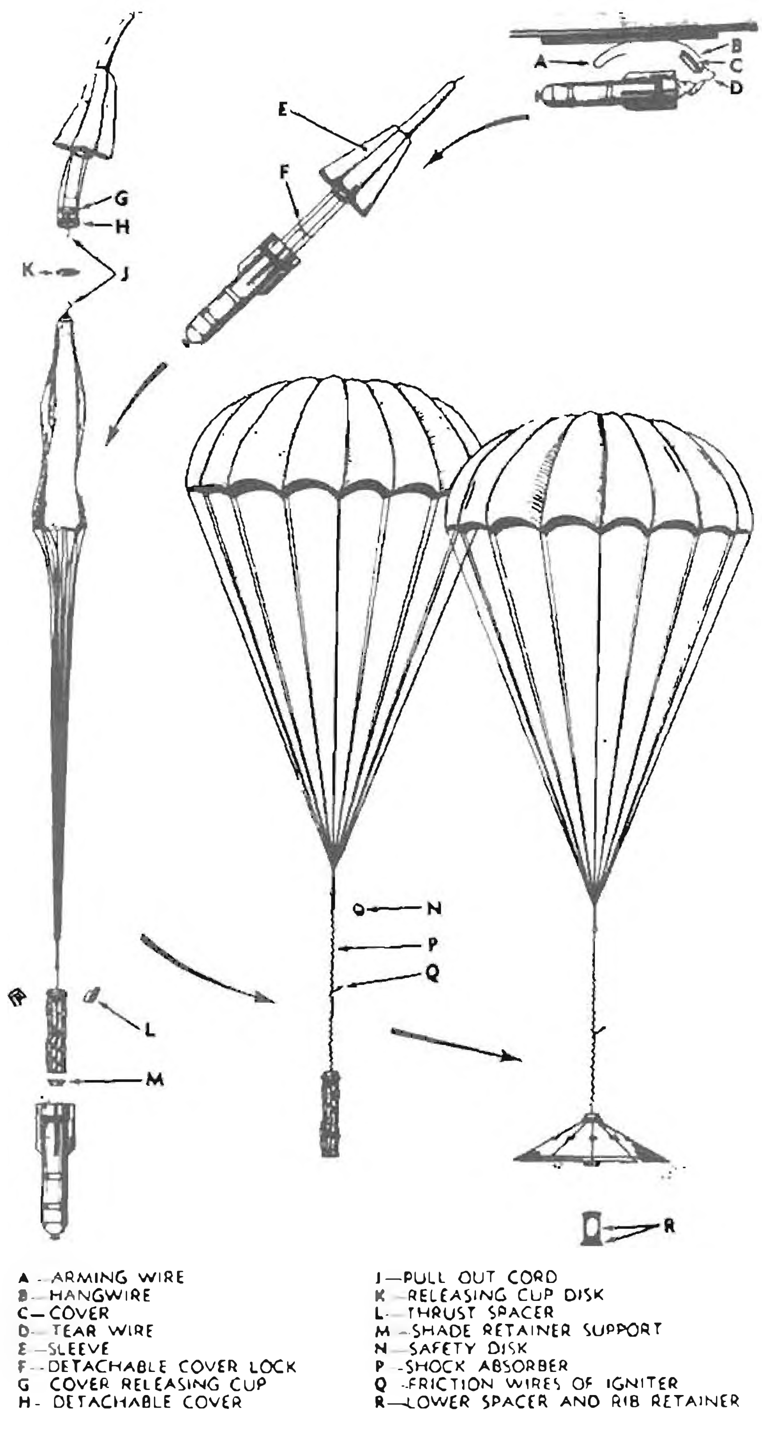


Figure 4-28. Operation of Typical Aircraft Parachute Flare

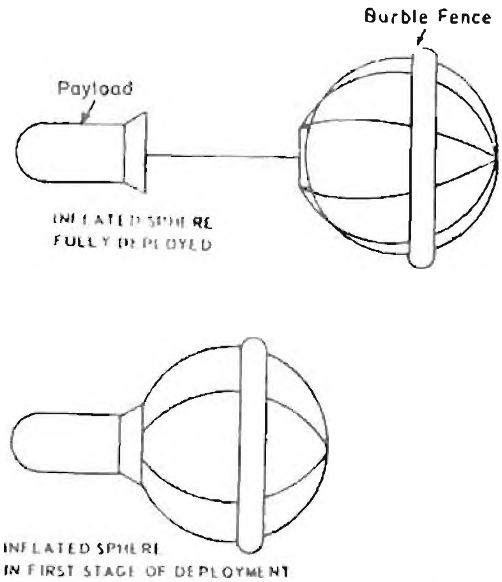


Figure 4-29. Spherical Decelerator

studied recently to improve flare support systems[38]. The new concepts make use of dynamic decelerators that have the following inherent advantages over parachutes and balloons:

(1) Relative insensitivity to wind drift

(2) Ability to operate continuously at optimum altitude

(3) Small weight and bulk.

Wind drift is a severe problem when using flares deployed by aircraft. This problem is illustrated in Fig. 4-30[38]. While the dynamic decelerator is relatively stable, both balloon and parachute tend to drift with the wind. In addition, the parachute descends in altitude and tends to oscillate.

Stability of the dynamic decelerator is achieved by employing a whirling rotoblade driven by a propellant actuated device (PAD) and an aerodynamic stability fin. Operation is as follows. After flare ejection from the aircraft, the PAD generator extends the rotoblade and its protective cover away from the flare body and initiates rotation. The long aerodynamic fin, located beneath the flare body during launch, is then released and positioned by preset springs. The fin provides directional control by pointing the opposite end of the flare directly into the wind much like a weather vane. Minimum wind drift caused by aerodynamic drag is thus realized because the minimum area of the flare is consistently pointed windward. As the burning flare consumes the pyrotechnic grain, flare weight is reduced. At the same time, the rotational speed of the rotoblade is reduced by a drop-off in PAD pressure thus maintaining a constant flare altitude.

The advanced concepts studied included flares burning at both ends (as sketched in Fig. 4-30), vertical position flares, flares of airfoil shape arranged in a pinwheel, and flares attached to a spinning disk instead of a rotoblade. The study also includes flare deployment techniques and contains an extensive literature survey[38].

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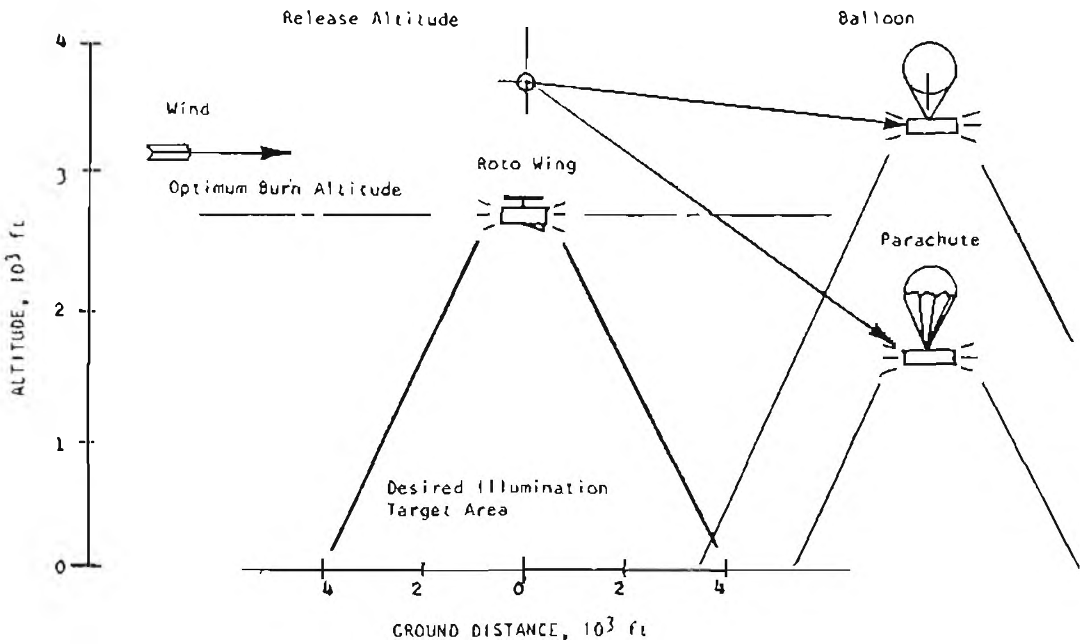

Figure 4-30. Relative Wind Drift Stability of Aircraft Flare Suspensions

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CHAPTER 5

INSTRUMENTATION

5-1 GENERAL

In developing and testing pyrotechnic ammunition it is necessary to measure parameters that determine if the round or its components can meet prescribed objectives. Physical properties, the effect of external forces, the timing of sequenced operations and the pyrotechnic output in its specific form may all have to be assessed qualitatively or quantitatively during the course of a development. Simple measurements of length, weight, and strength may be made with conventional measuring equipment. Many of the measurements, however, will be of such duration or magnitude that they will be impractical to assess with precision without the aid of special instruments.

In this chapter basic means of converting one physical phenomenon to another are discussed. Most often the conversion is from one physical phenomenon to electrical signals that are easily recorded, transcribed, and amenable to analog and digital techniques. Photography also plays an important role to record events, measure light or particular regions of the spectrum in spectroscopy.

Detectors and transducers, used to sense and convert phenomena from one form to another, are treated in some detail because of their widespread use in pyrotechnic applications. Signal conditioning, calibration, and recording methods are presented to give a broad picture of instrumentation from a system viewpoint.

5-2 TRANSDUCERS AND DETECTORS

5-2.1 GENERAL

A transducer is a device actuated by power from one system and supplying power in the same or another form to a second system. A detector is a device employed to recover a specific type of signal. When used in instrumentation, the term transducer is frequently used to designate both types of device. The two general groupings of transducers are self-generating (voltage-generating) and passive (variable-parameter) types. Self-generating transducers develop voltage within themselves under the influence of physical or electrical input energy. Their direct voltage output generally permits elimination of one of the stages of data processing that is necessary when using the passive types of transducer. Subordinate classes of these basic types are shown in Table 5-1.

5-2.2 PIEZOELECTRIC TRANSDUCERS

Piezoelectric crystal transducers generate voltage when the crystal element has its dimensions changed by mechanical force. Some naturally occurring materials are piezoelectric, capable of producing an electrical potential when stressed. A number of synthetic materials have been shown to produce the same effect, often with a more efficient production of electric charge than those occurring naturally. Quartz and most other naturally occurring materials generally show a higher electrical resistance than the synthetics[1]. The natural types can usually be

TABLE 5-1

MAIN CLASSES OF TRANSDUCERS

Self-generating	Passive
Piezoelectric	Variable Resistance
Magnetoelectric	Variable Capacitance
Photovoltaic	Variable Inductance
Thermoelectric	Photoemissive

operated at higher temperatures than the synthetics. Both types are suitable for use in transducers and have been so used.

Generally the physical properties of materials will limit the charge which determines the potential and the energy that may be produced. Hence, electrical loading of the output may distort the input-output relation. Piezoelectric materials therefore have been connected to other circuits with minimal loading by using vacuum electrometers and, more recently, field-effect transistors. It is well to operate piezoelectric transducers at frequencies well below any resonances because nominal calibrations do not apply under conditions near resonance. Applications for these transducers include microphones, pressure gages, accelerometers, and force transducers.

5-2.3 MAGNETOELECTRIC TRANSDUCERS

Magnetoelectric transducers depend upon the action of a relative motion between a conductor and a magnetic field[2]. This is an elementary type of transducer action that is applied to speed measurement and control, dynamic microphones, and generators.

5-2.4 PHOTOVOLTAIC TRANSDUCERS

Photovoltaic or barrier layer cells consist of a semiconductor material having small amounts of impurities deposited on a metal substrate with a light-transmitting film of thin metal applied by evaporation or sputtering to form a second electrode. Light impinging on the film surface causes a current to be generated with no external power required. With small resistive loads, this current is proportional to the light flux on the photocell surface over a wide range. Linearity can be enhanced further by the use of zero-input operational amplifier circuits. Selenium has a maximum spectral response close to that of the standard human eye and varies little from cell to cell. Therefore, it is most easily corrected to the standard eye or CIE response with standard colored glass filters.

A Weston photronic selenium cell presently is used for making light measurements of pyrotechnic items in both Army and contractor test facilities. These photocells, as received from the manufacturer, are subjected to spectral sensitivity testing to insure a close CIE match. Temperature effects over normal ambient ranges are usually less than 2% with low resistance loads used in photometric testing. Although the selenium cell is used extensively for the testing of illuminating flares and colored signals, it is deficient in two areas: (1) it has a slow rise time response to normal illumination (about 5 msec) and (2) it is unable to withstand elevated temperatures.

A silicon photovoltaic cell, on the other hand, is capable of withstanding high temperatures and has a rise time on the order of microseconds. Its spectral response covers the entire visible range and extends into the near infrared, making it more difficult to correct to the ICI response. A current development program has resulted in excellent ICI correction of individual silicon cells by hand tailored methods. Experimental photocells have been successfully used at the Yuma, Arizona test facility.

5-2.5 THERMAL ELECTRIC TRANSDUCERS

Thermal electric generators, thermocouples, and thermopiles are discussed in par. 5-3.2 particularly in connection with the detection of infrared energy. Additional detailed information is available in the literature[3].

5-2.6 RESISTIVE TRANSDUCERS

Resistive transducers which constitute a large portion of the passive group of elements are used to convert thermal or physical variables into an indicative resistance. The resistive group is further divided into thermoresistive types and mechanical types.

5-2.6.1 THERMORESISTIVE TRANSDUCERS

Thermoresistive devices may be made of either semiconductors or of metals. Metal elements have positive temperature coefficients of resistance while semiconductors generally have negative coefficients. Metallic sensing elements generally have low resistance initially and the change in resistance with respect to temperature is far less than with semiconductor devices, but metal devices are more linear and tend to be more stable. Semiconductors nominally have relatively large initial resistances and the change with temperature is more pronounced[1,4]

When a thermistor is used in temperature measurement, it is well to operate below its self-heating point to avoid the effects of the measuring current from becoming superimposed on the temperature being measured. The thermistor, being a relatively high resistance device, may be placed remotely from the recording instruments without adverse effects from long electrical leads. In addition, the sensitivity of thermistors makes them ideally suited for control applications. Little if any amplification is required for most applications.

5-2.6.2 MECHANOVARIABLE RESISTIVE TRANSDUCERS

Mechanovariable resistances include a number of devices – from a simple rotating potentiometer to complex mechanisms that drive strain gages to give an electrical output from a mechanical input. The most widely used type of mechanovariable transducer is the strain gage.

Strain gages are available in metal and semiconductor types, the metal type made of wire or foil being more popular. A strain gage resembles a postage stamp in size and shape with the wire or foil active elements bonded to a substrate. The entire device is cemented to the surface on which strain is to be determined. Strain gages have geen applied to pressure measurements, weighing equipment, displacement transducers, and many other measuring applications.

5-2.6.3 ELECTROLYTIC CELLS

The electrolytic cell is another variable resistance cell. The change in resistance of this cell depends on changes in length or cross section of the conducting path of an electrolyte between two electrodes. The change in resistance may be produced by movement of one of the electrodes that may be attached to a Bourdon tube element. These cells are not widely used.

5-2.6.4 PHOTORESISTIVE CELLS

Photoresistive cells use a light sensitive material whose resistance is changed by the absorption of light. The resistance of these cells in the absence of light, known as the dark resistance, is a function of potential, temperature, and the rate of change of these variables. Illumination of these cells causes a resistance change that is a function also of wavelength, exposure time, temperature, applied voltage, and previous exposure history[5]. The desired feature of the cell is that it measures light intensity.

The time response of semiconductor photoresistive devices is generally much longer than that of photoemissive tubes. The relatively slow response imposes limitations on the use of photoresistive devices for measuring light of short duration or rapidly changing intensity. In addition, photoconductors exhibit some instability and deviate from linearity of current with light intensity.

5-2.7 VARIABLE CAPACITANCE

Variable-capacitance transducers basically consist of two conducting plates separated by a dielectric. Current flow will be proportional to a change of distance between the plates, change of plate area, or chemical or physical changes in the dielectric. Capacitive transducers operate on the basis that the capacitive reactance is inversely related to the product of the frequency of the source and the capacitance of the transducer[6]. When the frequency is fixed, capacitance is the only variable.

5-2.8 VARIABLE INDUCTANCE

Transducers that rely upon inductance for their operation include those that exhibit a change in inductive reactance. The inductive reactance changes with the inductance which may be varied by insertion or removal of a core. Inductive reactance is measured with the result that the core displacement is known. The inductive effect also is related to transformer actions that depend upon inductive coupling from one winding to another for transducer action.

Inductances and capacitors are often combined to form a tuned circuit at a particular frequency[1]. This type of circuit may be used in at least two ways. The network may be used to control the frequency of an oscillator or it may be used to provide a limit on the amount of signal that is passed through it near resonance. In either case the inductance or the capacitance may be changed.

5-2.9 PHOTOEMISSION

When light strikes a metal surface it can transfer enough energy to dislodge surface electrons. This fundamental mechanism of photoemission is governed by the intensity and frequency of the incident radiation and the threshold frequency at which the electrons may be emitted by the metal. Emission current is mainly a function of the intensity of the radiation, i.e., the number of light quanta that strike the surface per second. Since light intensity measurements are often desired, the emitted current can be amplified and displayed to give a measure of light intensity.

5-2.10 PHOTOGRAPHIC TECHNIQUES

Photographic emulsions are commonly used to detect electromagnetic waves classified as light. Generally speaking, all wavelengths in the spectrum shorter than 13,000 Å, can be photographed. A great variety of sensitive photographic materials are available to make measurements in the region 2000-5000 Å and techniques for sensitizing emulsions for wavelengths up to 13,000 N are available in the literature[7]. See also par. 3-4.

5-3 LIGHT DETECTORS

5-3.1 GENERAL DETECTORS OF LIGHT

There are two fundamental means of converting light energy into some other form of energy: (1) the use of thermal effects produced by the light to heat the sensitive material of a transducer, and (2) quantum effects that result from the interaction of photons with the sensitive material. The essential difference between a photon detector and a thermal detector is that the former, in principle, counts the number of effective quanta of radiation absorbed, whereas the response of the latter depends on the total energy absorbed[8].

Materials that have a physical or electrical property with a measurable thermal coefficient, resistance for example, can be heated by radiation and used to supply another type of signal like voltage or current. Thermocouples, bolometers, and Golay cells are examples of thermal detectors.

Since every quantum-operated device has an energy threshold, there are certain frequencies below which quanta will produce no reaction. In today's technology this limit occurs within the near IR, hence detection of light is restricted to wavelengths shorter than those of the near IR unless the detector is cooled to very low temperatures. Recent advancements in doping of germanimum-silicon single crystals with antimony have resulted in extension of response to 120 μ in the far infrared when the detector is operated at liquid nitrogen temperature.

Pyrotechnic devices generally emit most of their light from the far infrared to the near ultraviolet range, covering the visible range. It is this range of radiation that must be measured in dealing with pyrotechnic devices.

To measure the quantity of infrared radiation incident upon an area, many physical phenomena can be employed. The far infrared must generally be measured by thermal effects, which result from radiant heating of the device; and the near infrared may be measured by quantum effect transducers.

5-3.2 THERMAL DETECTORS

For the thermal-type radiation detector to provide a measure of the radiant energy incident upon it, the device must change in temperature by a measurable amount as a result of the absorption of the radiation. It is generally desirable that the heat capacity of the element be sufficiently low so that equilibrium temperature can be reached quickly to give a short response time[3].

One of the earliest types of infrared detector is the thermocouple[8]. This detector, see Fig. 5-1, is constructed of two junctions J_1 and J_2 between metals A and B. Metal B in turn is connected to a third metal C which serves as a connection to the readout instrumentation. The junctions J_3 and J_4 are set at a uniform temperature T so that these junctions produce no net thermal potentials. The junction J_1 is connected thermally to a receiver upon which radiation falls, raising the junction temperature by an amount ΔT to $(T + \Delta T)$. The temperature difference between junctions J_1 and J_2 will cause a thermoelectric potential between the junctions. Semiconductors can be used that exhibit an electric potential several times that of bimetallic types.

Since amplifiers or meters are voltage or current operated devices, it is necessary to pass a current (bias current) through this detector so that the resistance change is expressed as a voltage or current proportional to incident radiation. The bolometer is a radiation detector that indicates the presence of radiation by the change of electrical resistance. The resistance change is due to the change in temperature of the element caused by the absorption of the radiant energy.

One circuit sample which can be used to indicate resistance change in the form of a voltage is shown in Fig. 5-2. As can be seen from the diagram, for small currents through the element, the output voltage will be directly proportional to the current. As bias current is increased however, a point is reached where power input to the element in the form of joule heating has a serious influence on the dynamic behavior of the detector. The magnitude of the bias current could be so high as to mask changes resulting from incident radiation.

The temperature coefficient of resistance α in ohm $°K^{-1}$ is the essential difference between metal-element bolometers and semiconductors, or thermistors. When used in this application the temperature coefficient is positive for metals and negative for the semiconductors. For bolometers whose behavior can be represented by a simple time

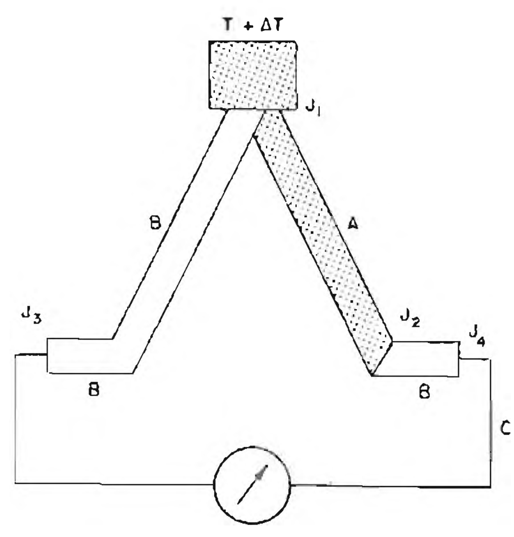

Figure 5-1. Typical Thermocouple Circuit

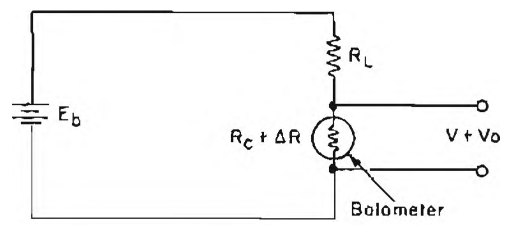

Figure 5-2.
Basic Operating Circuit of a Bolometer

constant, it has shown that the equivalent electrical circuits of positive and negative temperature coefficient bolometers are approximately as shown in Fig. 5-3 where the radiation signal is represented in Fig. 5-3(A) by an infinite-impedance current generator and in Fig. 5-3(B) by a zero-impedance voltage generator[9].

Thermal detectors based on a pneumatic principle have also been used. By observing the small expansion that occurs in a volume of gas, it is possible to indicate the presence of radiant flux due to heating of the gas by the absorption of radiation[10]. An example of a Golay cell is shown in Fig. 5-4[10]. The small movement of the diaphragm is amplified by

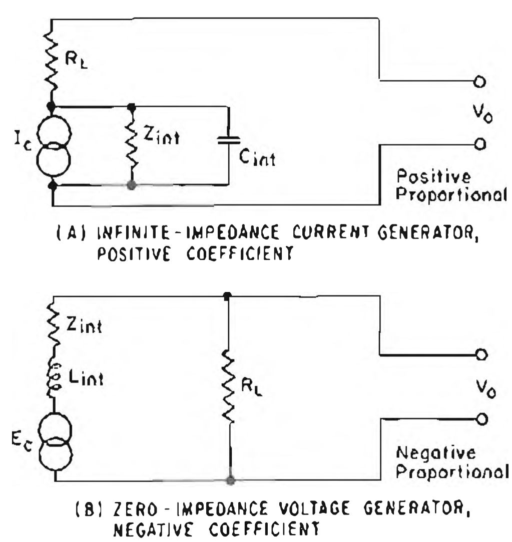

Figure 5-3.
Generator Equivalents of Bolometers

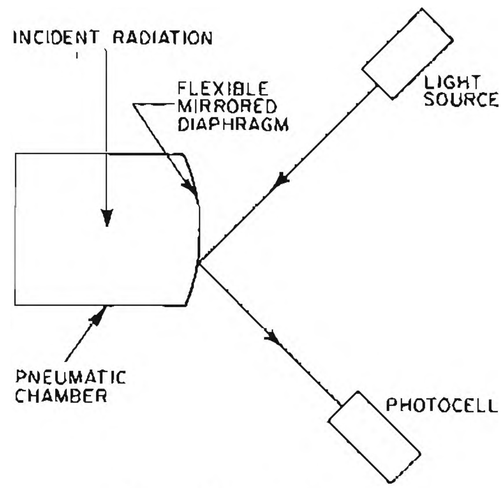

Figure 5-4. Golay Cell

optical means. Detectors of this type have been made that will detect 1.4×10^{-9} W with a time constant of 3 msec. The time constant has been made as short as 600 μsec by using helium instead of air in the cell[8].

5-3.3 PHOTON DETECTORS

The outstanding feature of the photon detector is its ability to respond without any dependence on a rise in temperature of the sensing element. Its operation depends on the emission of electrons resulting from the absorption of radiation. Any of the radiation which may be lost at the detecting element is of little consequence since the detectors usually have a high thermal capacity and the temperature rise due to the radiation is small. Since the time constant of the photon detector does not depend on the thermal capacity but on the photoelectric properties of the sensitive material, it can follow changes in the radiation very rapidly.

The photon detector will not respond equally well to all wavelengths when compared to the thermal detectors since there is a lower wavelength threshold.

The effective responsive quantum efficiency η_s is an indication of the relative effectiveness of the photons incident on the detector[3].

This quantity is defined as the ratio of the number of incident photons per unit time to the number of output events occurring in the same time

$$\eta_s = \eta_o (1 - E_r - E_t) \qquad (5\text{-}1)$$

where

- η_s = effective responsive quantum efficiency, dimensionless
- η_o = actual responsive quantum efficiency, dimensionless
- E_r = fraction of energy lost by reflection, dimensionless
- E_t = fraction of energy lost by transmission, dimensionless

By far the most important class of photon detector materials is that which includes semiconductors. The particular phenomena associated with the reaction of semiconductors to optical radiation are broadly classified as photoconductivity[11].

In certain materials, it is possible to excite electrons in the crystal structure by infrared radiation absorption to the extent that they are emitted from the surface of the material and become free to be collected by an external anode[3]. This type of detector is called *photoemissive*.

The two basic types of photocells used in photometry are the photoemissive and the photovoltaic. The photoemissive cell is generally used where high sensitivity, stability, precision, and proportionality of output to illumination input are more important than portability of the instrument. The photovoltaic cell generally is used when simplicity of the instrument and portability are of importance.

Even though the difference in sensitivity between the photovoltaic cell and the photoemissive cell is 500 μA lumen^{-1} and 10 μA lumen^{-1}, respectively, amplification of the output of the photoemissive cell[12] can be up to 20 A lumen^{-1}.

The phenomenon of secondary electron emission from a material when it is bombarded with high velocity electrons has been used to develop a photocell having high internal amplification. Such a cell is known as a photomultiplier. Electrons ejected from the cathode as a result of light interaction are focused on another electrode where each incident electron produces a number of secondary electrons. These are focused on a third electrode and the process repeated several times. The electrodes at which the secondary electrons are produced are known as dynodes.

The great advantage of the photomultiplier cell is the extreme rapidity of its response to a transient or fluctuating illumination (as fast as 10^{-13} sec). In this respect it is greatly superior to a system consisting of an ordinary two-element photoemissive cell and an amplifier.

5-3.4 CELL CONSTRUCTION

The different types of photon detectors described in the preceding paragraphs, when used in the visible and the UV regions, use filters or windows to increase or limit their spectral response. The filters used in the visible spectrum are generally of the color type, to limit the response of the detector to a particular type of light. The most commonly used window material in the UV region is lithium fluoride (LiF). Because of its good transmission properties between 1040 and 2000 Å, it is often used to the exclusion of all other materials[13].

Instruments used to measure the properties of IR radiation often require isolation in the form of transparent barriers or lenses or prisms to diffract the light. It is important to know the transmission limits in terms of wavelengths for the materials used in these instruments. Table 5-2 shows the upper limit of wavelength for transmission of a number of materials[1].

In the use of any of these materials, it is important to consider the environment in

TABLE 5-2

TRANSMISSION CHARACTERISTICS OF COMMON OPTICAL MATERIALS FOR INFRARED INSTRUMENTS

Material	Approximate Long-Wave-Length Transmission μ, Upper Limit
Glass	3.5
Quartz	4
Sapphire	5
Lithium Fluoride	6
Calcium Fluoride	9
Arsenic Trisulfide	11
Barium Fluoride	12
Sodium Chloride	16
Silver Chloride	27
Potassium Bromide	30
Thallium Bromoiodide	40

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which the optical piece is to be used. Some of the materials are water soluble and may have other characteristics that make them unsuitable for service in adverse environments.

5-3.5 CALIBRATION

A standard tungsten-filament lamp is most generally used as a secondary standard for laboratory work involving pyrotechnics. A specially constructed lamp may be purchased and sent to the National Bureau of Standards for calibration. These lamps are calibrated against a standard blackbody source. Emission of the lamps is confined to wavelengths greater than 2700 Å. Nominal output approximates a standard illuminant with a color temperature of 2854°K. The source subsequently is used for color temperature calibration and for light intensity calibration. It is also possible to obtain calibrations on translucent materials such as milk or opal glass slabs that serve to convert units of illuminance to units of luminance, for example, from foot-candles to foot-lamberts (see par. 2-1.1). These units are convenient for the calibration of sources that produce luminance such as chemical luminescent devices. The feature of these translucent materials is that they may be illuminated on one side with a standard lamp that produces a calculable illuminance on one surface of the slab and produce a known luminance on the opposite side of the slab. An absolute detector based on the principle of photoionization is the most precise and sensitive standard available for the measurement of absolute intensities.

To measure the absolute intensity of radiation in a wavelength span from approximately 2 to 300 Å, a properly constructed photon counter should be used[13]. In the range 250 to 1022 Å, it is simpler and more accurate to use the rare-gas ion chambers for the tendency of these detectors is to produce current directly proportional to the number of incident photons. For wavelengths longer than 1022 Å, a secondary standard with a flat response should be calibrated against a rare gas ion chamber. Probably the best secondary standard is the thermocouple. Calibrating the thermocouple directly with a rare gas ion chamber involves only one step compared with the three steps involved with the standard procedure. Moreover, most research laboratories can easily construct standard ion chambers for the calibration of thermocouples. A freshly prepared sodium salicylate coated photomultiplier can also be used as a secondary standard from 1000 to 3500 Å with moderate accuracy. When calibrated in the vicinity of 1000 Å, the accuracy over the range 1000 to 3500 Å should be within ± 20 percent. Once the conditions for establishing a flat response with sodium salicylate are understood, the accuracy is likely to be greater than that of the thermocouple; however, it is probable that the salicylate-coated photomultiplier would need recalibrating prior to any measurements. Thus the thermocouple probably remains the best secondary standard[13].

5-4 SMOKE DETECTORS

The properties of smoke which need to be

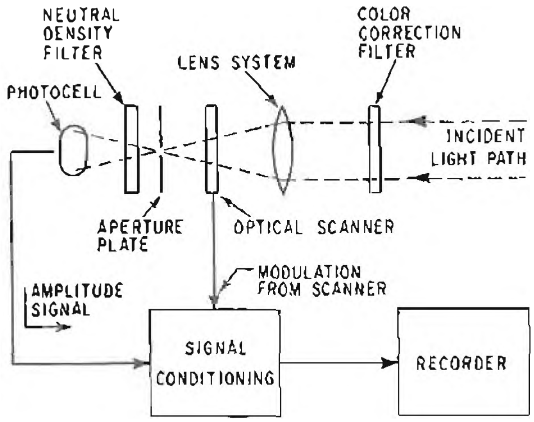

Figure 5-5.
Typical Photometer for
Obscuration Measurements

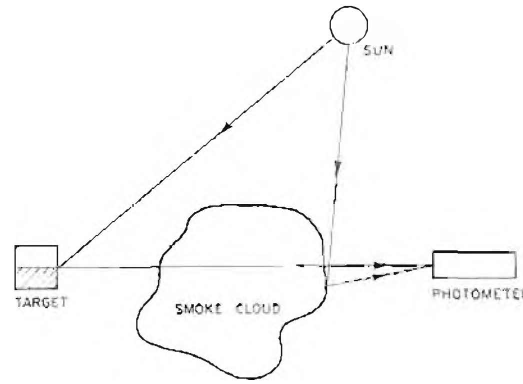

Figure 5-6.
Test Setup for Obscuration Measurements

specified or measured depend upon the ultimate use of the smoke-producing pyrotechnic. For signaling, the important properties of the smoke are color and visibility. For the production of particulate clouds such as tear gas, the important properties are smoke volume and persistency. The measurement of smoke properties will be highly dependent on the surroundings such as confinement, wind, temperature, humidity, and the location of the observer and the light source.

One method of obscuration measurement uses a portable photometer and a two contrast target[14-16] Some method of scanning the target is necessary such as a rotating target or an oscillating mirror in the photometer. Fig. 5-5 shows the construction of the photometer, and Fig. 5-6 shows a field test setup As shown, light enters the photometer from two sources. Light is reflected from the target and transmitted through the smoke cloud and also reflected from the smoke cloud. The output of the photometer consists of two signals an AC voltage proportional to the transmittance of the cloud and DC voltage proportional to the reflectance of the cloud. The obscurance is calculated as the ratio R/T where R is the percent reflectance of the smoke cloud and T is the percent transmittance of the cloud. T is a property of the cloud only, depending on the particle size and density. R is a property of the cloud and also a function of the ambient light.

Auxiliary measurements required are the incident illumination level and direction, and atmospheric phenomena such as wind speed and direction, temperature, and humidity. If desired, appropriate transducers may be used and the data recorded simultaneously with the photometer reading.

A simpler method of measuring the obscurance of smoke is to measure the attenuation of light through a known volume of smoke in a smoke chamber[17]. This method, however, is not suitable for field use and does not take into consideration such factors as dispersion and persistence. A typical smoke chamber is a cylindrical steel tank 8 ft in diameter and 20 ft long. Mixing fans are provided and rows of lights are positioned along the length of the tank for obscurance measurements. A photocell and spotlight are positioned a known distance apart, and a movable target is available for judgment assessment of obscuration. In practice, the pyrotechnic is fired and the chamber fans stir the smoke to uniformity. The light attenuation is measured as a function of time with the photocell, and an observer may position the movable target at the position of total obscuration and the

TABLE 5-3

CHARACTERISTICS OF COMMON PRESSURE TRANSDUCERS

Type	Max. Range, lb in.$^{-2}$	Max. Freq. Response	Comments
Piezoelectric	75,000	Near DC to 300 kHz	High impedance output. Temperature sensitive
Resistance	100,000 ‡	DC to 500 Hz	Simple signal conditioning
Strain Gage	+	DC +	Infinite resolution
Variable Reluctance	+	DC +	Requires AC signal conditioning
Semiconductor	40,000	DC to 25 kHz	High output, inexpensive

+ Depends upon mounting
‡ Approximate

distance recorded as a function of time.

It is important to note that such variables as temperature and humidity affect the output of many smoke compositions and should be measured and recorded in order to obtain meaningful and reproducible results.

Other parameters of smoke that may be easily measured are particle size and composition. Vacuum air sampling is often employed, collecting the smoke particles on membrane filter pads. A better instrument for particle size distribution measurements is the cascade impactor, a device which separates particles by size as well as collecting them[18]. Once the particles are collected, various techniques may be used to identify their composition such as photometry, chemical analysis, titration, X-ray fluorescence, and flame photometry.

5-5 HEAT DETECTORS

The measurement of heat is closely allied with the measurement of the radiation effects of infrared light. The thermocouple, described in par. 5-3.2, is a basic temperature transducer. The voltage vs temperature charts are published[19] for various combinations of materials and temperature ranges because the voltage output is not a linear function of temperature. Selection of a thermocouple depends upon the temperature range to be measured and upon the effect the thermocouple will have on the temperature being measured because the size and mass of the thermocouple and its composition may affect the temperature reading.

Other temperature transducers include resistance thermometers, liquid- and gas-filled thermometers and thermal expansion and bimetallic thermometers. Care should be taken when using any type of contact thermometer because the presence of the thermometer may alter the temperature by thermal conduction. This fact leads to the desirability of noncontacting thermometers. These units are called pyrometers or radiation thermometers. They actually measure the infrared radiation from a source and compute the temperature by comparing the radiation to a reference radiation source. Units are available to measure the temperature of objects that range from 60° to 7000°F.

In order to measure the heat output from a pyrotechnic device a calorimeter is used. The calorimetry technique utilizes the temperature rise of a known volume of material to calculate the heat output from a device. The pyrotechnic device to be evaluated is enclosed in a bomb and immersed in a known quantity of distilled water. The unit is initiated and the temperature change of the water is measured. The heat output is obtained by multiplying the temperature change by the effective heat capacity of the calorimeter system.

Heat flux measurements can be made using specially calibrated temperature transducers. Commercial units are available utilizing foil and thermocouple temperature sensors that operate in the range of 2 to 500 cal/cm^2-sec at temperatures up to 1500°F. Care should be exercised in applying calibration information because it is a function of the operating temperature and the mounting methods.

5-6 PRESSURE TRANSDUCERS

There are many applications where the measurement of pressure is useful. Ejection systems, some flares, gas generators, whistles, and propulsion systems are all characterized by the generation of a gas pressure which may need to be measured and evaluated. Often it is necessary to know the peak pressure inside a casing in order to assess the weight versus safety and reliability aspects of a particular pyrotechnic device. Pressure transducers may also be used to evaluate the pressure of a gas evolved into a closed bomb of known volume. Commonly used types of pressure transducers and their range and frequency responses are shown in Table 5-3. In addition to absolute and gage pressures, transducers are available to measure the pressure differential between two points. Many transducers are also available with signal conditioning equipment built into the transducers, producing an output voltage proportional to pressure.

The output of a pressure transducer is usually recorded as a function of time on a chart recorder or oscilloscope, depending on the frequency response and recording time required. The most useful parameters are peak pressure attained, time to achieve peak pressure, and duration of pressure. In mounting a pressure transducer—due to the phenomenon being observed—care should be taken to prevent damage to the transducer and yet obtain an accurate representation of the desired pressure. If there is a gas flow in the area to be measured, the opening for the transducer should be at right angles to the flow. For best high frequency response, the pressure measuring element should be flush with the inside of the wall where the pressure is being measured. If necessary to protect the transducer from hot particles or fragments, the transducer may be isolated by means of a small orifice or protected by a coating of zinc chromate, putty, or silicone grease without appreciably affecting the frequency response.

Since all transducers mentioned except the piezoelectric will respond down to zero frequency, a deadweight tester may be used for static calibration. The low frequency response of piezoelectric transducers may be extended sufficiently by means of high-input-impedance or charge amplifiers to permit static calibration. Calibration also may be accomplished by comparison with a calibrated transducer exposed to transient pressures, such as in a shock tube.

5-7 SOUND DETECTORS

The pyrotechnic applications of sound measurement include the evaluation of impact, vibration, and output from whistles, as well as the sounds associated with the firing of a weapon. The basic transducer for sound is the microphone. Common microphones are of the piezoelectric, condenser, or dynamic type. All types may exhibit a frequency response of approximately 20 Hz to 20 kHz although special units are available for measurements outside this range. Both the piezoelectric and dynamic microphones are inexpensive and rugged and require only a simple voltage amplifier for signal conditioning. The condenser microphone, operating on the variable capacity principle, is easily calibrated but requires an external power supply and special amplifier. It is not affected by temperature to the extent that the other types are.

Typical measurements on a sound producing device include sound amplitude and frequency as a function of time, as well as

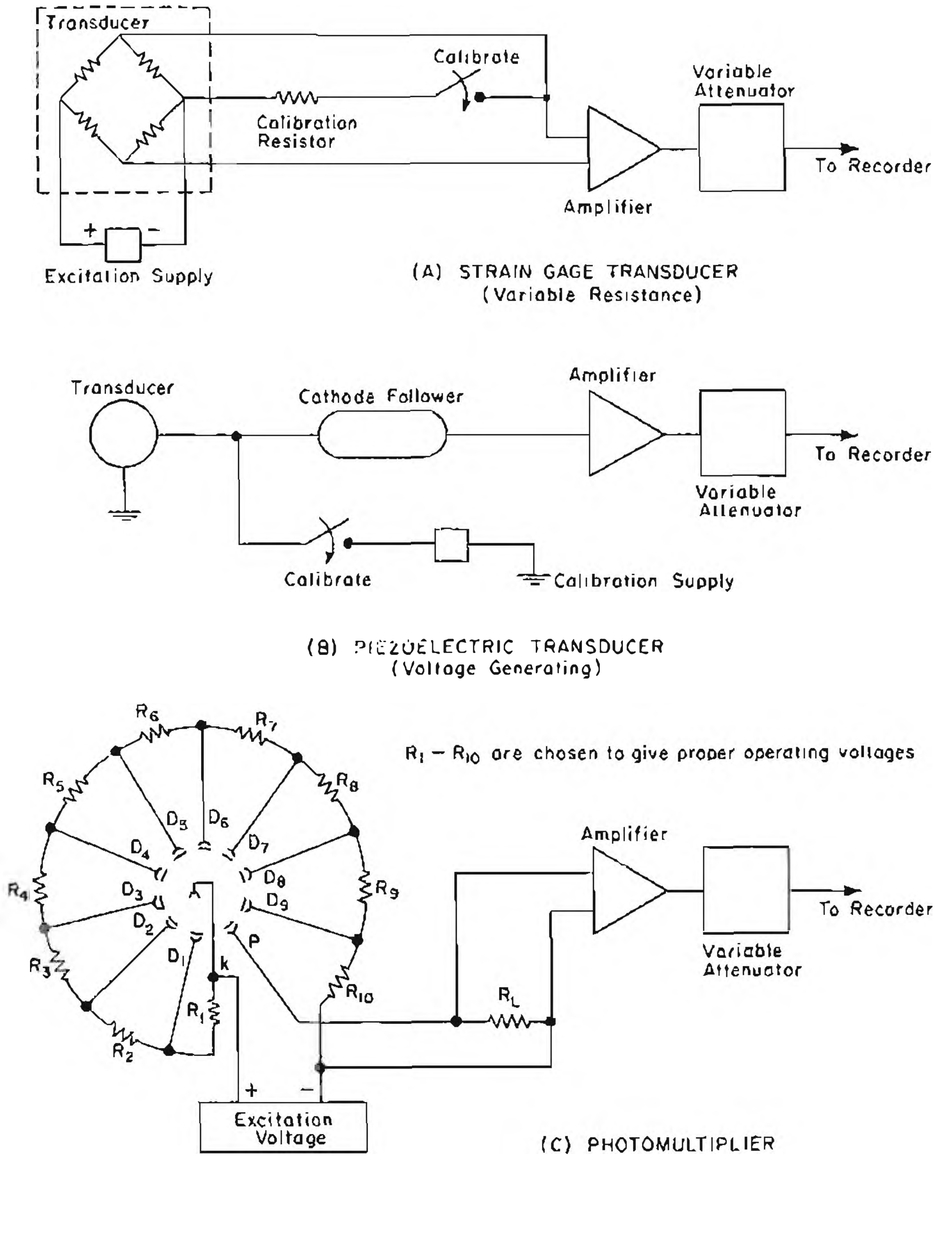

Figure 5-7. Typical Signal Conditioning Circuits

TABLE 5-4
SIGNAL CONDITIONING REQUIRED FOR VARIOUS TRANSDUCER TYPES

Transducer Type	Example	Approx. Full Scale Output	Average Excitation, Volt DC	Configuration	Amplifier	Linearization
Light detector	Photo-multiplier tube	10 mA	1500	Shunt load across P.M. gives volt. output	Impedance matching only	Not required
Light detector	Photo-voltaic tube	6 μA	Not required	Voltage source	DC	Not required
Strain gage	Pressure transducer	10 mV	5	Bridge	DC	Not required
Resistive	Pressure transducer	5 V	5	Voltage divider	May not be required	Not required
Semi-conductor	Pressure transducer	100 mV	5	Bridge	DC	Not required
Thermo-couple	Temperature measurement	25 mV	Not required	Voltage source	DC	Required
Piezo-electric	Microphone		Not required	Voltage source	AC	Not required
Piezo-electric	Pressure transducer	10 mV	Not required	Voltage source	High imped or charge	Not required
Capacitor	Microphone		150		AC	Not required
Moving coil	Microphone		Not required	Voltage source	AC	Not required
Variable reluctance	Microphone		Not required	Voltage source	AC	Not required

harmonic content[20]. A typical measuring system can record and analyze sound intensities in the range of 30 to 170 dB. On the same scale, a common conversation exhibits a sound pressure of 65 dB, the threshold of pain for humans is 120 dB, and the threshold of hearing is 0 dB. The data obtained may consist of a simple amplitude vs time record, or a more complex record of sound level vs frequency. The sound analyzer may also be used to indicate the energy of peak pressure at each frequency or band of frequencies desired. These data are useful when analyzing structural resonances and noise outputs from rocket motors. A microphone may be calibrated either by comparing it with a microphone of known calibration, or by using a sound source of known characteristics. For accuracies approaching ±0.3 dB error, the closed coupler reciprocity technique is used.

5-8 SIGNAL CONDITIONING AND RECORDING

5-8.1 GENERAL CONDITIONING AND RECORDING EQUIPMENT

The function of signal conditioning equipment is to provide an interface between a transducer and a readout device or a recorder. Signal conditioning consists of one or more of the following functions:

(1) Impedance matching and bridge completion

(2) Signal amplification or attenuation

(3) Transducer excitation

(4) Signal filtering or linearization

(5) System calibration.

Which of these functions the signal conditioning equipment must provide depends upon the type and range of the transducer, the input parameters of the recorder, the required frequency response, and the signal amplitude, duration, and character.

Typical signal conditioning requirements are shown in Table 5-4 and the signal conditioning equipment for several transducers is shown in Fig. 5-7.

The recorder selected must be capable of faithfully reproducing the highest frequency components of the input signal and yet have sufficient time base length to record the total event. Often there must be compromise in this respect because recorders which have long time bases, such as chart recorders, do not have the resolution or frequency response to record high frequency signals. In cases of long events where is is desired to observe high frequency signals, it may be necessary to restrict the recording to only a portion of the total event by means of appropriate triggering signals.

Impedance matching usually takes the form of an active device having a gain of approximately one, such as a cathode or emitter follower. Field effect amplifiers are also used with very high impedance devices such as piezoelectric transducers. In the case of some strain gage galvanometer-recorder combinations, the impedance matching consists only of resistors for damping and current limiting. A transformer may be used for impedance matching when there is an alternating current output from the transducer. Microphones and variable transformer transducers are representative of devices having an AC output.

Signal amplification includes the active devices necessary to amplify the transducer output so that it is of a magnitude acceptable to the recorder used. The attenuation function provides the range selection so that small signals may be resolved and yet large signals do not overdrive or saturate the recorder. In some situations the amplification and range selection are accomplished in the recorder. A good example of this type of instrument is the cathode ray oscilloscope.

Transducer excitation consists of providing the necessary operating voltage or current to the transducer. For variable resistance and strain gage devices this is in the range of 5 to 10 V DC. For capacitive devices and some photocells 150 V DC is required. The photomultiplier tube may require as much as 1500 V DC. Variable reluctance and variable transformer devices require an AC excitation of approximately 5 V.

Signal filtering is used to attenuate or segregate various frequency components of a transducer output signal. For example, a low-pass filter may be used to attenuate high frequency signals which are not necessary for data evaluation and may saturate the recorder or make evaluation difficult. A high-pass filter may be used to suppress a direct current offset or eliminate power supply variations and ripple. Band pass filters are useful for determining amplitude of a signal at a specified frequency. An instrument incorporating a variable band pass filter is known as a wave analyzer and is useful for evaluating sound and vibration data. Signal linearization is used when the output of the transducer is not a linear function of the input parameter. This is the case with thermocouples and hot wire devices such as anemometers. The linearizer may be as simple as a logarithmic converter or as complicated as a computer program operating on digitized data. Often the linearization is done manually using a calibration chart or curves after the data are recorded.

The field calibration of a measuring system usually takes the form of an electrical signal applied to the signal conditioning circuits because a direct mechanical calibration may be difficult to perform. In the case of variable resistance transducers such as transducers utilizing the strain gage or mechanovariable resistor, calibration can be made by connecting a resistor across the transducer element, simulating a known input signal.

As an example, consider the elementary strain gage circuits shown in Fig. 5-8. The first circuit (Fig. 5-8(A)) is probably the most simple that may be used with a strain gage. For this circuit the signal voltage may be represented by

$$V_s = V_b\left(\frac{R + \Delta R}{R + \Delta R + R_1} - \frac{R}{R + R_1}\right) \quad (5\text{-}2)$$

where

V_s = signal voltage due to the strain, volt

V_b = battery voltage, volt

R_1 = ballast resistor, ohm

R = strain gage resistance when relaxed, ohm

ΔR = change in strain gage resistance due to strain, ohm

The two terms in the parentheses of Eq. 5-2 represents the potential in the unstrained condition (the right term) and in the strained condition (the left term). By setting the value of the ballast resistor R_1 equal to the strain gage resistance R, a process that is often used in practice, the equation for the signal voltage can be reduced to

$$V_s = \frac{\epsilon F_g V_b}{2(2 + \epsilon F_g)} \quad (5\text{-}3)$$

where

F_g = gage factor, dimensionless

ϵ = strain, in. in.$^{-1}$

The simple bridge circuit of Fig. 5-8(B) effectively eliminates the DC component of signal that was present in the ballast circuit. Except for the elimination of the DC component, the magnitude of the signal voltage is identical to that of the ballast circuit provided the resistances R, R_1, R_2, and R_3 are equal.

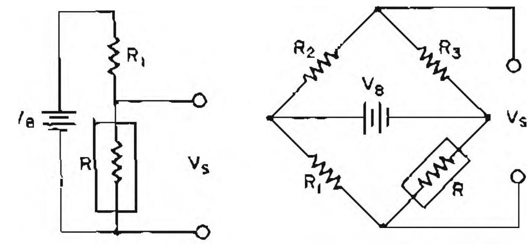

Figure 5-8. Simplified Strain Gage Circuits

There are limitations on the stability of most power sources and on amplifiers down stream from the strain gage circuits that make on-site calibration of strain gage circuits essential. Calibration practice is a relatively simple matter. Deliberate unbalance of the relaxed circuit may be created by switching a resistor across the strain gage, creating an artificial strain in the circuit and a corresponding reading on the output indicator. The change in resistance ΔR as a result of actual strain is

$$\Delta R = \epsilon F_g R \quad (5\text{-}4)$$

Shunting a resistor R_c across the strain gage when it is in the relaxed condition results in a resistance change

$$\Delta R = R - \frac{RR_c}{R + R_c} \quad (5\text{-}5)$$

By equating the resistance change from Eqs. 5-4 and 5-5, simplifying, and solving for strain, we arrive at the strain equivalent ϵ_c introduced as a result of switching the calibrating resistor R_c across the gage.

$$\epsilon_c = \frac{-R}{F_g(R + R_c)} \quad (5\text{-}6)$$

where

ϵ_c = electrically introduced equivalent strain, in. in.$^{-1}$

R_c = calibrating resistance introduced in shunt with the strain gage, ohm

In the case of capacitive transducers, a capacitor or a voltage source may be used for calibration depending upon where the calibration signal is applied. Voltage generating transducer systems are calibrated by applying a known voltage across the transducer output.

5-8.2 IMAGE CONVERTERS

An image converter is an electro-optical device used to intensify an image and/or to convert the input radiation into light of a different wavelength. Basically it consists of a transparent, conductive photo cathode upon which the object to be observed is focused, an electrostatic focusing system and a fluorescent viewing screen[21].

A common use for image converter tubes is in the electronic shutter. In this application, the image converter consists of a conductive photocathode, a conductive fluorescent screen, and a fine mesh electrode or control grid between the anode and cathode. A high voltage is maintained between the anode and cathode, and the converter tube is controlled by the potential on the grid. Exposure times as short as 5 nsec are available in commercial units. These units also offer image converter tubes sensitive to different wavelengths and with light gains of 50 or more.

5-8.3 METERS

In many instances, the recording of a transducer output is not required and an average value may be used to represent a measured parameter. This is often the case in sound and light intensity measurements, as well as temperature. For these applications, a hand-held portable instrument utilizing a meter movement offers quick set-up portability, and easily analyzed results.

The simplest photometer consists of a photovoltaic cell, usually selenium, and a microammeter calibrated in terms of the incident light intensity. A more sensitive unit contains a photoresistive cell (such as cadium sulfide), a battery, and a microammeter. Care should be taken when using all types of portable photometers to insure that the light seen by the instrument is the light to be measured and not background illumination or other light sources. Some photometers contain a lens system so that the observer can actually see the light source being measured.

Portable sound intensity measuring equipment consists of a microphone, amplifier, and meter calibrated in decibels. In addition some instruments may contain filters to restrict the audio bandpass of the meter.

Also available in hand held meters is the radiation thermometer. These instruments provide temperature measurements in the range of 60° to 3000°F. The instrument consists of an infrared detector and signal conditioning. The output is read on a meter, calibrated in temperature units.

5-8.4 CHART RECORDERS AND OSCILLOGRAPHS

A chart recorder is an instrument whic converts an electrical signal into a graph representation of the amplitude of the sign vs time. Thus, in combination with a transducer and signal conditioning, the chart recorder is used to give a record of the variations of a physical parameter vs time. The important parameters to consider when selecting a chart recorder include sensitivity, frequency response, number of channels, input voltage, impedance, power requirements, accuracy, resolution, and linearity. Chart recorders commonly are classified according to the method of converting the electrical signal to a chart reading and also according to the type of chart paper and writing method used. A brief description of the commonly used writing systems follows.

5-8.4.1 LIGHT BEAM GALVANOMETER AND PHOTOSENSITIVE PAPER (OSCILLOGRAPH)

This system uses a light sensitive paper which may be either the direct print type requiring only exposure to light to develop or the chemical process type which requires developing similar to ordinary photographic films. Those using the chemical process require less powerful light sources and have a higher upper frequency limit while the direct print type offers a usable chart immediately without any chemical processing required.

Galvanometers used with this system have sensitivities from 12 mA in.$^{-1}$ to 50 mA in.$^{-1}$ and frequency response from DC to 13,000 Hz, the higher frequencies being available only in the less sensitive galvanometers. Due to the low driving power required, these galvanometers may be used without amplifiers under certain conditions.

Also available are recorders using cathode ray tubes as a light source instead of the galvanometer and light used in the recorders mentioned. These units require special amplifiers to drive the cathode ray tube, but offer frequency response up to 1 MHz.

5-8.4.2 ELECTRODYNAMIC PEN MOTOR USING INK ON ORDINARY CHART PAPER

This system uses the least expensive chart paper. Frequency response is limited to 50 Hz or less depending on chart width and pen motor design. The simplest recorder consists of a pen motor similar to an ordinary meter movement. The trace is a curvilinear function of the input voltage, making analysis difficult. Another variation of recorder utilizing the pen motor principle incorporates a Scott-Russel mechanism to give a true rectilinear trace. An electronic feedback system may also be used to give a rectilinear trace.

5-8.4.3 ELECTRODYNAMIC PEN MOTOR USING TEMPERATURE SENSITIVE PAPER

This system uses a hot wire to mark a wax coated paper as it travels over a knife edge. The trace is rectilinear and upper frequency response may reach 150 Hz over small chart widths. Paper cost is exceeded only by the light sensitive types. Feedback may be used to increase linearity and give higher frequency response than is available with a simple amplifier circuit.

5-8.4.4 POTENTIOMETER RECORDER

This recorder uses a closed loop feedback system to position the pen. The frequency response is limited by inertia to less than 5 Hz, but accuracies of 0.1% are easily achieved.

5-8.4.5 SAMPLING RECORDER USING ELECTROSENSITIVE PAPER

This recorder has no moving parts except the paper feed mechanism. A series of fixed styli are positioned along the width of the chart that mark the paper when a voltage is applied. A decoding circuit is used to energize the proper stylus corresponding to the input voltage applied. Commercially available recorders offer sampling rates of 3000 samples sec^{-1} and chart speeds up to 10 in. sec^{-1}

5-8.4.6 MAGNETIC TAPE RECORDER

This instrument is perhaps the most versatile type of recorder. Two types of analog recording are used, recording up to 14 channels on 1-in. tape or seven channels on 0.5-in. tape. In the frequency modulated (FM) mode, a carrier frequency is generated and frequency modulated by the input signal. This method offers response down to DC but has a limited high-frequency response. Typical frequency response of an FM system is DC to 625 Hz at 1-7/8 in. sec.$^{-1}$, and DC to 400 kHz at 120 in. sec.$^{-1}$ In the direct mode, the signal amplitude variations are impressed directly on the tape.

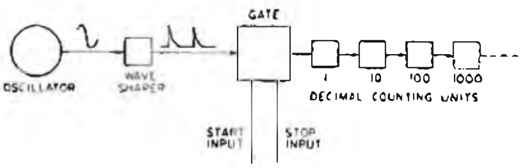

Figure 5-9.
Counter Chronograph Block Diagram

Simpler electronic amplifiers are required to drive the tape heads but the low frequency response does not extend to DC. Typical frequency response is 100 Hz to 6 kHz at 1-7/8 in. sec.$^{-1}$ and 400 Hz to 1.5 MHz at 120 in. sec.$^{-1}$ Most recorders offer plug in or switchable record and playback amplifiers so that either mode may be used. A signal level of 0.1 to 1 V is needed to drive most commercial recorders. One of the main advantages of tape recording is that it can play back at a different speed than was used for recording. This allows the user to scan large volumes of data quickly or play back high-speed event slowly for analysis. Another advantage is that the data are still available in electrical form and may be played back directly into wave analyzers or computers. The tape is reusable.

5-8.4.7 CATHODE RAY OSCILLOSCOPE

The oscilloscope offers the highest frequency response and most versatility of any measuring instrument. It basically consists of a cathode ray tube, associated power supplies, amplifiers, and an electronic time base. Input sensitivity ranges form 50 mV cm^{-1} to 20 V cm^{-1}, and the oscilloscope may be used with voltage divider probes, lowering the sensitivity to 20,000 V cm^{-1}. Frequency response for random signals using direct amplification extend from DC to 100 MHz or higher, while sampling techniques extend the upper frequency limit to 4 GHz for recurring signals. Oscilloscopes are available having as many as 4 simultaneous traces, and time sharing techniques may be used to provide more traces, if needed.

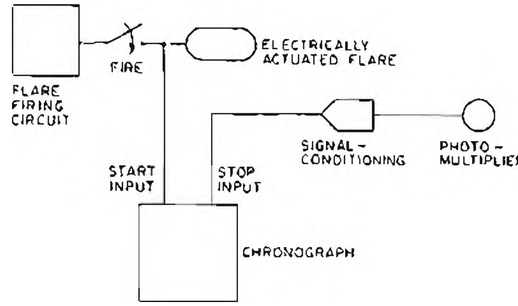

Figure 5-10. Functioning Time Measurement

Oscilloscope plug-ins also provide signal conditioning units and spectrum analyzers which may be used to analyze data. Common practice is to record the oscilloscope trace photographically, but storage oscilloscopes are available which will retain the image on the cathode tube for analysis.

5-8.5 TIME MEASUREMENT AND RECORDING

The applications of time measurement in pyrotechnic device testing range from a simple stopwatch determination of flare burning time to the measurement of initiator functioning time with microsecond resolution. Since electronic signals are often used to initiate and measure the output of pyrotechnic devices, the basic instrument for time measurement is the electronic counter chronograph. If electronic signals are not available, they may be obtained from mechanical phenomena by means of switches or transducers. The block diagram of a typical counter chronograph is shown in Fig. 5-9. The output from a quartz crystal oscillator is shaped to produce square waves or pulses and then passed through a gate. The gate is actuated by a signal on the start terminal and opened by a signal on the stop terminal. The pulses out of the gate are then counted to give a digital representation of the time the gate was actuated. If a 1 MHz crystal oscillator is used, the first decimal counter will record μsec. As many decimal counting units may be used for the seconds digit and any larger count required. Commercially available counters exhibit counting rates to accommodate frequencies greater than 10 MHz, giving a least significant digit of 0.1 μsec. There is an inherent uncertainty due to the gating technique of ± one count in the least significant digit as well as the inaccuracy due to time base error. A typical set up for functioning time measurement of an electrically actuated flare is shown in Fig. 5-10. In this example the firing current to the flare triggers the counter, and the light output from the flare stops the counter. Similar systems may be used to measure the delay time in pyrotechnic delay mechanisms.

In addition to direct timing of events using the chronograph, it is often desirable to record a time signal along with the experimental data. Theoretically the chart speed on a recorder is a known, linear function of time and is usually specified as a chart length per unit time. However, inaccuracies due to motor speed variation may be present, especially in field and portable set ups where a frequency-stable power supply is not available. It may also be necessary to synchronize two or more recorders with a common time reference. For these applications, an external oscillator is used to supply a time signal to all recorders. This signal is usually a square wave or pulse signal and may be generated by a crystal oscillator, a tuning-fork oscillator, an astable multivibrator, or a mechanical system such as a motor driven cam and switch, depending upon the time scale desired and the accuracy required.

5-9 SYSTEMS

5-9.1 GENERAL ASPECTS OF SYSTEMS

A measuring system consists of a recorder, signal conditioning equipment, and one or more transducers. When integrating these individual components into a system, several factors should be taken into consideration such as voltage levels, impedance matching, frequency response, accuracy and resolution desired, environmental effects, signal vs noise ratio, power requirements, ease of operation, and analysis of data. Of primary importance is the voltage and impedance compatibility of the transducer, signal conditioning, and recorder. Most transducer manufacturers offer signal conditioning units which are compatible with their transducers as well as similar units from other companies.

In addition, many general purpose units are available, often as accessories for specific recorders. The manufacturers' recommendations should be followed in using these units. Consideration should be given to excitation voltage and current available, input impedance, signal amplification, calibration facilities, and output voltage and current. The effects of long interconnecting cables on signal level and high-frequency attenuation should be considered as well as the effects of extraneous signals due to ground potentials and noise pickup. Portable, mobile, and field instruments also require protection from environmental effects such as moisture, dust, shock, and vibration.

Also, the effects of power supply voltage and frequency variation should be considered when operating from a portable power source or a long distance from primary power lines. Often accuracy must be sacrificed in a field instrumentation system in order to gain portability, reliability, or ease of operation. The use of solid-state devices has made portable, battery-operated instruments practical, and their use should be considered whenever designing a portable or field measuring system.

5-9.2 FIELD SYSTEMS

The basic distinction between a field instrument and a range instrument is portability. A field system may be easily moved and set up at any location where measurements are desired. This allows the testing of pyrotechnic devices under conditions more nearly approximating those in which the device will be used. A tactical system has even more restricted specifications such as small size, light weight, and fast, reliable operation. The basic concept of tactical measuring systems requires that all data analysis also be done in the field. One example of a tactical measuring system is the XM8 Chemical Agent Alarm[22]. This unit is designed to give an alarm whenever toxic agents are present. The unit will detect quantities of toxic agent vapor below lethal concentrations in the presence of smoke, dust, motor vehicle exhaust, or other pollutants normally found on the battlefield. The instrument weighs 18 lb and may operate in temperatures from $-40°$ to $120°F$ for 12 hr using a self-contained power supply.

An example of a field used system is the Sound Analysis Laboratory developed by Frankford Arsenal[20]. This unit consists of a trailer mounted anechoic chamber, measuring and recording instruments, and a gasoline engine-driven generator. The mobility of this unit enables it to be moved to the test area and set up in a short time. Instruments are available for recording and analyzing the sounds emitted from a pyrotechnic device and also for measuring the velocity of a projectile. Small devices may be mounted in the anechoic chamber and tested under known acoustic conditions.

5-9.3 LABORATORY AND RANGE SYSTEMS

Although many pyrotechnic measuring systems have been developed for specific uses, the techniques used may be of interest to anyone faced with a situation requiring measurement of pyrotechnic characteristics. The unique aspects of most systems are the test fixtures or chambers, so the choice of transducer is not restricted to only the make and model specified in the original system. Similar transducers may be used as long as the signal conditioning equipment is adjusted to suit the new transducer.

In the MAPI flare measurement system the transducer consists of an array of photocells which are scanned to give the light intensity at a given location[23]. Computer techniques are used to compute the candlepower at each location and also the average candlepower. The data reduction equipment utilizes an automatic optical reader which analyzes the pulse height from an oscilloscope picture. The output is fed into a card punch which generates data cards in the proper format for computer processing.

Many times a measurement system is specified in the Military Specification for the pyrotechnic item. For instance, MIL-C-60303 contains the requirements for a facility to obtain the burning time and particle dispersion of a gas generating device[24]. Other Military Specifications give descriptions and requirements for facilities for measurement of a specific parameter such as flare candlepower without reference to any particular pyrotechnic item[15].

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CHAPTER 6

TESTING

6-1 GENERAL DISCUSSION

6-1.1 THE TESTING PROGRAM

Test programs at various stages of the development and manufacture of pyrotechnic devices are required to assure that ammunition delivered for field use is free of defects, safe under all field conditions, and that it performs as intended.

This chapter presents the tests designed to evaluate safety, reliability of functioning, and the qualitative and quantitative methods currently in use for measurement of pyrotechnic effects.

For personnel unacquainted with pyrotechnic ordnance, purchase descriptions of existing military pyrotechnic devices which contain minimum requirements and instructions are a guide for tests of similar new developments.

A typical flare Purchase Description[1] contains a list of:

(1) Applicable Documents—including specifications, standards, drawings, and other publications

(2) Requirements—quantities and performance characteristics

(3) Quality Assurance Provisions

(4) Preparations for delivery

(5) Special Notes.

The basic safety and reliability tests are those specified by Military Standard (MIL-STD) designations which are approved by the Department of Defense to assure uniformity of test conditions to judge suitability under conditions of military usage.

A list of applicable Military Standards is contained in Table 6-1. Note that some tests are designed strictly to assess safety. Ammunition need not function after these tests. After the other tests, correct operation is demanded. Each specification listed contains the details needed to perform the tests. General discussions of the standards are contained in other military handbooks[2].

6-1.2 KINDS OF TESTS

The different types of tests used in the process of developing pyrotechnic ammunition are described in the paragraphs that follow.

6-1.2.1 DEVELOPMENT TESTS

Development tests are performed by the designing agency to be sure that component subassemblies or complete ammunition function in the manner for which they were designed. These tests evaluate the latest efforts of the designer and may be repeated until successful results are obtained. The ammunition is subjected to a series of tests that serve to determine that it is safe and reliable, and to ascertain its readiness for test and use by field forces. Part of the task of planning an ammunition development project is to specify the type of test, the order of execution, and other testing details.

Development tests are usually made in the laboratory or developer's testing facility and need not include all of the parts of the complete device.

TABLE 6-1

TESTS UTILIZED IN THE DEVELOPMENT OF PYROTECHNIC ITEMS

Type of Test	Specification	Procedure	Specification Title or Procedure Title	Passing Criteria	Using Service
a. Drop (Impact)	MIL-STD-331	Test 103	Forty-foot Drop	S	A, N, AF
	MIL-STD-331	Test 111	Five-foot Drop	O	A, AF
b. Rough Handling	MIL-STD-331	Test 101	Jolt	S	A, N, AF
	MIL-STD-331	Test 102	Jumble	S	A, N, AF
	MIL-STD-810	Meth 516	Environmental Test Methods for Aerospace and Ground Equipment Shock	O	AF
c. Vibration	MIL-STD-331	Test 104	Transportation Vibration	O	A, N, AF
	MIL-STD-810	Meth 514	Vibration	O	AF
	MIL-E-5272	XII or XIV	4.7 Vibration Tests		
	DPS-1190		The Development of an Engineering Tests Standard covering the Transportation Environment of Material	O	A
d. Radiation	BUWEPS Instruction 5101.2A of 26 Apr 1962		BUWEPS Code PREN controls all RAD HAZ Testing	S	N
	MIL-P-24014		Preclusion of Hazards from Electromagnetic Radiation to Ordnance, General Requirements for	S	N, AF
e. Aircraft Survivability	MIL-STD-331	Test 201	Jettison (Aircraft safe Drop) (Fuzes)	S	A, N, AF
	MIL-STD-331	Test 202	Jettison (Simulated Aircraft Safe Firing from Ground Launcher) (Rocket Type)	S	A, N, AF
	MIL-STD-331	Test 203	Jettison (Simulated Aircraft Safe Drop, from Ground Launcher)	S	A, N, AF
	MIL-STD-331	Test 204	Jettison (Aircraft Firing) Rocket Type	S	A, N, AF
	MIL-STD-331	Test 205	Jettison (Aircraft Safe Drop) (Fuze System)	S	A, N, AF
	MIL-STD-331	Test 206	Accidental Release (Low Altitude, Hard Surface)	S	A, N, AF

TABLE 6-1

TESTS UTILIZED IN THE DEVELOPMENT OF PYROTECHNIC ITEMS (Cont'd)

Type of Test	Specification	Procedure	Specification Title or Procedure Title	Passing Criteria	Using Service
e. Aircraft Survivability (cont'd)	MIL-STD-331	Test 209	Missile Pull Off from Aircraft on Arrested Landing (Ground Launcher Simulated)	S	A, N, AF
	MIL-A-8591		Carrier Suitability Remarks (Aircraft Catapult and Arrested Landing Test Conducted by NATC Patuxent River, Maryland)	S	N, A, AF
f. Firing Train Interrupter	MIL-STD-331	Test 115	Static Detonator Safety	S	A, N, AF
g. Bullet Impact	SMUPA-VL 222		Standard Procedure for Rifle Bullet Impact Tests	S	A
	NAVWEPS WR-50 dtd 13 Feb 64	Par. 5.2	Warhead Safety Tests, Minimum for Air, Surface and Underwater Launched Weapons (excluding Mine and Nuclear Warheads)	S	N, AF
h. Kinetic Heating			Remark (No Standard tests in use by the Navy, Army or Air Force)		
i. Miscellaneous	MIL-STD-331	Test 105	Temperature Humidity	O	A, N, AF
	MIL-STD-810	Meth 507	Humidity (Cycling)	O	AF
	MIL-STD-810	Meth 501	High Temperature	O	AF
	MIL-STD-810	Meth 502	Low Temperature	O	AF
	MIL-STD-810	Meth 503	Temperature Shock	O	AF
	MIL-STD-331	Test 106	Vacuum Steam Pressure	O	A, AF
	MIL-STD-331	Test 107	Salt Spray (Fog)	O	A, N
	MIL-STD-810	Meth 509	Salt Fog	O	AF
	MIL-STD-810	Meth 510	Sand and Dust	O	AF
	MIL-STD-810	Meth 513	Acceleration	O	AF
	MIL-STD-331	Test 108	Waterproofness	O	A, AF
	MIL-STD-331	Test 114	Rough Handling (Packaged)	O	A
	BUWEPS Weapons Requirement WR-11		Design and Test of Packaging, Packing, Shipping and Handling Equipment for Weapon System Components	O	N

TABLE 6-1

TESTS UTILIZED IN THE DEVELOPMENT OF PYROTECHNIC ITEMS (Cont'd)

Type of Test	Specification	Procedure	Specification Title or Procedure Title	Passing Criteria	Using Service
i. Miscellaneous (cont'd)	Ordnance Part 8837375		Picatinny Arsenal Experimental Testing Criteria for Shipping containers	O	A
	MIL-STD-331 MIL-STD-810	Test 110 Meth 508	Fungus (Components only)	O	AF
	MIL-STD-810	Meth 512	Leakage (Immersion)	O	AF

Tests Not Named in Body of Chart:
MIL-STD-331 - Fuze and Fuze Components, Environmental and Performance Test for Tests 109, 112, 113, 207, 208, 210, 211, 212, 301, 302, 303.
MIL-E-5272 - Environmental Testing, Aeronautical and Associated Equipment, General Specification for
MIL-R-22449 (WEP) - Requirement (Certification) for Pyrotechnic Items

All tests except DPS-1190, MIL-STD-331 Test 114, MIL-STD-810 Method 516, BUWEPS Weapon Requirement WR-11 and Ordnance Part 8837375 are performed on unpackaged items. Packaged as well as unpackaged items are tested under MIL-STD-810 Method 514.

Key to last two columns.

Passing Criteria: S- safe O - safe and operable
Using Service: A-Army, N-Navy, AF- Air Force.

6-1.2.2 EVALUATION TESTS

Evaluation tests are made to assess the usefulness of a pyrotechnic system. It is used to expose the characteristics of hardware to observation by personnel experienced with pyrotechnic applications. An evaluation of a flare launcher[3], for example, includes a description of the launcher, evaluates projected altitude, illumination duration, effects of water soaking, day and night range, and ability to penetrate foliage; compares the performance of cal .38 with cal .45 cartridges; and makes recommendations.

Evaluation tests are usually carried out at a test center under field conditions using the complete device.

6-1.2.3 SERVICE TESTS

Service tests are intended to determine the suitability of hardware for use by the military under field conditions. They compare the hardware with requirements set down in the documents for the device being tested. The tests are always carried out on the complete device under field conditions.

Acceptance tests are one form of service test.

6-1.2.4 SURVEILLANCE TESTS

Surveillance tests are made on specific lots of ammunition taken from storage to determine if changes are needed in components to provide satisfactory operation as well as to determine the degree of degradation of the original lot[4]. Such tests should include adequate sampling of the lot to assure true representation and isolation of troublesome components and adequate tests to assure satisfactory performance of renovated ammunition. Tests of this nature will salvage lots of satisfactory ammunition whenever possible.

6-1.2.5 MALFUNCTION TESTS

Malfunction tests are carried out whenever failures have occurred[5]. The rationale and planning for such tests is usually the responsibility of the investigator. Special tests are applied to pinpoint the cause of failure and for recommending corrective action.

6-1.2.6 NATO TESTS

NATO tests are prescribed for safety and environmental survival of all ammunition planned for use by NATO countries. Engineering design tests are listed for airborne devices for both unpackaged stores and packaged stores. An approved test series does not currently exist.

6-2 LIGHT

6-2.1 GENERAL

Light producers may be tested by use of human observers, simple electrical light detectors, or complex arrays of light detectors coupled to recording instruments and to computers for analysis of the light intensity and spectral content as a function of time.

Observers are used in many field situations that are difficult to assess by instrumentation systems and hence play an important role in the ultimate testing of pyrotechnic light producers. Many test programs for quality assurance of existing candles and the development of new types are performed indoors at large military installations having flare tunnels. A few instrumented outdoor sites are available to evaluate the light output from complete pyrotechnic ammunition under a semblance of field conditions.

6-2.2 LABORATORY TESTS

The candle of a pyrotechnic device is usually tested as a separate component in development, production, and quality control efforts. Candles with outputs up to 10^6 candlepower are commonly tested in areas equipped to contain the burning candle safely and to measure the emitted light under controlled conditions. Fig. 6-1[6] shows typical hearths or fireplaces and light tunnels used by the military for indoor measurements. These facilities are very well suited for making comparative measurements of burning time and candlepower of flares, but caution is required in relating values to those obtained in different tunnels, outdoor facilities, and actual end item conditions. Large variations can easily occur depending on the test system, test procedures, and the inherent variability of the flares. If the candle is tested with its burning surface upward, for instance, it will give a larger reading than if faced downward — due to the resulting differences in flame shape and smoke patterns.

Usually large volumes of smoke issue from the test flare which can reflect light or obscure the flame depending upon the motion of the smoke. Blowers and dampers are used to adjust the wind velocity to maintain control of this variable. Light intensity measurements in tunnels are affected by the following variables:

(1) Power density radiated by flare

(2) Area of the flare in the field of the photocell

(3) Smoke screening the flare from the photocell

(4) Field of view of the photocell optical system

(5) Reflectivity of the background

(6) Accuracy of the spectral correlation

(7) Accuracy of the intensity calibration.

The flare is not truly an isentropic source as assumed in calculations because flux is not radiated uniformly over the entire burning surface. Radiation from the cylindrical sides may be twice that from end on. Measurements in tunnels normally are made from the side of the flare.

Intensity readings also will be incorrect if the field of the optical system includes only a portion of the flame produced by the flare. The entire flame produced by the flare should be in the field of view of the photocell and any light reflected from the smoke in the

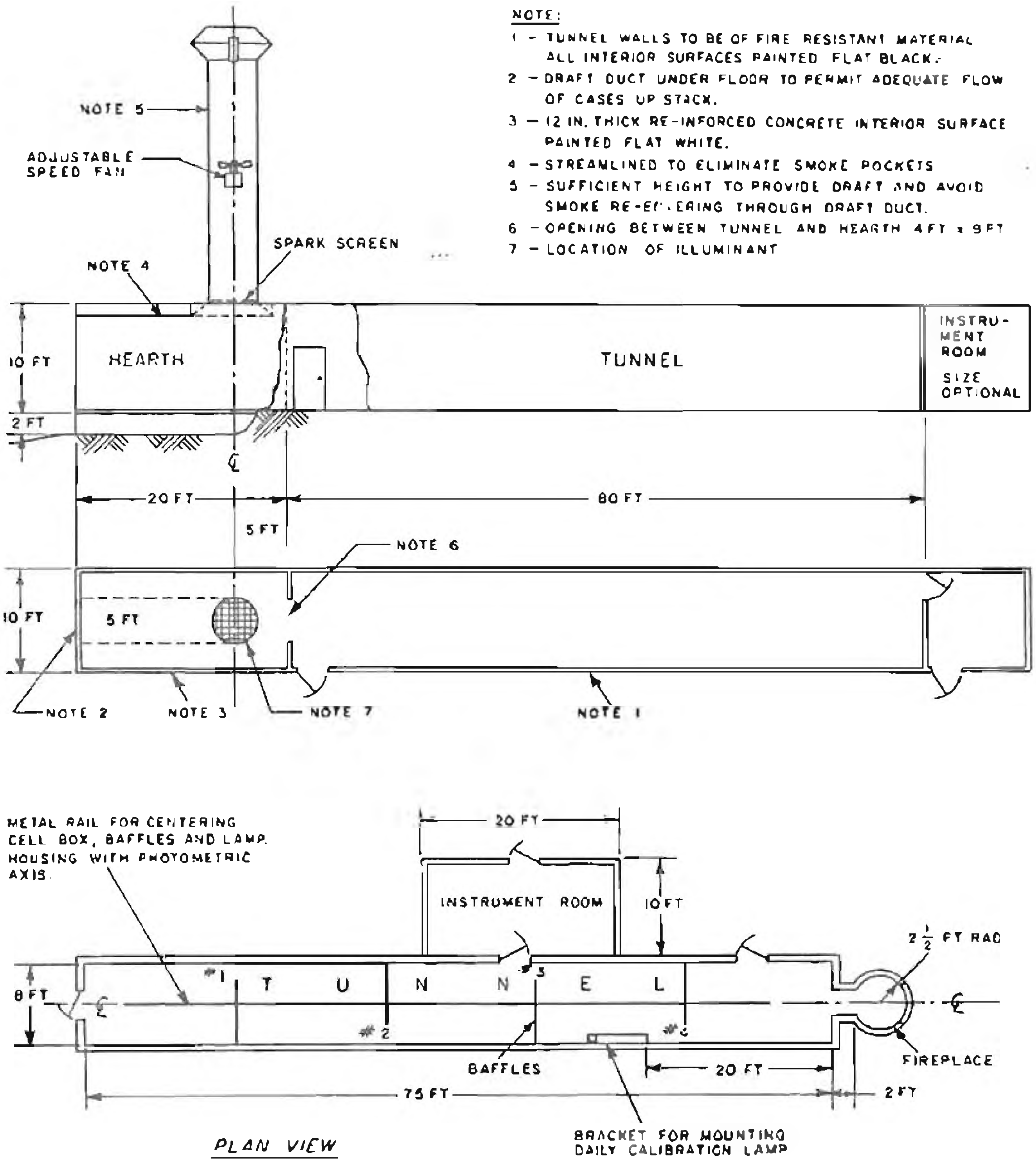

Figure 6-1. Typical Range Tunnels for Flare Testing

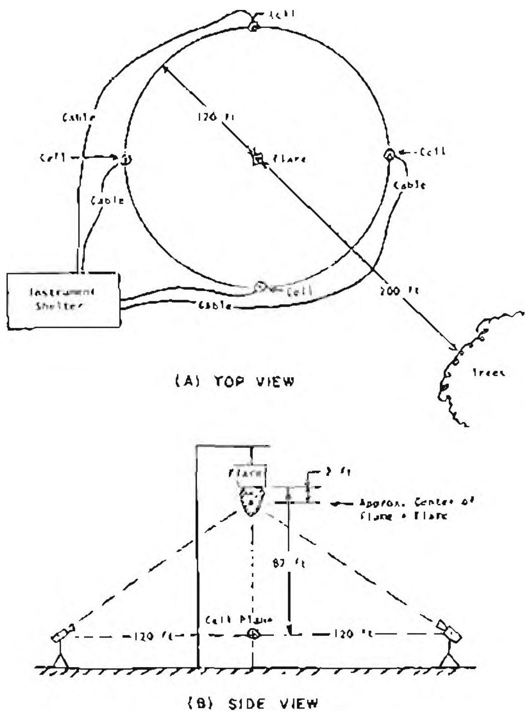

Figure 6-2.
Typical Outdoor Flare Test Facility

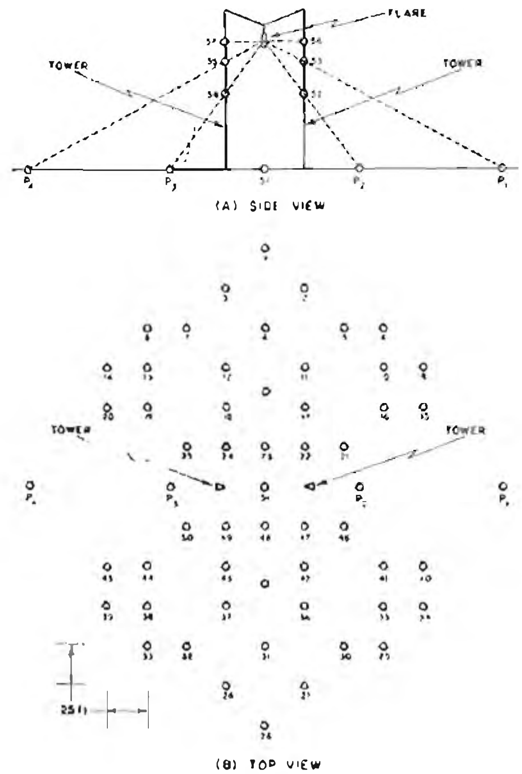

Figure 6-3.
Photocell Layout at MAPI Test Site

vicinity of the burning flare should be kept to a minimum.

Background reflections can produce particularly large errors in the measurements and should be avoided. Apparent increases up to 40% have been noted by reflections from the tunnel floor. It is necessary to restrict the view of the measuring instrument to that portion of the flare producing the light. Spectral correction conforming to the response of the International Commission of Illumination and intensity calibration with standard sources for the test equipment are also required.

The practical difficulties in measuring true candlepower of pyrotechnic flames makes it desirable to refer to candlepower measured in accordance with a given specification[6], nevertheless, measurements made under comparable conditions are valuable to rate light output and to maintain quality standards.

The light output of small arms tracer projectiles is measured in a spinner that spins the tracer projectiles at high cyclic rates (up to 130,000 rpm) which simulates the down range flight of the projectile. Tracer light is observed by a photocell the signal of which is fed to an oscilloscope. The trace is then recorded photographically. As a result of these laboratory tests, costly firing programs can be minimized. Typical output exhibited by cal .50 tracer is 600-900 candlepower[7]. Detailed test procedures are contained in Ref. 8.

6-2.3 FIELD TESTS

The flame size and volume of smoke produced by some flares such as the XM165 are too great for indoor tests. Such flares are tested outdoors at test sites that are relatively flat open areas approximately 400 ft in diameter and have a means of suspending the flare at least 80 ft above the center of the plane containing the photocells (Fig. 6-2).

The Multi-Aspect Assessment of Pyrotechnic Illumination (MAPI) site at Naval Ammunition Depot (NAD), Crane, Indiana, is an example of such a site. It contains a gridwork of cells at various angles on a ground plane which are directed at a flare suspended 80 ft above the center of the gridwork between two towers (see Fig. 6-3[9]). The output from the cells is fed to recorders and data processing equipment to determine average candlepower as a function of time and radial distribution about the suspended flare.

Picatinny Arsenal has recently developed instrumentation that will permit dynamic assessment of actual rounds as fired by a variety of launchers. The round is fired over a matrix of detectors which will respond only if a predetermined light level has been exceeded. The detector field is sampled periodically at a fixed rate and visual presentation of the performance is obtained electronically at a central control station. This facility being installed at the Yuma Proving Ground in Arizona will offer more realistic estimates of the effects of environmental conditions, the contributions made by associated flare hardware, and the effect of the ballistic forces on candle performance.

Often the most practical method of evaluating light effects is visual observation supplemented with photography. Small arms tracers, for example, are viewed by two observers located 75 yd perpendicularly to the line of the trajectory[10]. A camera is located in front of the weapon in such a way that the field of view covers a distance of 15 to 125 yd on the trace path. Lights are located at the 15- and 125-yd points along the trace path to serve as markers since the tests are made in darkness. The camera is mounted on a tripod that can be tilted after each shot so that 25 cartridge traces may be recorded on one film plate.

An instrumented test range has been operational since 1970 at the Yuma Proving Ground[11]. The range permits the evaluation of pyrotechnic flares under dynamic conditions. The output (illumination, duration, and pattern) of the flares is measured under conditions approximating tactical situations.

The light sensing system consists of 361 photocell sensors arranged in a square of 19 by 19 rows with a separation of 450 ft between sensors. The sensors are highly stable silicon solar cells corrected with filters to the response of the human eye. The light received is compared with either a 0.05 or a 0.20 footcandle reference level, as desired. Suitable instrumentation reads the output of the sensors sequentially–it takes about 6 msec to scan the complete field and transmits the output to the display and recording units. At the same time three cinetheodolites track and record the space position of the descending flares.

The test range has three limitations: (1) the system measures only two threshold levels (0.05 and 0.20 footcandle), (2) testing periods are limited to moonless nights, and (3) data acquisition and reduction man-hours are excessive. However, preliminary tests successfully evaluated pyrotechnic luminants under actual firing conditions. Developments are currently under way to alleviate the limitations.

6-2.4 COLOR MEASUREMENT

Color of light-producing illuminants is assessed by visual observation of flare burning or by the use of instruments that can dissect the light into characteristic colors or wavelengths. Quantitative spectral data allow the engineer to observe dilution of a desired color by unwanted colors, thus enabling him to make corrections. These procedures may also be used for quality control in the production of flares.

A flare radiometer has been developed by Picatinny Arsenal for rapid and simple spectral examination of illuminating flares and

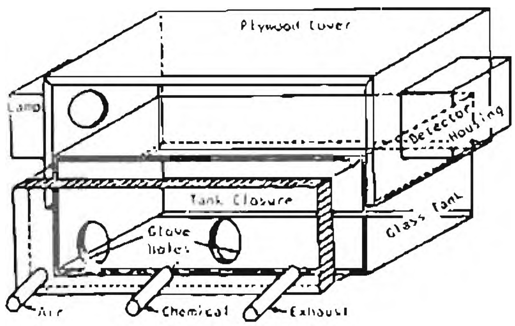

Figure 6-4.
Chamber for Preliminary Observation of Smoke Producers

similar pyrotechnic devices[12]. The instrument consists of ten interference filters covering the visible spectral region. The filters are chosen to have a uniform spectral response at a precisely chosen peak wavelength. Miniature photocells positioned behind each of the ten filters have trimming resistors which are adjusted to provide a uniform output across the spectrum. When the radiometer is directed at a source, each filter is illuminated in sequence from blue to red by a motor-driven elliptical mirror. The optics are arranged so that every cell sees precisely the same field of view. A marker cell is provided to identify the beginning of each sweep.

Many modern facilities are equipped to digitalize the analog data of the type described for use in immediate computation or storage on magnetic tape for later use. Present equipment will sample analog data at the rate of 50,000 times per second and provide digital output with a definition of 0.1% (Ref. 13). Up to 30 spectral distributions per second may be calculated with computers, a task requiring 30 manhours by manual methods. Correction for human eye response is made automatically. Candlepower is computed by integration of the luminous intensity over the wavelength range of interest. Dominant wavelength and purity are determined by multiplying the radiant energy distribution by the three color distributions of the International Commission of Illumina-

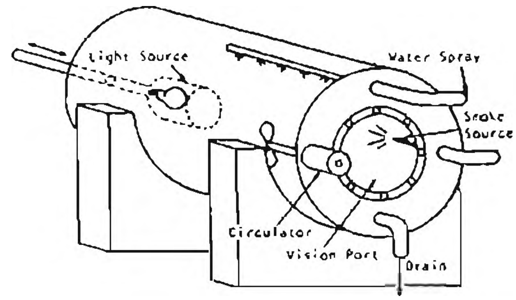

Figure 6-5.
Laboratory TOP Measurement Chamber

tion, wavelength by wavelength. Chromaticity coordinates are calculated from the integrals under the three product curves and plotted in a chromaticity diagram to determine dominant wavelength and purity.

6-3 SMOKE

6-3.1 GENERAL

In early stages of development—when gross effects are sought—much is gained by simple, visual observation of the smoke produced. Visual observation is usually followed with still and motion photography to make better estimates of volume and color. In the case of screening smokes, quantitative measurements of the obscuring power can be made by measuring the attenuation of light by the smoke. Signaling smokes have four properties of importance to the military- color, visibility, duration, and volume.

Since instability is one of the main features of the smoke cloud, its ability to persist is usually judged by comparing it with smoke from a control burned simultaneously within close proximity of the test smoke generator. Care must be taken so that two independent plumes are observed under similar atmospheric conditions. For smoke detection instrumentation see par. 5-4.

6-3.2 LABORATORY TESTS

The test volume of the equipment in use to measure smoke production may vary from a few cubic feet to several thousand cubic feet[14]. The test chambers usually provide glove holes for manual manipulations; parts or fittings for air, smoke, and exhaust; and an optical system for obscuration measurement as is shown in Fig. 6-4. Some chambers also provide means for controlling the temperature and humidity of the system.

The screening value of smokes is determined by a figure of merit known as the total obscuring power (*TOP*), the area in square feet that can be obscured by a pound of smoke formulation.

TOP can be determined either by measuring the light attenuation produced by smoke or by adjusting the position of a target located in the smoke until the target is obscured in chambers similar to the one shown in Fig. 6-5. The light attenuation method changes the concentration of the smoke and maintains a constant distance from the light source to the photocell.

The light transmission method of evaluating obscuring power[15] is based on the Beer-Lambert relationship

$$I = I_o e^{\epsilon CL}, c \tag{6-1}$$

where

I = observed light intensity, c

I_o = initial intensity without smoke present, c

C = concentration of smoke, lb ft^{-3}

L = path length, ft

ϵ = scattering or extinction coefficient, ft^2 lb^{-1}

TOP is defined as

$$TOP = \frac{1}{C_t L_t} \tag{6-2}$$

where

C_t = concentration of smoke required for obscuration (the weight of smoke producing formulation used divided by the chamber volume), lb ft^{-3}

L_t = fixed distance between the lamp and the photocell, ft

The concentration of smoke from Eq. 6-1 is related to the concentration expressed in Eq. 6-2 by the relation

$$C = YC_t, \text{ lb ft}^{-3} \tag{6-3}$$

where Y is the yield or the ratio of the weight of aerosol produced to the unit weight of smoke-producing composition. These three equations, Eqs. 6-1, 6-2, and 6-3, can be combined:

$$TOP = \frac{\epsilon Y}{\ln(I_t/I_o)} \tag{6-4}$$

where I_t is the transmitted light intensity under obscuration conditions. A ratio of 0.0125 for I_t/I_o has been adopted as the obscuration point by some researchers based on physiological studies of the discriminating capacity of the human eye. Introduction of this limit into Eq. 6-4 yields

$$TOP = \frac{\ln(I_t/I_o)}{(\ln 0.125)CL_t} \tag{6-5}$$

For fixed chambers and weights of smoke-producing compounds, this equation reduces to

$$TOP = K \log(I_t/I_o) \tag{6-6}$$

If dilute smokes are used, so that particle coalescence is minimal, this relationship is valid and useful for rating the quality of smoke mixes.

A cylindrical steel tank with dimensions of 28 ft long, and 8 ft in diameter has been used successfully by NAD Crane[15]. Three mixing fans, equally spaced along one side of the chamber, provide for homogeneity of the chamber contents. Two rows of eight 60-W lamps run the length of the chamber to provide illumination for a track-mounted movable target that may be viewed through a port. A flood light, optically in line with a collimator, and a photocell provide for attenuation measurements.

Smoke producers are activated at the tank center and their product is stirred constantly by the fans. Light attenuation measurements are begun three minutes after activation of the smoke producer; and a minute later visual observations are begun to determine obscuration, usually at five minute intervals. Since a number of units are evaluated, minimum light transmission and maximum target obscuration are used as representative values for the particular device.

Titanium tetrachloride (FM) is used as a standard in this instance for convenience and because it is less corrosive than FS (sulfur trioxide-chlorosulfonic acid solution) that is usually used for calibration.

6-3.3 FIELD TESTS

In the field, observers are often used in the assessment of smoke producing ammunition. A number of observers are commonly used in order to obtain statistically significant results. Any person with serious visual defects is eliminated, usually by tests made immediately before the observation. Color blindness of observers is particularly searched out when testing colored smokes. Observers are sometimes supplied with binoculars during tests of smoke. They compare performance with controls having well-known characteristics.

Wind tends to produce both good and bad effects in smoke production and use. In outdoor tests of smoke producers, wind speed and direction are normally recorded. Wind may aid in distributing the smoke for screening purposes. If the smoke is produced continuously, wind often helps to pinpoint a marked area by observing the origin of the plume. On the other hand, the wind may scatter the smoke.

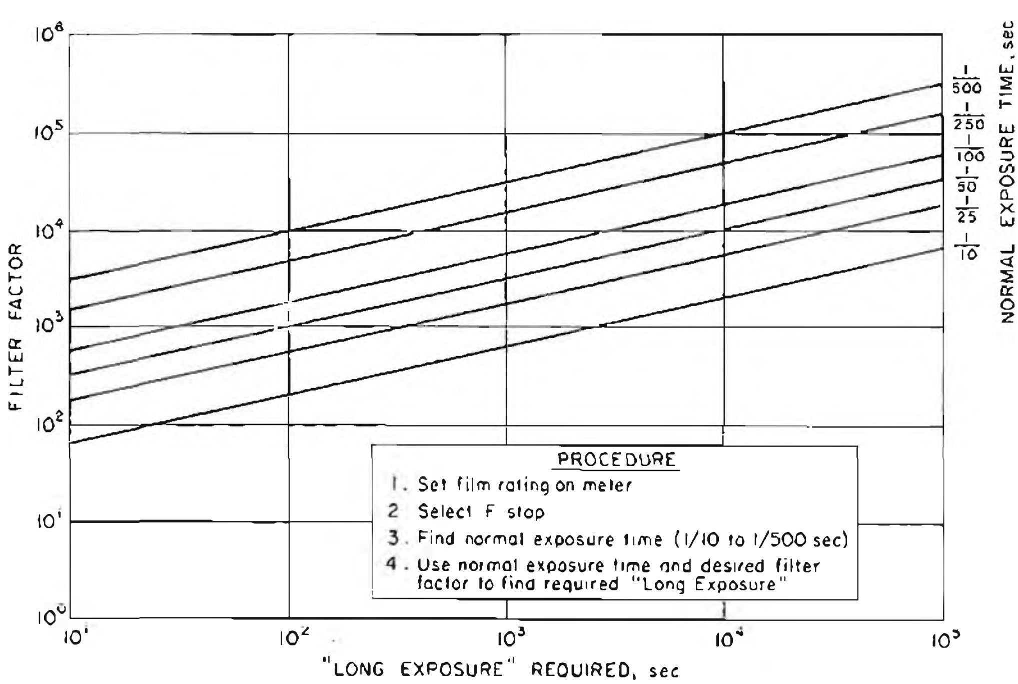

Figure 6-6. Factors for Long Time Exposures (Panatomic X Film)

In testing field-ready smoke producers, each sample is numbered; and ignition time and burning time of each sample are recorded[16]. Comments are recorded to describe out-of-ordinary conditions that may occur during the test—such as excessive sparking upon ignition, flame-ups while burning, and fuze failures.

6-3.4 PHOTOGRAPHIC TECHNIQUES

Smoke plumes have been studied with time-exposure photography[17]. Long photographic exposures (measured in minutes) of smokes have been applied in a number of technical applications in which diffusion of smoke into the atmosphere is of interest. Time-exposure photography in daylight requires one or more of the following: very slow film, small apertures, or dense filters. If these conditions cannot be obtained, an alternative is to make dispersion photographs under conditions of twilight.

Fig. 6-6[17] serves as a guide for exposure time, filter requirements, and aperture settings. The filter factor on the ordinate represents the light reduction by the action of a filter. A one-percent neutral-density filter has a filter factor of 100. Two of these would combine to have a filter factor of 10,000. A Wratten No. 25 (red) filter has a factor of eight. Each of the plotted lines in the figure is coded with exposure times that are read from a light meter. The corresponding aperture used on the light meter is used in the practice of setting up the camera. The exposure time required for the given aperture and filter factor is read on the abscissa.

The data shown in Fig. 6-6 were determined by trial and error using Panatomic X film; however, limited tests with Polaroid, Kodachrome, Plus X, and Microfilm indicate that little or no modification of the curves will be required for successful results at exposure times of up to 15 min.

Plumes recorded on photographs may be analyzed to determine dispersion coefficients. This method employs Roberts' opacity theory to define the visible edge of smoke plumes, maximum plume width and length, and ratios of these to determine dispersion parameters. The vertical dispersion coefficient C_y is given by

$$C_y = \sqrt{2}\, y_m^{n/2} \left(\frac{x_m}{y_m}\right) \qquad (6\text{-}7)$$

where

n = Sutton's stability parameter

$\frac{n}{2-n}$ = $\ln (y_t/y_m)$

y_t = total plume length, m

y_m = distance from the source to the point point of maximum plume width, m

x_m = maximum plume width, m

Motion pictures are used in the same manner as time exposures to determine dispersion coefficients.

6-4 HEAT

Incendiary devices are normally evaluated in terms of their ability to inflict specific damage against specific, defined targets such as burning a hole through metal plates[18,19]. The Hand Grenade, Incendiary, TH 3, AN-M14, for example, is required to burn through a steel plate 1/8-in. thick. The burning time (40 sec in this grenade) is another of the parameters that is commonly measured.

Attempts have been made to improve the testing of heat producers by the use of photographic techniques, spectrometers, and radiometers[20]. The following factors should be measured or assessed qualitatively in tests of flame producers:

(1) Fuel dissemination in terms of "blob" size, spectral and spatial distribution

(2) Percentage of fuel ignited

(3) The adhesiveness of fuel "blobs" to

different surfaces as a function of the type of surface, "blob" velocity, and altitude

(4) Fuel spread and run-off during burning

(5) Oxygen depletion or contamination

(6) Heating of the air in the vicinity of the target

(7) Damage capability as a function of target type.

Quantitative methods for evaluating all these factors have not yet been devised. Spectroradiometric methods may be useful in some aspects of these problems but are not likely to play a dominant role in evaluation of effectiveness against targets of flame producing weapons.

Photography with infrared film and appropriate filters can provide an effective means of evaluating the temperature distribution over the surface of a large flame, provided the fuel is relatively homogeneous and the observation path is also homogeneous. The film should be calibrated with a blackbody source of IR, and the calibration film and recording film should be processed identically.

Small arms incendiary rounds are evaluated by firing them against aluminum target plate. These rounds are fired to penetrate the aluminum plate in rows to conserve target material. Each shot is photographically recorded for flash characteristics. Acceptance is based on a comparison of the photographic results with photographic standards representing the minimum acceptable flash for that type of round.

6-5 GAS-OPERATED DEVICES

Pyrotechnic gas generators may be designed to produce various quantities of gas at various rates and temperatures and under a variety of loading conditions. It is good practice to test gas generators under conditions nearly the same as those anticipated in use. Special test fixtures may be necessary for close simulation, but ordinarily closed bomb tests with a fixed volume approximately equal to the volume in the actual application will suffice[21].

A closed vessel of adequate strength to withstand the pressure released from the gas generator is used with proper instrumentation to measure pressure as a function of time.

Normally, the volume of the closed bomb is fixed but some bombs are made so the volume can be changed by the use of inserts or an adjusting plug. Some test fixtures provide for expansion of the chamber with a movable member as pressure is applied from the pyrotechnic gas producer. This type of test measures the ability of the charge to deliver a certain minimum quantity of work. The pressure in the chamber and the displacement of the movable member are both measured as a function of time. Piezoelectric gages are most often used for pressure measurements and capacitance, inductive, or resistive elements for the displacement measurement.

Similar tests are made on propellant actuated devices used to eject or separate components of pyrotechnic ammunition. Pressure and time are monitored in the charge container as observations are made on system motion or trajectory.

Piston, dimple, and bellows motors are actuated by expanding gas. These motors are evaluated using force measuring transducers or by working them against springs. These devices are nominally closed and sealed. Testing includes measuring the time (1) from initiation impulse to start of motion, and (2) from start to the end of motion. The designer must be concerned with the input such that the electrical power is sufficient to ignite the explosive material. Also he must consider the output of the explosive material so that excessive pressure is not created in the container that may puncture it or cause leakage at the joints.

Problems that will be encountered in the testing of gas producers include the provision of adequate seals at the interface of the generator and pressure bomb, and at the pressure transducer. Copper washers are often helpful in both places. Some pressure transducers are fitted with beveled plugs that fit into similarly contoured seats. Further problems will be encountered in providing protection for the face of the pressure transducer that may, in some instances, be exposed to the hot gases or particles from the pyrotechnic gas generator. Manufacturers of pressure gages often recommend lubricants, either semifluid or dry, that provide adequate protection of the gage interfaces in these circumstances without materially altering transducer performance.

6-6 CHEMICAL AGENTS

Chemical agents are disseminated in the form of small liquid droplets or small solid particles. The particle size, shape, and concentration of these substances are the important variables in their role as chemical agents[22]. Particle size and concentration are usually measured to assess effectiveness of pyrotechnic chemical generators, i.e., pyrotechnic munitions that produce clouds of chemical agents. Microscopy, sieving, sedimentation, light scattering, and impaction methods have all been used to determine particle size with some success[23]. While particle size in itself is of little value, it is related to a number of other factors that become important in the evaluation of these generators. The human respiratory system is one of the finest aerodynamic classifying systems for airborne particles—rejecting or returning most particles that fall outside the range 1 to 5 microns. Hence, particle size becomes a critical factor.

Cascade impactors have become a major means of monitoring particle size included in the broad impaction and impingement category. First models of impactors were chambers with an adhesive-coated slide on one side and an orifice at right angles to the slide. A spring-operated piston sucked samples through a cylinder on the outside of the chamber to produce impact of the sample with the plate. The particles collected on the plate were examined under a microscope to determine particle size and distribution.

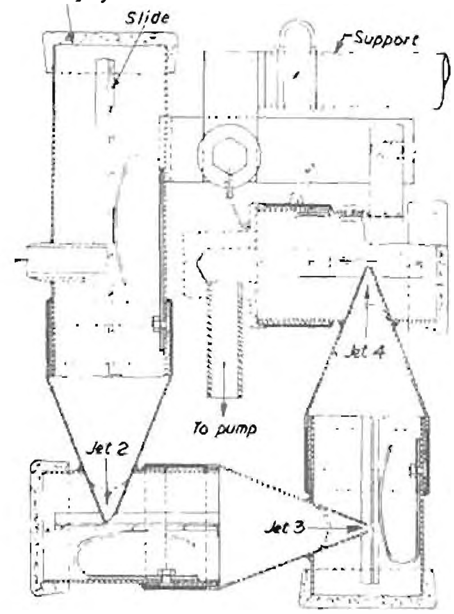

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Figure 6-7. Diagram of Cascade Impactor

A cascade impactor was then developed which maintained a vacuum at a fixed rate. Impact takes place in separate chambers that may vary in number depending upon the design of the instrument[24]. The sample is passed through progressively smaller orifices, each in a separate chamber and each having its own collection plate, as shown schematically in Fig. 6-7[24]. This arrangement permits segregation of the contents of the sample by particle size. Each plate then has particles within specific statistical variations of sample size, although the size ranges will overlap to some extent as shown in the generalized example of Fig. 6-8[24].

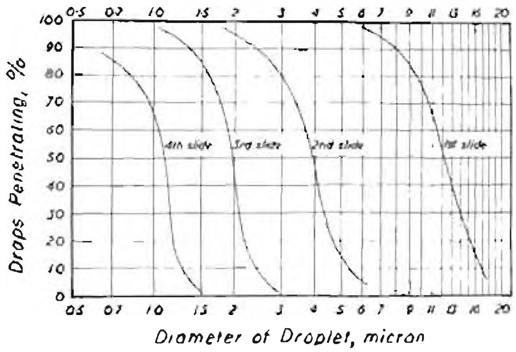

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Figure 6-8.
Efficiency Curves for Four Stages of a Cascade Impactor

Limits on particle size for cascade impactors are approximately 200 microns on the upper end of the scale and particles as small as 0.2 micron have been collected with certain instruments. Considerations in the design of impactors include ease of slide removal, portability, ease of use in the field, and particle size range.

Pyrotechnic munitions that produce clouds of chemical agent are tested in chambers with provisions to measure the burning times of the munition and to sample the resultant cloud quantitatively. The basic facility required is a test tunnel consisting of an inlet plenum, burning chamber, sampling chamber, agent decontaminating chamber, air moving system, and exhaust stack. Operation entails moving air past the functioning pyrotechnic munition into the sampling chamber where aliquots of the agent are collected. The residue is fed from the sampling chamber to a decontamination chamber where the remaining agent is rendered inert or collected, and finally the remaining flow is expelled through the stack.

Criteria have been established for test tunnels that provide some conformity without placing unnecessary restrictions on exact configuration. The criteria are to be included in the design of a tunnel used for the testing of pyrotechnic munitions that disseminate chemical agents are:

(1) The test tunnel shall be the dynamic type with once-through air flow.

(2) Tunnel capacity shall be sufficient for 100 g of pyrotechnic agent per test.

(3) A homogeneous air stream shall be maintained in the sample chamber.

(4) Operation shall be in all weather conditions.

(5) Minimum air dilution shall be 2000 ft^3 min^{-1} per pound of agent.

(6) Munitions shall be initiated remotely.

(7) Provision shall be made for viewing the burning munition.

(8) Nine samplers shall be provided in the sample plane and equally distributed across the sampling chamber; each sampler shall have a sampling rate of 1.5 to 5 liters min^{-1} within $\pm$ 0.05 liter min^{-1} of the sampling rate specified.

(9) Sampling time shall be at least 10 min.

(10) The air velocity through the chamber shall be maintained constant and shall be measurable to an accuracy of $\pm$ 3%.

(11) The test tunnel shall provide test results with an accuracy of $\pm$ 5%.

6-7 GENERAL SENSITIVITY TESTS

6-7.1 TEST LIMITATIONS

It is important to determine the sensitivity of pyrotechnic material to initiation by the input energy: it is also important to determine the capability of said pyrotechnic material to ignite a subsequent explosive or pyrotechnic charge (output). This knowledge will permit not only greater safety and reliability but also enable the designer to pinpoint performance requirements. While a number of different tests have been devised to indicate the sensitivity and output of a given explosive material, most authorities in this field view such tests as being merely indicative of the relative sensitivity or output. Few feel that such tests yield numerical results that may be applied to a specific design problem. To make matters worse, most of the tests employed are designed for testing general explosive materials rather than specific pyrotechnic materials.

In spite of these shortcomings, the general sensitivity tests are valuable in establishing a relative sensitivity of the materials used. Once a specific pyrotechnic has been selected, the sensitivity tests are ideal for quality assurance determinations. If they accomplish nothing more than identifying a safety problem, they have well paid for the effort. Additional details for the tests that follow are found in handbooks on explosives[25,26,27].

6-7.2 IMPACT

Impact tests with the Picatinny Arsenal apparatus or with the Bureau of Mines apparatus provide a relative value of the energy required to initiate an explosive[27]. A known weight is raised a distance above a carefully housed sample of explosive, and the weight is allowed to fall into the assembly containing the explosive sample. Sensitivity is expressed as the minimum height of the weight necessary to cause initiation.

6-7.3 ELECTROSTATIC SENSITIVITY

An electrostatic sensitivity test was developed for the specific purpose of testing the sensitivity of pyrotechnic compositions. The usual apparatus consists of a capacitor, a movable probe or sparking mechanism, a sample holder, voltage controllers, switches, and timing mechanisms arranged as shown schematically in Fig. 6-9[26]. With this tester

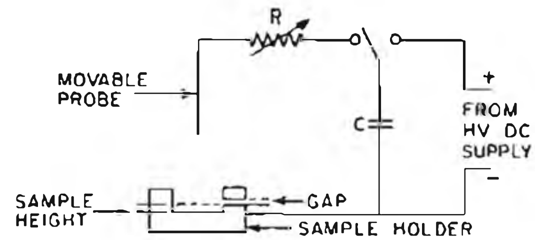

Figure 6-9.
Schematic Drawing of Electrostatic Sensitivity Tester

capacitance, series resistance, and potential difference can be varied in order to arrive at an energy value indicative of the sensitivity of bulk explosive materials. The series resistor is nominally a short circuit, zero ohms. This resistance may be increased if splattering of the explosive sample occurs. Energy E is computed by

$$E = \tfrac{1}{2}CV^2 \qquad (6\text{-}8)$$

where

E = energy, J

C = capacitance, F

V = potential, volt

6-7.4 EXPLOSION TEMPERATURE

Explosion temperature tests are made by immersing, in a bath of Wood's metal, metal shells of No. 8 blasting caps that have been previously loaded with the explosive or pyrotechnic mix being tested. The temperature and time to explode are recorded, and the temperature required to provide firing in 5 sec is determined—usually by a plot of explosion time vs temperature from which the temperature for a 5-sec explosion time is taken.

If the sample fails to explode during the test, the temperature at which decomposition occurs is recorded. Decomposition temperature is defined as the evolution of smoke, gas, or fumes as contrasted to an explosion.

TABLE 6-2

SUMMARY OF TESTS FOR STABILITY OF EXPLOSIVE MATERIALS

Test Name	Sample Size, g	Process	Indicators	Notes
Material Stability	10	75°C for 48 hr	loss of weight in excess of water	Observe discoloration, fumes, odors
Heat	10	Determine moisture content	% moisture	
	0.6	100°C, 48 hr	weight loss	Precaution: heat each sample inside pipe bomb
	0.6	100°C, 100 hr	reaction	Note whether explosion occurs
Vacuum Stability	5	90°, 100°, or 120°C vacuum to 5 mm Hg	gas liberation	Room temp., barometric pressure; temp. to ± 0.5 deg C
Surveillance	45	65.5°C	liberation of colored gas	Time to emit colored gas: 90 days or less, impaired; 20 days or less, destroy

6-7.5 STABILITY

Stability tests generally measure the resistance of an explosive to decomposition by heat. The end point may be the change in color of a blue test paper or the evolution of oxides of nitrogen. Also, loss of weight of the sample or gas liberation are measured to determine stability. Two tests commonly used for stability determination are the differential thermal analysis (DTA) and thermal gravimetric analysis (TGA). They have proven to be valuable tools in the analysis of pyrotechnic materials. The DTA test consists of measuring the temperature differential between the sample and a thermally inert reference compound while both are heated at a constant rate. Temperature difference is plotted versus sample temperature. An exothermic reaction may take place due to a phase change in the sample and is identified by a sharp rise in ΔT. An endothermic reaction may take place due to a phase change in the sample and is identified by a decrease in ΔT[26]. TGA tests are similar to the DTA in that the temperature of the sample is monitored. It differs in that the weight of the sample is monitored and is the determining criterion for indicating that the sample has reacted.

Table 6-2 lists some of the tests that are used routinely in determining the stability of pyrotechnic materials and the types of materials to which these tests are nominally applied.

6-7.6 REACTIVITY

Reactivity tests are made to determine the compatibility of a pyrotechnic material with its container because pyrotechnic materials are always housed in a container that is materially different from the explosive. The container material may combine with the pyrotechnic to produce a compound far more reactive than the original pyrotechnic mixture. The result could be a compound that ignites spontaneously or with very little need for external energy.

Reactivity is measured using the vacuum stability test to compare a combination of the contiguous materials intimately blended with pure, individual samples of the explosive and the contact material. Two 2.5 ± 0.01-g samples are made of the pyrotechnic and the contact material. One sample of each of the materials is blended with the other. The gas liberated from the mixture is compared with the sum of the gas volumes liberated from the pure samples. All samples are heated at a nominal temperature of 100°C for a period of 40 hr; however, if necessary or desirable, lower or higher temperatures may be used. The usual alternate temperatures are 75°, 90° or 120°C. If the gas liberated by the mixture exceeds the sum of the constituents by 5 cm^3, the reaction is considered excessive; 3 to 5 cm^3, considered normal, and 0 to 3 cm^3, negligible.

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CHAPTER 7

HUMAN FACTORS ENGINEERING

7-1 VISION

The factors involved in vision are both physiological and psychological. The physiological factors are those which control the admission of light to the eye, the formation of an image on the retina, translation into neural impulses, and transmission to the brain for processing. The psychological factors are derived from neurological signals in the brain and relate to apparent size, shape, color, motion, and distance of the target object.

7-1.1 THE HUMAN EYE

A horizontal cross section of the human eye is shown in Fig. 7-1[1]. Light entering the eye passes through the cornea, the lens, and the vitreous humor (a gel-like substance) finally impinging upon the retina which contains the photo-transducing elements called rods and cones. The distribution of the rods and cones in the retina is shown in Fig. 7-2[1]. Generally speaking, the cones serve daytime vision and the rods serve in dim illumination. Only the cones are able to distinguish hue (color).

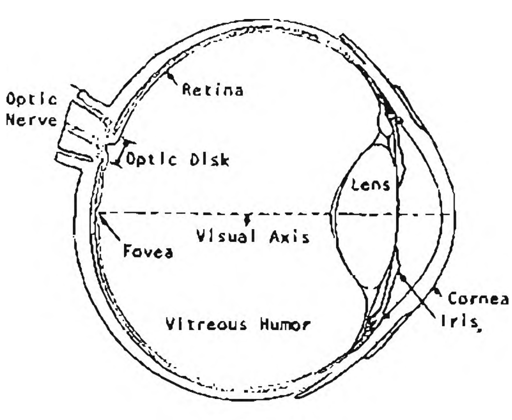


Figure 7-1.
Horizontal Section of the Right Human Eye

The lens of the eye is focused by an internal eye muscle system enabling it to see clearly at both near and far distances. This adjustment, called accommodation, takes approximately 0.5 sec. For persons over 40 yr of age accommodation takes longer. The eye is protected from excessive illumination by the action of the iris which can contract to its minimum size in approximately 1.0 sec. Although the protection provided by the iris may not be sufficient or fast enough, the eyelid can close in 60 msec.

As soon as an image is formed on the retina of the eye the rods and/or cones respond and send a neural message to the brain causing a conscious perception. Under any given lighting condition (bright, dark, dim, etc.) the ability to perceive an object is dependent upon the contrast sensitivity of the eye. The ability to recognize details and thereby identify the object depends on the contrast, the background luminance, the receptor mosaic

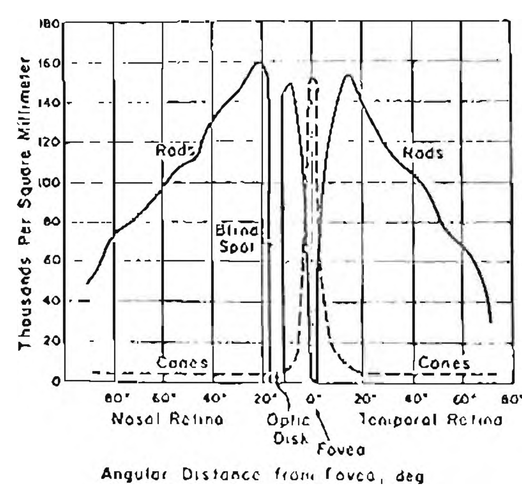


Figure 7-2.
Distribution of Rods and Cones in the Human Retina (Right Eye)

of the retina, and the interpretive ability of the observer. In addition to these factors an observer may further recognize the color, the distance of the object, and the presence of motion.

7-1.2 ILLUMINATION

Illuminant flares form a large and important part of the family of pyrotechnic devices. Their primary purpose is to aid in the detection of a target or in the accomplishment of a visual task which would not ordinarily be possible due to insufficient illumination. In most of these tasks it is not usually necessary to distinguish color differences. The detection of the presence of an object (which may be camouflaged) against a background and some object detail are sufficient for most purposes. For this reason the contrast threshold and the visual acuity of the human eye as a function of the illumination level are of primary importance in the design of illuminating flares[1,2]. It is often possible to know the range, size, and contrast brightness of the target and thereby estimate the necessary illumination level in terms of candlepower at a given range.

7-1.2.1 CONTRAST

Contrast is an important property of a target, signal, or object of interest which enables the human observer to detect it. It may be defined as a difference of adjacent parts (within the viewed field) with regard to brightness or color. It has been shown experimentally that brightness contrast is of greater importance than color contrast for the detection of targets. It is customary to express brightness contrast by the equation (see par. 2-1.4, Eq. 2-8)

$$C_b = \frac{B - B'}{B'}$$

where

C_b = brightness contrast, dimensionless

B' = luminance of the background, c-m^{-2}

B = luminance of the object, c-m^{-2}

When B is greater than B', the contrast is positive and may vary between 0 and ∞. When B is less than B', the contrast is negative and may change from 0 to -1. The contrast threshold, or the minimum detectable brightness contrast under a given level of illumination, is a sensitive measure of visual performance.

7-1.2.2 VISUAL ACUITY

Visual acuity is an important performance measure that refers to the ability to resolve detail. The size of any object in the visual field can be measured by the angle it subtends at the eye (visual angle) and visual acuity is expressed as the reciprocal of the visual angle in minutes of arc. For example, a visual acuity of unity, or one, indicates an object subtending a visual angle of one minute of arc can be seen. This value has long been accepted as a standard for normal vision although research has shown that much greater detail can be resolved under certain circumstances (12 seconds of arc or an acuity of 5).

It is appropriate to distinguish three stages of vision dependent upon the luminance to which the eye is adapted:

(1) *Photopic* or daytime vision refers to the state of essentially pure cone activity in the eye and is used in luminance levels between 1 millilambert* and the limit of comfortable vision, which may not be higher than 10^4 millilambert.

(2) *Scotopic* or night vision pertains to the stage of pure rod vision used in luminance levels between 3×10^{-4} millilambert and the vision threshold (just barely perceptible), approximately 10^{-6} millilambert.

(3) *Mesopic* or twilight vision refers to the intermediate stage in which the activities of both retinal receptor types (rods and cones)

* Note 1 millilambert ≃ 1 foot-lambert

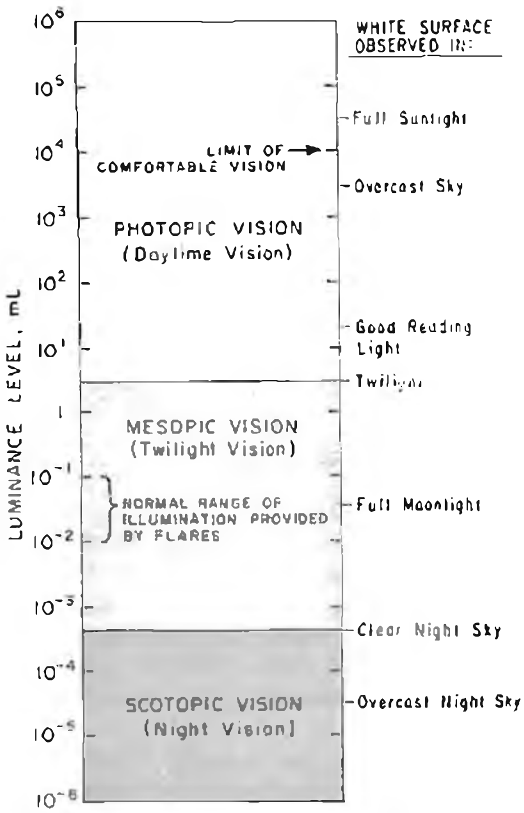


Figure 7-3.
Range of Response of the Human Eye to Various Levels of Luminance

overlap. It applies to luminance levels between 1 millilambert and 3 X 10^{-4} millilambert.

The process of adaption is discussed further in par. 7-1.4.1. Fig. 7-3 shows the range of response of the human eye in terms of various luminance (or brightness) levels. Fig. 7-4[2] presents the relationship between visual acuity and brightness contrast for various luminance levels. The luminance levels in this figure include those which might reasonably be expected on target surfaces from pyrotechnic illuminants (0.1 to 1.0 foot-lambert). In practice, approximations of the necessary intensity of an illuminant flare are based on the calculated brightness contrast and the size of the target.

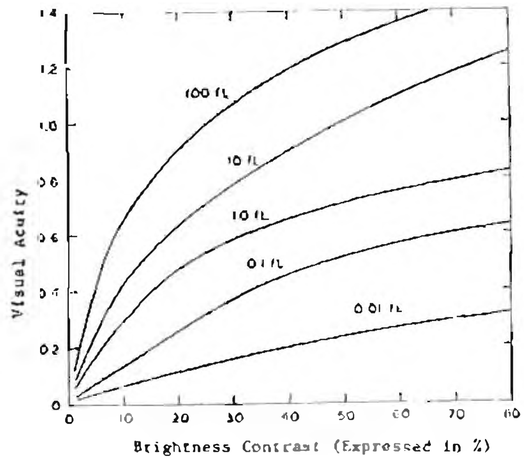


Figure 7-4.
Relationship Between Visual Acuity and Brightness Contrast for Various Levels of Brightness

Some guides for the design of illuminant flares are[1,2,3]:

(1) The illuminant should be essentially white light.

(2) The illuminant source (or sources) should have an intensity adequate to provide a brightness level from 0.1 to 1.0 foot-lambert. A man is easily visible at 1000 ft under this brightness range.

(3) The illuminant should burn at peak intensity for at least 30 sec and preferably 90 sec. This is necessary because data acquisition and tracking are much more difficult under the low illumination levels generally provided by flares and under combat conditions (muzzle flash, noise, glare, etc.).

7-1.3 COLOR PERCEPTION

Color perception is an important consideration in the design of pyrotechnic signals when colored smokes and flares are used as signals[1,2,4]. The threshold sensitivity of the eye in the terms of radiant flux is shown in Fig. 7-5[1] for both daytime (photopic) and nightime (scotopic) vision. Color is not neces-

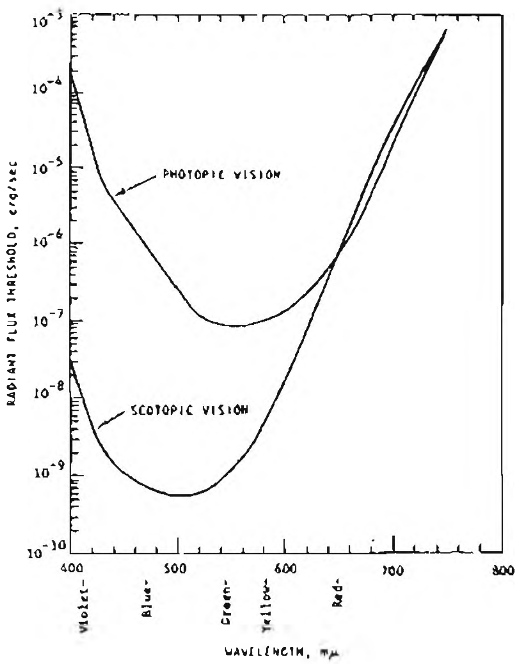


Figure 7-5.
Thresholds of Radiant Flux for Vision

sarily perceived in scotopic vision although flux sensitivity varies over the range of perceptible wavelengths.

Because of the structure of the eye (see Figs. 7-1 and 7-2), color is perceived best by the foveal or cone area; while brightness contrast is best perceived by the rods outside the foveal area (parafovea). Thus the intensity required for the detection of a signal within a 180 deg field of view is less than for the subsequent color recognition of the same signal once it has been brought into direct sight.

Table 7-1[2] lists the foveal and parafoveal threshold illuminance for white and colored lights at night. Although these values are extremely small for practical signaling purposes they may serve as a guide in the selection of colors for night signal lights.

If pyrotechnic signal lights are to be used in the daylight, the intensity, and preferably the color saturation (purity) of the signal, should

TABLE 7-1

THRESHOLD ILLUMINANCE VALUES FOR WHITE AND COLORED LIGHTS AT NIGHT

Color	Foveal Threshold, mile candles*	Parafoveal Threshold mile candles*
Tungsten at 2800°K (white)	0.24	0.010
Blue	0.25	0.00087
Green	0.32	0.0040
Orange	0.20	0.046
Red	0.14	0.13

*A mile candle is 5280 footcandles

be increased to provide adequate contrast against the daylight sky. Red signals have been found to provide the best visibility and recognition for *general* day and night time use. A light red smoke has been found most effective for maximum visibility with red-purple and orange somewhat less effective. The *saturation* of the smoke color and the *density* of the smoke appear to be important factors in achieving maximum recognition.

Normal color vision is called *trichromatism*. Color deficiency or abnormal color vision occurs to some degree in about 8% of the male population and about 0.4% of the female population. The types and characteristics of color deficiencies are:

(1) Anomalous Trichromatism—this group accounts for the largest portion of the color deficient population and is characterized by various (slight) deficiencies in red and/or yellow-green perception.

(2) Dichromatism—characteristic of about 2% of the male population and is characterized by a deficiency in the perception of red (protanope) or green (deuteranope).

(3) Rod-Monochromatism—a rare (0.005% of total population) condition in which no color at all is perceived, i.e., only shades of gray are seen.

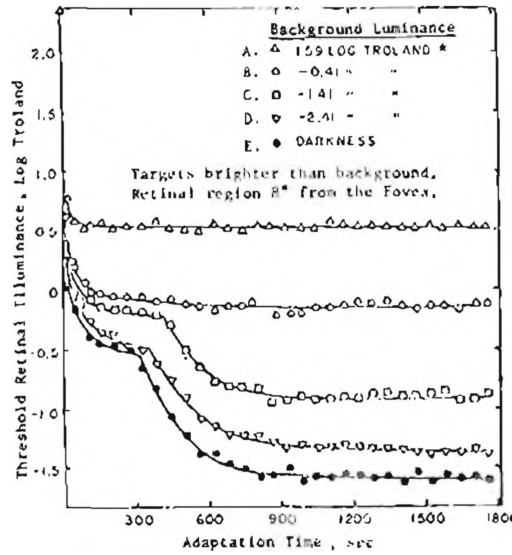
7-1.4 FACTORS IN RESPONSE

7-1.4.1 ADAPTATION

Daytime seeing is done in photopic vision (see Fig. 7-3). At sunset, there may exist mesopic levels in shadowy areas. After sunset seeing is done in the upper mesopic level of vision (1 to 10^{-1} millilambert) and night seeing occurs at the lower level of mesopic vision (10^{-2} to 10^{-3} millilambert). The process of change in types of vision with changing illumination levels is know as *adaptation*[1].

Of particular interest in pyrotechnic illumination is the process of adaptation from a low level of luminance, e.g., the night sky, to a higher level such as that provided by a suddenly ignited flare. Fortunately, dark to light adaptation is relatively short requiring only 30 to 60 sec to see in bright sunlight after being in a very dark room. Although an observer would not normally have to adapt to a level as bright as sunlight, some time for adaptation (e.g., 15 sec) should be provided in the total burning time of a flare *in addition* to that needed for target acquisition.

When an observer must adapt from a high level of luminance to a lower level longer periods of time are needed depending on the level to be adapted to. Adaption times to different low levels of background luminances after being exposed to a bright, pre-adapting source for several minutes are shown in Fig. 7-6[1]. In this figure, the criterion used to measure adaptation at any given time after the pre-adapting source is shut off is the threshold luminance of the target (always brighter than the background) which just makes it visible. In Fig. 7-6, background *A* is in the range of photopic vision and the terminal (the maximum) threshold sensitivity is reached in less than 150 sec; background *B* is in the mesopic vision range and about 5 min is needed to reach terminal sensitivity; backgrounds *C*, *D*, and *E* are various scotopic vision regions and the final threshold sensitivity is not reached until after 15 min. The abrupt change in curves *C*, *D*, and *E* marks the point at which the cones stop participating in the visual process.



*Troland – A retinal illumination unit. The retinal illumination in Trolands is equal to the product of the pupil area (mm) and source luminance (c/m^2).

Figure 7-6.
Adaptation to Backgrounds of Different Luminances

7-1.4.2 FLASH AND FLICKER

A light source may exhibit nonsteady characteristics such as a flash or flicker[1,2]. For flashes shorter than 0.20 sec the empirical photochemical reciprocity law states that the product of intensity and duration is equal to a constant photochemical effect

$$It = h \tag{7-1}$$

where

I = intensity, c

t = time, sec

h = constant

There is a time interval between the onset of a stimulus and the onset of its perception.

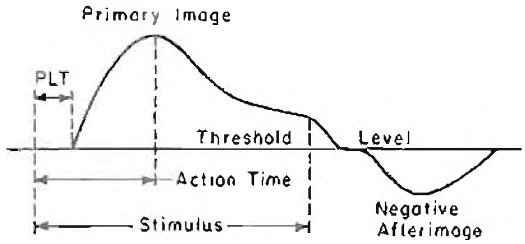


Figure 7-7.
Time Factors in Viewing a Stimulus of Medium Intensity and Duration

This is known as the perceptual latency time (PTL) and is shown in Fig. 7-7[1]. In the fovea, this time ranges from 35 msec for an intense stimulus up to 300 msec for a weak stimulus. There is a reciprocal relationship between the logarithm of the intensity of the stimulus and the PLT at all stages of vision, but the PLT can never be abolished entirely. The shortest latency time is found in the fovea at photopic and mesopic levels of vision. In scotopic vision, the shortest PLT is found 15-20 degrees from the visual axis of the eye, yet the perception does not approach the rapidity found in photopic vision. Unequal illumination of both eyes may cause a difference in perceptual latency between the two eyes, and thus produce distortions in the apparent paths of moving objects. The PLT decreases with increasing size of the target.

The PLT is followed by a sensation known as a "primary image" which reaches an intensity maximum within 100-200 msec, and then gradually drops to a substained level. After the stimulus has ceased, the primary image continues for a short time before it dissappears, and then is followed by a periodicity of after images which depend on intensity, hue, and duration of the initiating stimulus. After a stimulus a medium brightness and of several seconds duration, a longer lasting negative after-image is easily perceived.

A light may become more conspicuous when it is presented as an intermittent or flickering light. At a frequency of 8-12 flashes per second the flash appears brighter than when the same light is seen as a steady light. This phenomenon is most effective at a light level of 200 to 300 millilamberts and dark-light distribution in a cycle such that the light is on for 1/3 of the cycle. This brightness enhancement may be due to synchronization of impulses from visual stimuli with the alpha rhythm of the brain waves. At high contrasts (between flashing light and background) the effect wanes and steady light is more conspicuous.

Flicker frequencies between 3 and 6 flashes per second can produce discomfort. The *flicker fusion frequency* is the point at which successive light flashes appear to blend into a continuous light: it increases with increasing flash intensities and with decreasing proportion of the dark-light cycle occupied by the flash. The flicker fusion frequency may vary between 12 and 60 flashes per second depending upon the conditions stated earlier in this paragraph.

7-1.4.3 OTHER VISUAL PHENOMENA

Other phenomena related to seeing may be of importance to the designer in specialized applications.

(1) Perception of Motion. Perception of motion is produced by alterations of the retinal images, which may occur[1]:

(a) When the eyes are fixed and an object is displaced in a stationaryenvironment

(b) When the eyes are following a moving object, but the background changes

(c) When the eyes are stationary and the object grows or shrinks in size giving the impression that the object is moving toward or away from one in a stable environment.

The minimum perceptible speed is 1 to 2 min of arc per second of time in the presence of stationary reference objects and 15 to 30 min of arc per second of time in the absence

TABLE 7-2

DURATION OF SACCADIC EYE MOVEMENTS

Extent of Movement, deg	Duration of Movement, msec
10	40
20	55
30	80
40	100

of reference objects. Long tracking time and good illumination tend to improve motion perception.

(2) Object Blur. When a motion of the eyes is not able to hold a steady image of the target on the retina, the image becomes blurred and contrast decreases[1]. Smooth lateral pursuit movements of the eyes are possible up to a target velocity of 30 deg per second. At higher speed, the pursuit movements lag increasingly behind the target and must be accompanied by frequent saccadic eye movements.

(3) Convergence. The act of aiming both eyes at the same point is called convergence and is a function of both internal and external eye muscles[4]. The average time required to aim the eyes and focus them on a new point displaced in distance is about 165 msec. This act is called *fixating* or refixating. Beyond 20 ft, convergence needed in order to fixate is negligible.

(4) Saccadic Eye Movement. The simple, conjugate movement of the eyes without complication by change of convergence is known as the saccadic eye movement[4]. These movements are used to change from one fixation point to another. Table 7-2 shows the duration of these movements for various angular eye movements.

(5) Apparent Motion. Lights presented in succession at the proper time interval, distance from each other, and intensity give the impression of movement from one to the other[1,4]. Apparent motion is also observed through the successive presentation of two stationary objects juxtaposed in space or through increasing the brightness of a fixed object.

(6) Stroboscopic Effects. During nighttime visual observation, detection of slow moving targets may be enhanced through the use of intermittent flashing of the light source causing the target to appear at many discrete locations[1].

(7) Space Myopia. A condition in which the eyes tend to accommodate for a distance of about 20 ft in front of the observer. Space myopia is due to the lack of something definite on which an observer can focus[4]. Objects beyond this distance are consequently out of focus and may not be seen. Such a condition can occur at night as well as in empty space.

7-2 HEARING

7-2.1 USE OF SOUND

Pyrotechnic devices are used to familiarize unseasoned troops with the appearance and sound of battle conditions without exposing them to lethal ammunition. For simulation of rifle fire and explosive charges, hand grenades, booby traps, and land mines, a small firecracker type such as the M80 Simulator may be used (see par. 3-22.1). The degree to which the simulated sound must correspond with the actual device is not critical for training purposes provided that it gives a sharp report sufficient to startle or indicate to the trainee that something has happened. Sophistication of design may increase as attempts are made to reproduce the sound more faithfully, in terms of frequencies, magnitude, and duration. The M115A2 Simulator, for example, produces a high pitched whistle and a flash of light followed by a loud report. Close reproduction of the actual sound becomes more important when the simulator is used under actual combat to confuse the enemy.

Modern sound spectrometers can be used

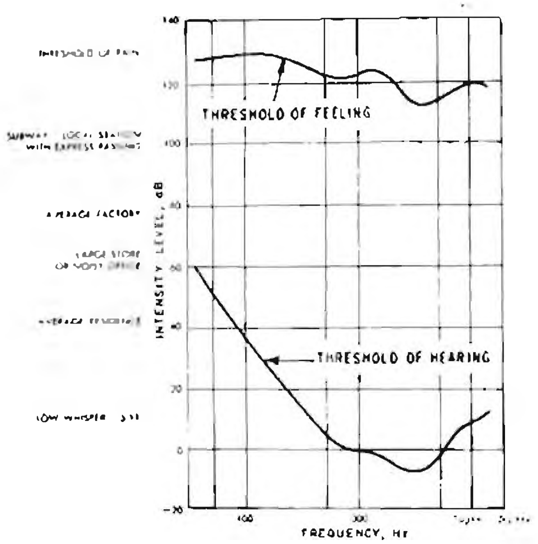


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Figure 7-8.
Threshold of Hearing as a Function of Frequency

to produce-three dimensional composite visual records of the frequencies present, their relative intensities, and the time of occurrence of each. Recorded patterns of this kind have been made to identify voices of individual persons and have been called voice prints[6]. Fig. 7-9 (par. 7-2.3) is similar to a contour map, showing frequency on the vertical axis, real time along the horizontal axis, and intensity or sound amplitude indicated by contour levels. The darkest contour represents the highest intensity. The same techniques can be applied to the matching of pyrotechnic sounds.

The reception, identification, and localization of the sounds when the human ear is the sensor will be due mainly to the frequency, duration, and amplitude of the sound as well as individual's hearing ability.

7-2.2 THRESHOLD OF HEARING

The threshold of hearing or the minimum

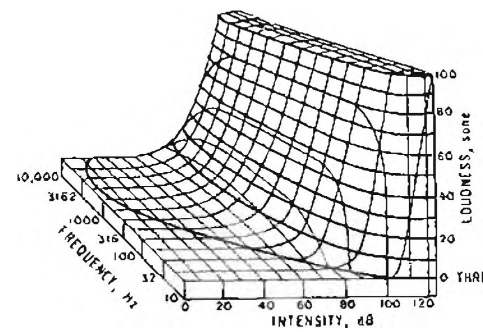

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Figure 7-9.
Relationship Among Frequency, Intensity, and Loudness

intensity at which a sound can be heard varies with the individual and his age. Fig. 7-8[4] shows the average variation of hearing threshold with frequency. Normal hearing is most sensitive to a sound frequency of 3000 Hz.

It is important to distinguish between the physical sound which may be generated by a sound source and the response to that sound which is called hearing. A sound source with twice the intensity of another will not necessarily sound twice as loud to a listener.

Loudness is affected by the duration of a sound. Maximum loudness is attained at a duration of 0.5 sec, beyond this interval there may be a slight decline in loudness as the ear adapts to the sound. The critical duration below which a tone sharply loses loudness is about 0.15 to 0.12 sec. To maintain equal loudness for tones shorter than this critical duration the intensity required is inversely proportional to the duration.

The intensity of a sound diminishes according to the inverse square of the distance. Interfering reflections such as echoes, and refractions caused by wind, trees, and temperature gradients will usually decrease the intensity of a sound before it reaches a listener.

Higher frequencies are more likely to be attenuated than lower frequencies.

7-2.3 FREQUENCY EFFECTS

The human auditory response to frequency is commonly accepted as falling between the frequencies of 20 and 20,000 Hz. No clear generalizations can be made concerning the frequency limitations of hearing, however, since intensity has an effect especially near the extremes.

When the intensity of sound is increased to very high levels, frequency components normally considered below or above the usual thresholds can elicit a hearing response. The hearing elicited by these very intense sounds is probably brought about through distortion within the ear which breaks up a portion of the sound energy into components, some of which fall within the range of hearing. Hearing has thus been reported of sounds up to 100,000 and as low as 5 Hz.

The relationship among frequency (measured in Hz), physical sound intensity (measured in dB) and subjective loudness (measured in sone) is shown in Fig. 7-9[4].

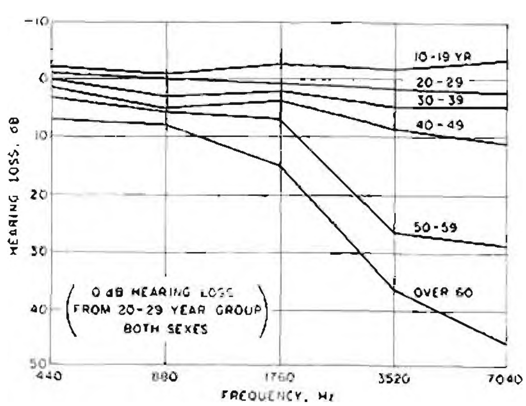

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Figure 7-10. Loss in Hearing Ability for Men of Various Ages

7-2.4 SOUND LOCALIZATION

The ability to locate sounds is dependent primarily upon binaural cues, which resolve into differences of loudness, time of arrival, and sound composition. Pure tones, which are relatively rare in pyrotechnics, are not as accurately localized as complex sounds. The greatest errors occur in trying to locate a tone of 2000 Hz.

7-2.5 VARIATIONS IN HEARING ABILITY

Hearing ability varies greatly within the population. Aside from individual differences, age accounts for much of the variation in hearing ability. Fig. 7-10[4] shows the changes in hearing sensitivity for men, with the zero point obtained from the median value of the total sample of male and female subjects aged 20 to 29 yr.

Some hearing loss is directly related to past exposure to loud noises. Exposure to noises in excess of 85 dB over long periods of time generally results in permanent hearing impairment.

7-3 PHYSICAL MEASUREMENTS

7-3.1 MALE HUMAN BODY MEASUREMENTS

As an aid in the design of equipment, selected dimensions of the human body (ages 18 to 45) are listed in Table 7-3[4] and illustrated in Fig. 7-11[4].

Useful limits for arm reach should be based on those of the small man. In Fig. 7-12[4], selected data for a man with a 5th percentile arm reach are shown. In Fig. 7-12(A) the subject is in shirt sleeves and not restricted by a shoulder harness. In Fig. 7-12(B) the subject is restricted by a shoulder harness, and in Fig. 7-12(C) the subject wears a pressurized suit.

7-3.2 STRENGTH

As a general rule the weight of hand-held launching devices and ammunition should be

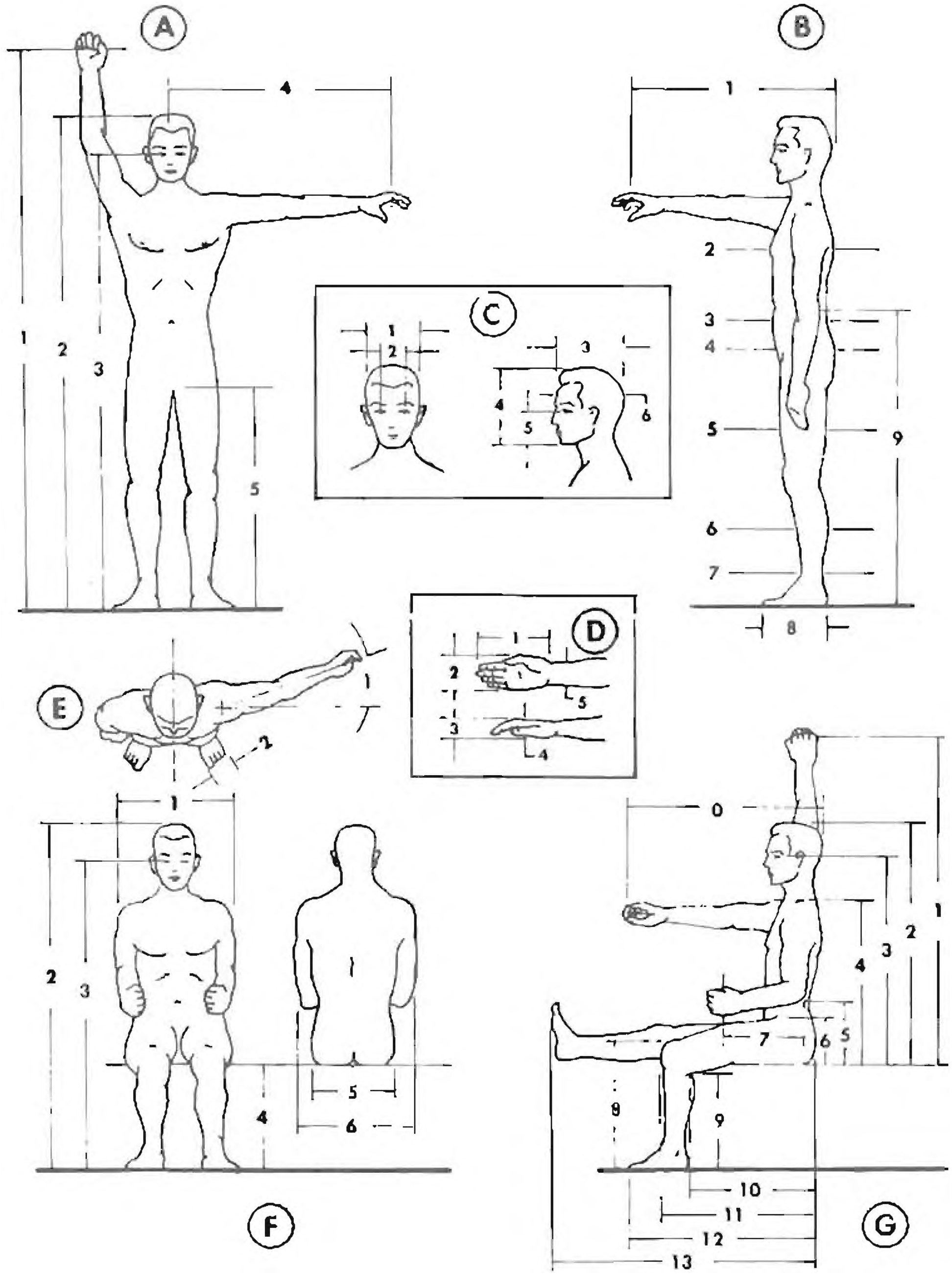
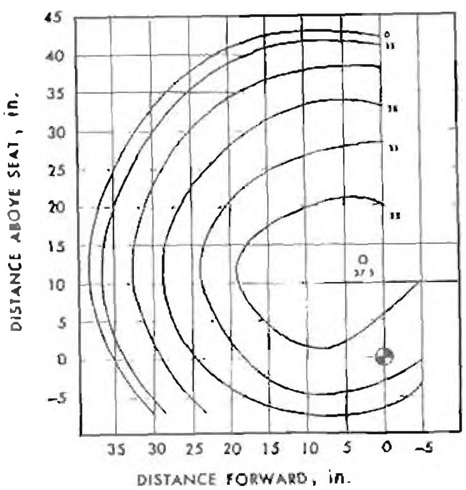
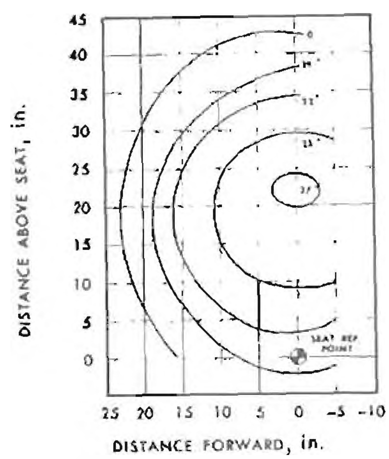


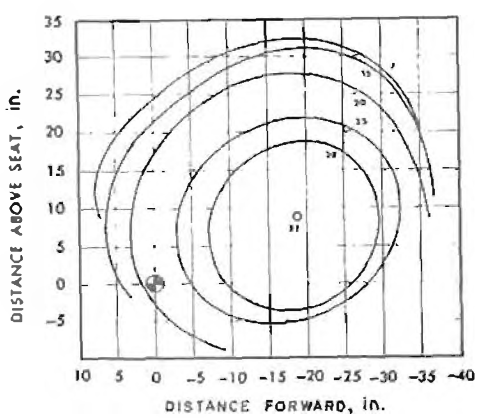
Figure 7-11. Key for Male Human Body Dimensions in Table 7-3



(A) Subject in Shirt Sleeves



(B) Subject in Shoulder Harness



(C) Subject in Pressure Suit

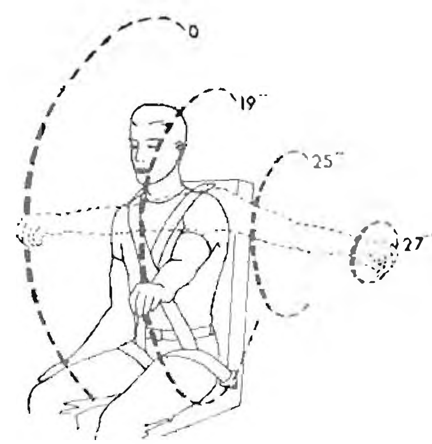


Figure 7-12. Arm Reach Envelopes

as light as possible to increase the fire power and mobility of troops. For short times the average man can exert forces as large as 450 lb with the leg if his back is supported against a backstop. For design purposes, the maximum weight that individual troops are expected to carry are limited to a maximum 50 lb. Two men can carry 75 lb without difficulty.

When forces must be applied with the knee at a right angle, strain can be expected to occur at about 28 lb.

Devices such as grenades that must be hurled should be limited to less than 2 lb.

7-4 IDENTIFICATION CODES AND OPERATING INSTRUCTIONS

7-4.1 IDENTIFICATION

Pyrotechnics are identified by lot number and the standard nomenclature common to other types of ammunition. Standard nomenclature is used so that each item may be specifically identified by name. In accordance with Federal item identification guides for supply cataloging, standard nomenclature consists of: item name (a generic term), a colon, and other identification markings such as model number, serial number, etc. Also before the colon will be included, where necessary, descriptive adjectives such as: dummy, blank, or inert ammunition. The use of standard nomenclature is mandatory for all record purposes.

When ammunition is manufactured, a lot number is assigned in accordance with pertinent specifications. A lot consists of a number of items manufactured under similar conditions, which may be expected to function alike. The lot number consists, in general, of the loader's initials or symbol and the number of the lot.

A model designation is assigned to identify a particular design at the time the model is classified as an adopted type. This designation becomes an essential part of the nomenclature and is included in the marking of the device. The present system consists of letters or a letter followed by an Arabic numeral, for example: An Army device may be marked M1, a Navy device Mk1, a device used by both Army and Navy ANM1, and a device still in the development stage XM1. Items which have been modified are marked with a letter or letters followed by the appropriate Arabic numeral, which is placed after the original model designation. The Army generally uses A1 to indicate the first modification. Using the given example, for the Army, a device which has undergone its first modification would be marked (M1A1). The Navy uses the letters (Mod) followed by an appropriate Arabic numeral, for example, Mk1 Mod 1, would be the model designation after the first modification.

Pyrotechnic assemblies are painted in accordance with MIL-STD-709A. They are usually painted white, except those having cases of either aluminum or plastic, or those aircraft signals assembled in a tube of rolled cartridge paper, which are coated with colorless lacquer. Ground flares (Army designation) M49 and M49A1, which have primary roles of giving warning of infiltrating enemy troops and secondary roles as signals, are painted light green.

Pyrotechnics, in general, are marked in black. These markings show the type, model, ammunition lot number, and date of manufacture. Signal types are marked with colored bands and patches to indicate the color of the signal produced. The top of launcher-type and hand-held ground signals are painted the color of the signal and also marked with two embossed letters for identification in the dark. The first letter is the initial of the color. The second letter indicates type "P" for parachute or "S" for star. Thus, "RP" indicates the signal will produce a parachute-supported red star. Overage flares and those assigned to ranging are stenciled with a 2-in. blue band.

It has been shown that embossed letters

TABLE 7-3

MALE HUMAN BODY DIMENSIONS[a]

		DIMENSIONAL ELEMENT	DIMENSION (in inches except where noted) 5th PERCENTILE	95th PERCENTILE
		Weight	132 lb	201 lb
A	1	Vertical reach	77.0	89.0
	2	Stature	65.0	73.0
	3	Eye to floor	61.0	69.0
	4	Side arm reach from CL* of body	29.0	34.0
	5	Crotch to floor	30.0	36.0
B	1	Forward arm reach	28.0	33.0
	2	Chest circumference	35.0	43.0
	3	Waist circumference	28.0	38.0
	4	Hip circumference	34.0	42.0
	5	Thigh circumference	20.0	25.0
	6	Calf circumference	13.0	16.0
	7	Ankle circumference	8.0	10.0
	8	Foot length	9.8	11.3
	9	Elbow to floor	41.0	46.0
C	1	Head width	5.7	6.4
	2	Interpupillary distance	2.27	2.74
	3	Head length	7.3	8.2
	4	Head height	–	10.2
	5	Chin to eye	–	5.0
	6	Head circumference	21.5	23.5
D	1	Hand length	6.9	8.0
	2	Hand width	3.7	4.4
	3	Hand thickness	1.05	1.28
	4	Fist circumference	10.7	12.4
	5	Wrist circumference	6.3	7.5
E	1	Arm swing, aft	40 deg	40 deg
	2	Foot width	3.5	4.0
F	1	Shoulder width	17.0	19.0
	2	Sitting height to floor (std chair)	52.0	56.0
	3	Eye to floor (std chair)	47.4	51.5
	4	Standard chair	18.0	18.0
	5	Hip breadth	13.0	15.0
	6	Width between elbows	15.0	20.0
G	0	Arm reach (finger grasp)	30.0	35.0
	1	Vertical reach	45.0	53.0
	2	Head to seat	33.8	38.0
	3	Eye to seat	29.4	33.5

*CL = chest line

TABLE 7-3 (Cont'd)

	DIMENSIONAL ELEMENT	DIMENSION (in inches except where noted) 5th PERCENTILE	95th PERCENTILE
	Weight	132 lb	201 lb
4	Shoulder to seat	21.0	25.0
5	Elbow rest	7.0	11.0
G 6	Thigh clearance	4.8	6.5
7	Forearm length	13.6	16.2
8	Knee clearance to floor	20.0	23.0
9	Lower leg height	15.7	18.2
10	Seat length	14.8	21.5
11	Buttock-knee length	21.9	36.7
12	Buttock-toe clearance	32.0	37.0
13	Buttock-foot length	39.0	46.0

provide a rapid means of nighttime identification with only a minimum of training[5]. Some letters (T,I,K,L,Y) are easier than others to identify due to distinctive shape.

7-4.2 INSTRUCTIONS

Proper instruction labeling of pyrotechnic devices cannot be overemphasized. Although ease of operation may have been embodied in the design of a device, ambiguous, inconspicuous, or illegible instructions may make personnel reluctant to use the device or cause them to use it in an unsafe manner. A few basic considerations apply to the design instruction labels:

(1) Instructions should be clear and logical with no possibility of misinterpretation. Individuals can interpret instructions differently because of intelligence and psychological differences; hence, instructions should be tested on a mock-up device using a broad cross section of subjects. Short, concise instructions are highly desirable, but clarity should never be sacrificed.

(2) One of the first instructions in the sequence should include a check of the integrity of the device. Are the seals broken? Is there evidence of damage? etc.

(3) Size of the lettering should be compatible with the expected illumination, with an adequate allowance for possible eye fatigue. For illumination of 1 foot-lambert or less the size of lettering to be viewed at 28 in. (approximately arm length) should be between 0.10 and 0.30 in. depending on the nature of the instruction[4]. Best legibility is obtained with black letters on a white background. Black on yellow, dark blue on white, and green on white are also good. Distinctive borders may be placed around critical labels to make them more conspicuous than routine labels[4].

(4) Instruction labels should be placed in a conspicuous position that will not be subject to abrasion or scraping in handling.

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CHAPTER 8

GENERAL CONSIDERATIONS

8-1 GENERAL PROPERTIES OF MATERIALS

8-1.1 GAS LAWS

The pyrotechnic designer is faced with the control of materials that react to generate gas at various rates. The generation of gas may be desirable as the source of power for mechanical motion or may be an undesirable result of a pyrotechnic reaction that must be contained or vented. Familiarity with the behavior of gases will permit adequate design[1].

At a constant temperature T, the volume V of a given quantity of gas varies inversely as the pressure P to which the gas is subjected. For a perfect (ideal) gas at constant temperature, we have the relationship

$$PV = k \text{ (a constant)} \tag{8-1}$$

which is the well known Boyle's Law.

At a constant pressure, the volume of a given mass of an ideal gas will increase 1/273 of its volume at 0°C for each degree centigrade rise in temperature, i.e., it is directly proportional to the absolute temperature in °K. This is Charles' Law which relates volume to the absolute temperature for a constant pressure

$$V = k_1 T \tag{8-2}$$

The two laws are usually combined to give what is known as the ideal gas law

$$PV = nRT \tag{8-3}$$

where the gas constant R has a universal value for all gases, 1543 ft-lb (°Rankine-lb mole)$^{-1}$, 0.09206 liter-atmospheres (°K-g mole)$^{-1}$, or 8.31432×10^7 ergs (°K-g mole)$^{-1}$; and n is the number of moles of gas.

The ideal gas law is very convenient to use in the form

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{8-4}$$

Although it does not hold strictly for real gases, it is often sufficient for approximations made at high temperatures and low pressures.

Pyrotechnic designs often require solutions for conditions of high temperature and high pressure where intermolecular forces and the physical size of actual molecules cause a departure from the behavior expected from an ideal gas. An improved equation of state which specifies the fundamental relationship between pressure, volume, and temperature was proposed by van der Waals in 1873. Cohesive forces are present between the molecules of real gases which tend to reduce the pressure of the gas. These forces are proportional to the square of the density and the reduction in pressure can be written in the form a/V^2 where a is a constant depending on the exact law of attraction[1]. The physical space occupied by each molecule if it were a hard sphere would reduce the available space by some factor b related to the number of molecules. The two effects were combined by van der Waals to yield what is known as van der Waals' Equation of State

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT \tag{8-5}$$

Qualitatively, the constant b in Eq. 8-5 is the excluded volume due to the size of the molecules and the constant a is a measure of the force of attraction between the molecules.

Many other attempts have been made to determine equations of state that agree more closely with the response of actual gases since the assumption of hard spherical molecules is not really warranted. The equation by Beattie

TABLE 8-1

CONSTANTS OF THE BEATTIE-BRIDGEMAN EQUATION OF STATE

Gas	A_0	a	B_0	b	$C \times 10^{-4}$	Temp. range, °C	Maximum pressure, atm.	Minimum volume, cc/g-mole
He	0.0216	0.05984	0.01400	0.0	0.0040	400 to −252	102	100
Ne	0.2125	0.02196	0.02060	0.0	0.101	400 to −217	106	118
A	1.2907	0.02328	0.03931	0.0	5.99	400 to −150	114	167
O_2	1.4911	0.02562	0.04624	0.004208	4.80	100 to −117	103	111
Air	1.3012	0.01931	0.04611	−0.01101	4.34	200 to −145	177	125
CO_2	5.0065	0.07132	0.10476	0.07235	66.00	100 to 0	111	82
CH_4	2.2769	0.01855	0.05587	−0.01587	12.83	200 to 0	243	167
$(C_2H_5)_2O$	31.278	0.12426	0.45446	0.11954	33.33	325 to 150	90	370
C_2H_4	6.1520	0.04964	0.12156	0.03597	22.68	200 to 0	286	125
NH_3	2.3930	0.17031	0.03415	0.19112	476.87	325 to − 35	130	340
CCl_2F_2	23.7	0.305	0.59	0.622	0	126 to 30	18.5	1,430
C_2H_6	5.8800	0.05861	0.09400	0.01915	90.00	25 to 250	193	200
C_3H_8	11.9200	0.07321	0.18100	0.04293	120.00	97 to 275	305	100
n-C_4H_{10}	17.7940	0.12161	0.24620	0.09423	350.00	150 to 300	118	280
n-C_7H_{16}	54.520	0.20066	0.70816	0.19179	400.00	275 to 350	315	200
Iso-C_4H_8	16.9600	0.10860	0.24200	0.08750	250.00	150 to 250	250	111
CH_3OH	33.309	0.09246	0.60362	0.09929	32.031			

NOTE: The constants for N_2 can be used for CO and the CO_2 constants for N_2O at moderate pressures and temperatures not too near the critical ones.

The equations will not, in general, be accurate if used in any region where the molal volume is less than the minimum listed.

Units: atm, liter, g-mole, °K

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and Bridgeman can be fitted to many gases within 1% over a wide range of pressures and temperatures[2].

$$P = \frac{RT}{V^2}\left(1 - \frac{c}{VT^3}\right)\left(V + B_0 - \frac{bB_0}{V}\right) - \frac{A_0}{V^2}\left(1 - \frac{a}{V}\right) \qquad (8\text{-}6)$$

where A_0, B_0, a, b, and c are constants. Table 8-1[3] lists constants of the Beattie-Bridgeman equation of state for several gases.

The equation of state has also been expanded in a power series form

$$PV = A + BP + CP^2 + \ldots \qquad (8\text{-}7)$$

The coefficients A, B, C–functions of temperature and mole fractions–are called virial coefficients; PV is the virial. Coefficient A is equal to RT to make the ideal gas law hold at zero density or pressure.

The virial equation is really a condensed summary of the fit to experimental data with great accuracy over large pressure ranges. It requires a different set of coefficients for each temperature and as a result is very cumbersome for practical applications[4]. At low pressure and low density only the first two terms of the series are required to give satisfactory results.

8-1.2 STRENGTH OF MATERIALS

Any structural material exhibits an elongation when subjected to an external load or force and, within the elastic limit, the elongation Δ is directly proportional to the load F[5]

$$F \cong \Delta \tag{8-8}$$

If the total deflection or elongation Δ of the test piece is averaged over the initial unloaded length L, a dimensionless quantity ϵ, the strain, results

$$\epsilon = \frac{\Delta}{L}, \text{ in. in.}^{-1} \tag{8-9}$$

If the applied load F is divided by the cross-sectional area A of the unloaded test specimen, the stress S is defined in pounds per square inch

$$S = \frac{F}{A}, \text{ psi} \tag{8-10}$$

A simple relationship is Hooke's Law, stress is proportional to strain

$$S = \epsilon E \tag{8-11}$$

where E is the proportionality constant, Young's Modulus or the modulus of elasticity, with dimensions in pounds per square inch.

Beyond the limits of Hooke's Law, elongation or strain increases as the force increases, but the linearity of the relationship ceases. Stress plotted against strain for any material gives the tensile-test diagram, Fig. 8-1[5]. Fig. 8-1(A) is typical of a ferrous material such as carbon or alloy steel while Fig. 8-1(B) is typical of some nonferrous materials, such as brass and aluminum, and of some stainless steels. The important distinction between the two curves is that Fig. 8-1(A) shows a definite inflection point and change of curvature, whereas Fig. 8-1(B) does not.

Certain points on these curves have been defined and are important material properties. Consider first the stress-strain curve in Fig. 8-1(A). The region from zero to A is a straight line, showing that the material is obeying Hooke's Law. This leads to the definition of point A as the *proportional limit*. It can readily be seen that the equation of this line is the now familiar $S = \epsilon E$ where E is the slope.

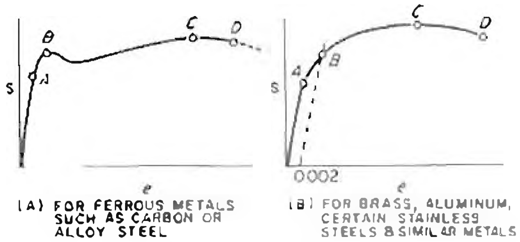

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Figure 8-1. Typical Tensile-test Diagrams

Beyond point A linearity ceases, and at point B a sudden increase in elongation takes place with little or no increase in load. This phenomenon is called *yielding*, and point B is called the *yield point* of the material. The stress associated with this point is the *yield stress*. Once this point is reached in the material, all load can be removed from the specimen and the stress returned to zero, but a residual strain, *permanent set*, will remain. Any permanent set is usually considered detrimental to a structural member.

Beyond point B, stress and elongation continue to increase until the maximum stress, the *ultimate stress*, is reached at point C. Rupture of the material occurs at point D, which is reached without any increase in stress or load—in fact, decreasing the load beyond point C will not necessarily avert fracture. Notice that the curve of Fig. 8-1(A) exhibits this definite, observed yield point, one which can easily be recognized as it occurs during a tensile test. The materials represented by Fig. 8-1(B), however, do not exhibit as definite a yield point, although the other points on the curve are defined in the same manner as their counterparts in Fig. 8-1(A). In materials such as those represented by Fig. 8-1(B), it is generally accepted that the yield point is the stress at the 0.2 percent "offset point", or the point at which the strain reaches 0.002 in./in. To find this point, draw a line through the point $\epsilon = 0.002$ with a slope of E; where this line intersects the curve (point B) is the defined yield point of the material.

Similar diagrams will result for tests in compression and in shear. These structural properties are listed in tables in various handbooks; such as MIL-HDBK-5A, *Strength of Metal Aircraft Elements*.

The properties presented in most of the handbooks including MIL-HDBK-5A are the room-temperature properties. If a problem involves elevated temperatures, the allowable properties must be those for the elevated temperature; these are usually lower than for room temperature.

8-1.2.1 PROPERTIES OF SECTIONS

Area, centroid, center of gravity, moment of inertia, and product of inertia are among the properties which must be computed, and their significances recognized, for stress analysis.

(1) The *centroid* of an area is that point at which the whole area may be considered to be concentrated without changing its moment of inertia about an axis. The location of the centroid $(\bar{x}, \bar{y})$ of a homogeneous area is found by evaluating the expressions

$$\left.\begin{aligned} \bar{x} &= \int x dA / A \\ \bar{y} &= \int y dA / A \end{aligned}\right\} \quad (8\text{-}12)$$

where

x = distance from reference axis to centroid of incremental area dA

y = distance from reference axis to centroid of incremental area dA

A = total area of homogenous plate

(2) The *moment of inertia* I_{ii} of an area has no physical significance except as a representation of a mathematical quantity which enters into stress and deflection calculations. Formally, it is represented by the mathematical expressions

$$\left.\begin{aligned} I_{xx} &= \int y^2 dA \quad \begin{pmatrix}\text{moment of inertia}\\ \text{about } x\text{-axis}\end{pmatrix} \\ I_{yy} &= \int x^2 dA \quad \begin{pmatrix}\text{moment of inertia}\\ \text{about } y\text{-axis}\end{pmatrix} \end{aligned}\right\} \quad (8\text{-}13)$$

(3) The *product of inertia* I_{ij} of an area is also a parameter which has only mathematical significance. It is determined when the following integral is evaluated

$$I_{xy} = \int xy dA \quad (8\text{-}14)$$

where x and y are the distances from the x-axis and y-axis, respectively, of the centroid of area dA

(4) The *radius of gyration* ρ_i of a cross section is an important parameter in the design of compression members or columns, and is defined as the distance from the inertia axis to that point at which, if the entire area could be concentrated, the moment of inertia would remain the same.

Thus, if $\int y^2 dA = \rho_x^2 A$ and $I_{xx} = \rho_x^2 A$

$$\rho_x = \sqrt{\frac{I_{xx}}{A}} \quad (8\text{-}15)$$

Note that there is a separate radius of gyration associated with each of the moments of inertia.

Many of the standard geometric forms of structural members have been investigated by means of the foregoing relations, and the resulting equations for I and ρ are presented in handbooks[6]. In addition, brochures and catalogs which give the dimensional data of shapes available on the market will usually include values for the various pertinent geometric properties.

8-1.2.2 LOAD ANALYSIS

In a complex design in which there are numerous load sources and other design conditions, load analysis is necessary.

In most structures it is found that the same design conditions are not critical for all members; it is the critical conditions which require investigation and definition.

For a load analysis, use the basic equations of equilibrium derived from Newton's Laws:

1. For every action there exists an equal and opposite reaction in the state of equilibrium.

2. A force F applied to a mass M will impart to it an acceleration a in the direction of the applied force

$$F = Ma = W\left(\frac{a}{g}\right) = Wn \qquad (8\text{-}16)$$

where n is considered equal to one for the equilibrium equations and for the load analyses.

By applying Newton's Laws, we can say that a body is in equilibrium if and only if the following three equations are satisfied

$$\left.\begin{aligned} \Sigma F_v &= 0 \\ \Sigma F_h &= 0 \\ \Sigma M &= 0 \end{aligned}\right\} \qquad (8\text{-}17)$$

which state that the sum of all vertical forces F_v, the sum of all horizontal forces F_h, and the sum of all moments M acting on the body must be equal to zero at any instant of time. If these conditions do not obtain, the body will experience either translation or rotation, or both, in accelerated motion. The first step required in the application of these equations

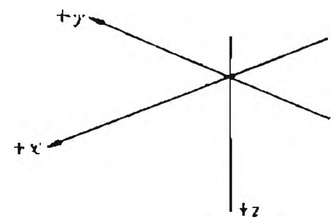

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Figure 8-2. A Three-dimensional Right-hand System of Coordinate Axes

is the definition of the vertical and horizontal directions in the problem. A set of coordinate axes must be defined and carried unchanged throughout the design. Usually a three-dimensional right-hand system is chosen as shown in Fig. 8-2[5].

To apply the equilibrium equations properly, it is necessary to understand the most important concept of the "free body". By definition, a free body is a mass which is in equilibrium and which is divorced from its surroundings in space. All forces on the mass are shown as vectors applied at their points of action.

As an example, consider a rectangular container loaded with a pyrotechnic material that is bolted to a bulkhead. In order to determine the loads which act upon the container, it is considered as a free body as shown in Fig. 8-3[5]. The container is held in place by four bolts whose locations are numbered on the figure, and its center of gravity is located as shown. No other external forces are known to exist on the container in this problem.

Fig. 8-4[5] shows the container in three orthogonal projections from which the equations for the reactions can be derived in terms of its dimensions.

Note that the coordinate axes are shown on the free-body diagrams and all vectors are

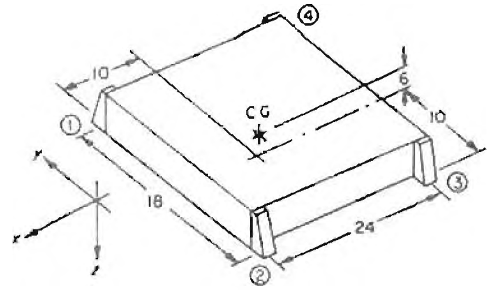

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Figure 8-3. Free Body Diagram of Container

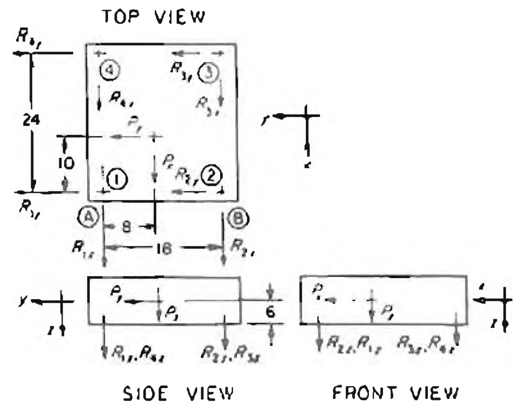

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Figure 8-4. The Container of Fig. 8-3 in Orthogonal Form for Equation Derivation

shown in the positive direction, so that a negative sign which appears as the equations are solved indicates that the vector is actually pointing in the negative coordinate direction. One other convention, which is observed when $\Sigma M = 0$, is to make all clockwise moments on the body positive and all counterclockwise moments negative. It is recommended that the analysis proceed by considering one load direction at a time to completion; therefore, the x-direction will be considered first.

From the plan view, assuming $R_{1x} = R_{2x} = R_{3x} = R_{4x}$ and taking moments about A

$$\Sigma M = 0 = P_x(8) + 2R_{2x}(18)$$

$$R_{2x} = R_{3x} = -\frac{P_x(8)}{2(18)}$$

Taking moments about B

$$R_{1x} = R_{4x} = \frac{-P_x(10)}{2(18)}$$

From the side view, assuming $R_{2z} = R_{1z}$ and $R_{3z} = R_{4z}$:

$$R_{3z} = R_{4z} = \frac{P_x(6)}{2(24)}$$

and

$$R_{3z} = R_{4z} = \frac{-P_x(6)}{2(24)}$$

Investigating the y-direction in a similar manner, i.e., finding the reactions due to P_y

$$R_{1y} = R_{2y} = -\frac{P_y(14)}{2(24)}$$

$$R_{3y} = R_{4y} = -\frac{P_y(10)}{2(24)}$$

$$R_{1z} = R_{4z} = -\frac{P_y(6)}{2(18)}$$

$$R_{2z} = R_{3z} = -\frac{P_y(6)}{2(18)}$$

For the z-direction, the load P_z is first apportioned into the plane of bolts 1 and 4 and the plane of bolts 2 and 3, and from this point the individual bolt reactions are found in accordance with the geometric location of the center of gravity.

$$R_{1z} = \frac{-P_z(10)(14)}{2(18)(24)}$$

$$R_{2z} = \frac{-P_z(10)(10)}{2(18)(24)}$$

$$R_{3z} = \frac{-P_z(8)(14)}{2(18)(24)}$$

$$R_{4z} = \frac{-P_z(8)(10)}{2(18)(24)}$$

Thus, the reactions have been found to maintain the container in equilibrium for loads in any direction because the load may be resolved into components P_x, P_y, and P_z as required. These reactions are to be supplied by the supporting structure, and therefore are presented as loads on the structure by reversing the sign, which reverses the vector direction.

Load analysis has determined the loads which exist on the structure under consideration; stress analysis is the means by which the designer determines whether his structure is adequate to withstand these loads without failure. Since no universal criteria for failure exist, they must be defined to suit each problem. Basically, failure can be divided into these four general categories:

(1) Rupture. A physical parting of the fibers of the material when the ultimate tensile or shear stress is exceeded.

(2) Yielding. The stress in the material exceeds its allowable yield stress in tension, compression, or shear. Permanent set takes place when the proportional limit of the material is passed.

(3) Buckling. The stress exceeds an allowable stress which is predicted upon the geometry of the loaded member. For example, columns buckle at a stress which is dependent upon the length to radius-of-gyration ratio; thin flat panels buckle under a shear stress which is dependent upon the ratio of panel width to metal thickness.

(4) Deflection. Since all structural members deflect under load, this deflection becomes a failure criterion in certain problems, particularly those associated with vibration environments.

8-1.2.3 SAFETY FACTORS

Some confusion exists among designers in the definition and use of safety factors, load factors, and margins of safety. Therefore, definitions of these terms are offered.

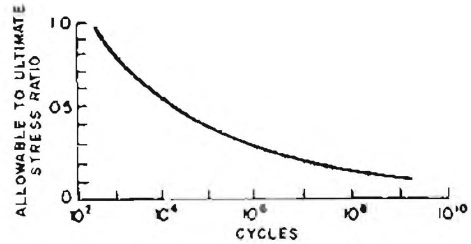

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Figure 8-5. Curve Indicating a Relationship Between Allowable Stress and Load Cycles

Safety factors are numbers representing a degree of uncertainty in the expected load, the material properties, or other pertinent data of the problem. These are applied to reduce the guaranteed properties of the material to a lower allowable value which shall then not be exceeded in the design calculations. For example, the ultimate tensile stress for 2024T4 aluminum alloy extruded bar stock is published in MIL-HDBK-5A as 57,000 psi. A safety factor of 3 applied to a member designed in this alloy would reduce the allowable tensile stress to 19,000 psi. Fatigue from repeated or cyclic loads is usually considered by applying a safety factor to the allowable ultimate stress of the material. Much data have been published relating allowable stress to the number of cycles of load, usually in the form of curves or tables, although the actual mechanism of fatigue failure is not clearly defined. An example of such a curve is shown in Fig. 8-5[5] from which the engineer may choose an allowable stress if he knows how many load cycles his structure is to experience during its design life.

Abrupt changes in cross section, notches, grooves, or other discontinuities should be avoided in the design of structural parts because these function as "stress raisers".

When these cannot be avoided, the designer must apply certain safety factors in these local areas. Many handbooks publish tables and examples or guides to the magnitude of safety factor which may be used and which is considered adequate.

8-1.2.4 LOAD FACTORS

Load factors are numbers representing multiplying factors applied to the load on the structure. These may be caused by any number of environmental conditions, such as an aircraft in arrested landing or in catapult take-off, a truck proceeding across country on rough or bumpy roads, or a ship subjected to an underwater blast or the firing of its own guns. Load or design factors usually are expressed in terms of g, or gravity units. Since the load analysis has been performed under a 1-*g* condition, the load factors can easily be taken into account by mulitplying calculated loads and reactions by the proper load factor. By this simple means it is easy to take into account different loading conditions in different directions or at different points in the structure without directly affecting the original load analysis.

In this regard, an important definition to remember is the *limit load factor*. This is the load which the structure is expected to experience—it is the limit of the load on the structure. The *design load factor* is larger than the limit load factor and is used to compute the stress in the structural members. Common practice is to define

$$\text{design load} = 1.5 \times (\text{limit load}) \qquad (8\text{-}18)$$

Although the 1.5 factor may be modified by the individual designer it is recommended that the range of selection remain between 1.5 and 2.0. Larger factors tend to be too conservative and result in an overweight and more costly structure.

8-1.2.5 MARGIN OF SAFETY

Margin of safety *MS* is expressed as a percent of the computed stress, or it is the percent increase of the computed stress required to equal the allowable stress. It is computed by the relationship

$$MS = \left(\frac{\text{allowable stress}}{\text{computed stress}} - 1\right)(100) \qquad (8\text{-}19)$$

If the computed stress equals the allowable stress there is obviously a zero margin of safety, and failure may be imminent. Therefore a positive margin is desired in all design, and experience has shown that a 15 percent margin is adequate for most purposes.

8-1.2.6 ALLOWABLE STRESS

An allowable stress is defined as the stress which a member may be allowed to reach (zero margin) and beyond which failure, as previously defined, is imminent. The allowable stress in all cases, except for yielding, is the ultimate stress of the material whether it be taken directly from the handbook as the ultimate tensile stress or whether it be calculated from a formula such as Euler's column formula. This means that all computed stress (with the noted exception) must be based upon the design load factor and margin of safety computed on these values. In some special problems where it is specified that the yeild stress shall be used as the failure criterion, the limit load factor should be multiplied by a minimum 1.15 factor instead of the 1.5 previously noted to conserve weight and cost. All problems and examples in this discussion, however, should consider that design load factors and the margins of safety are computed on the ultimate stress. Some sample problems will serve to illustrate the preceding discussion.

8-1.2.7 THIN-WALL CYLINDER

One of the most common containers for pyrotechnic materials is a thin-wall cylinder (Fig. 8-6[7]). These find such wide use that special analysis methods have been developed for them. For design analysis, the information from structural testing is usually converted to reduction factors that are then applied to the

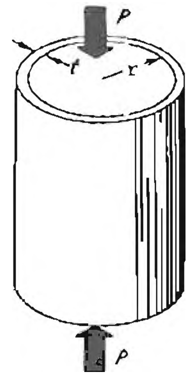


Figure 8-6. Thin-wall Cylinder

equations obtained from classical theory. Prior determinations of these reduction factors for radius r to thickness t ratios (r/t) above 500 have been based on fairing-in curves through the apparent mean of scattered test data.

The method presented here draws upon these prior studies and a considerable amount of additional test data to provide design curves for a wide range of materials and cross sections. The method is based on the equation

$$S_b = a\left(\frac{Et}{r}\right) \qquad (8\text{-}20)$$

where a is given by

$$a = 0.606 - 0.546\,(1 - e^n) \qquad (8\text{-}21)$$

and n by

$$n = -\frac{1}{16}\sqrt{\frac{r}{t}} \qquad (8\text{-}22)$$

and

S_b = critical buckling stress, psi

E = Young's modulus, psi

t = thickness of cylinder, in.

r = inner radius of cylinder, in.

This equation for S_b is simply a modified form of the classical buckling equation based on small-deflection theory. In the classical form, the equation contains a constant, 0.605, instead of the term a.

The critical axial (buckling) load P is then determined from

$$P = S_b A \qquad (8\text{-}23)$$

where

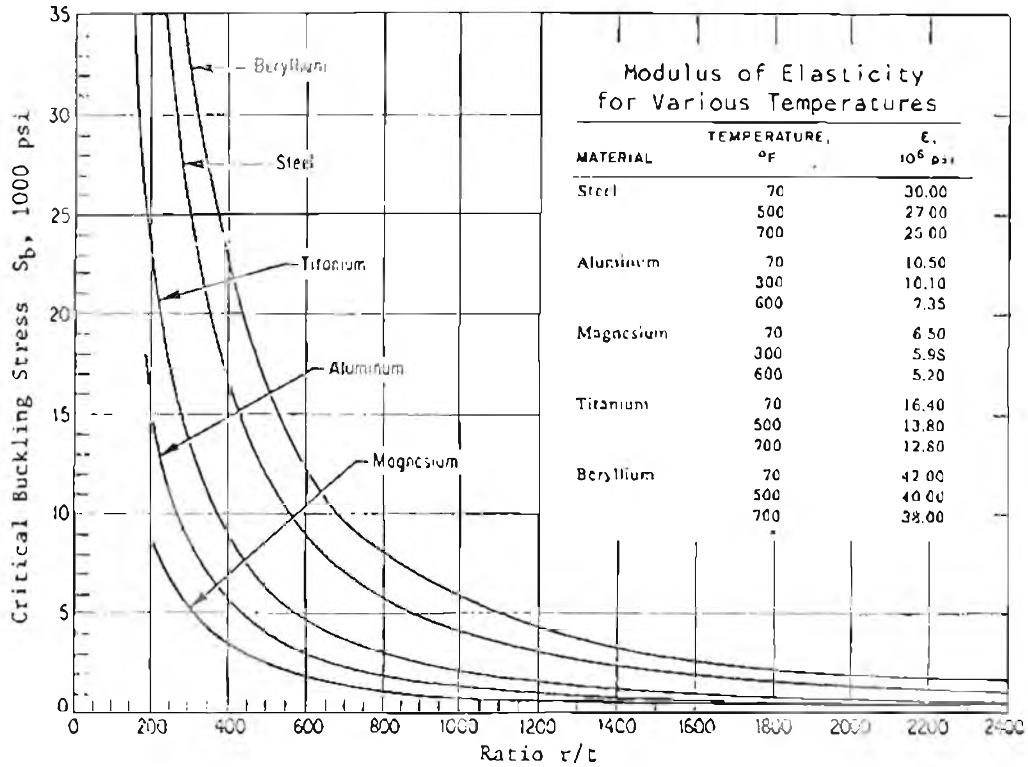
A = cross-sectional area of the thin-walled cylinder, in.^{2}

Graphical representations of the equation for S_b for various metals is shown in Fig. 8-7[7]. For all practical purposes, these curves apply to any alloy of these metals because the relevant property, modulus of elasticity, varies little from alloy to alloy. For high-temperature applications, critical loads can be computed by multiplying the room-temperature critical load by the ratio of elevated-temperature modulus to room-temperature modulus. Data for such calculations are provided in Fig. 8-7.

8-1.2.8 PLASTICS

Plastics have found widespread use because of their low cost and ease of molding into various forms, plastic ammunition cases being a common example. The strength of materials theory previously discussed is also valid for plastics; however, it should be realized that the properties of plastics can be radically different than those of metals. A summary of the mechanical properties of some plastics is given in Table 8-2[8].

The American Society for Testing Materials defines a plastic as *a material that contains as an essential ingredient an organic substance of large molecular weight, is solid in its finished state, and at some state in its manufacturing process it can be shaped by flow*[9]. Plastics are divided into two classes: thermoplastics and thermosetters. The former softens with increasing temperature and returns to its original hardness when cooled. The



MATERIAL	TEMPERATURE, °F	E, 10^6 psi
Steel	70	30.00
	500	27.00
	700	25.00
Aluminum	70	10.50
	300	10.10
	600	7.35
Magnesium	70	6.50
	300	5.95
	600	5.20
Titanium	70	16.40
	500	13.80
	700	12.80
Beryllium	70	42.00
	500	40.00
	700	38.00

Figure 8-7. Critical Buckling Stress as a Function of r/t

thermosetters harden when heated and remain hard when cooled. They "set" into permanent shape when heated under pressure. For compatibility of plastics see par. 8-1.3.2.

8-1.3 CHEMICAL COMPATIBILITY

Chemical compatibility is the ability of materials to remain in intimate contact for long periods without harmful chemical reaction. Incompatibility may cause loss of effectiveness, or produce a hazard. This concept is important because pyrotechnic materials are required to have a shelf life as long as 20 yr. Under such a time span, materials normally considered nonreactive can show change.

Compatibility of pyrotechnic materials may be judged under three main categories:

(1) Interactions with metallic components (corrosion)

(2) Interactions with nonmetallics (deterioration)

(3) Interactions of different pyrotechnic substances with each other (degradation or sensitization).

8-1.3.1 CORROSION OF METALLIC COMPONENTS

In almost every pyrotechnic application involving metals, some form of corrosion is possible. Corrosion of metallic surfaces may affect the integrity of the container, particularly at the joints. Hence, appropriate means of protection from corrosion is required. The designer must know the

TABLE 8-2

PROPERTIES OF PLASTICS

Material	Physics		Mechanical			Electrical		Environmental	
	Transparent	Flammable[c]	Ten Str, 1000 psi	Ten mod, 1000 psi	Impact Str[d]	Dielec Constant, 60 Hz	Dielec Str, V/mil[e]	Max Use Temp[f], °F	Weather Resistant[g]
THERMOPLASTICS									
ABS	No	Yes	4.5–8.5	200–420	2–3.5	2.8–2.9	300–450	160–236	No
Acetals	No	Yes	8–10	400–410	1.2–1.4	3.7–3.8	500	180–220	No
Glass Fiber Reinf	No	Yes	9–13	600–1000	3	–	–	220	No
Acrylics	Yes	Yes	8–11	350–450	<1	3.7	500	180–195	Yes
Impact Grade	Yes	Yes	5–8	200–300	1–2.5	3.5–3.7	450–480	165–185	–
PVC Alloy	No	SE	6.5	335	15	3.86	430	180	Yes
Cellulosics									
Cellulose Acetate	Yes	Yes	2–8	80–400	<1–6	3.5–7.5	250–360	140–170	No
Cellulose Acetate Butyrate	Yes	Yes	2.5–7	50–200	2–11	3.4–6.4	250–400	140–175	No
Cellulose Acetate Propionate	Yes	Yes	1.5–7.8	60–220	<1–11	3.7–4.2	300–1500	140–175	No
Cellulose Nitrate	Yes	Yes	7–8	190–220	5–7	7.0–7.5	300–600	120–140	No
Ethyl Cellulose	Yes	Yes	2–6.5	220–250	3–8	3.0–4.2	350–500	140–180	No
Chlorinated Polyether	No	SE[a]	6	160	<1	3.1	400	250	No
Fluorocarbons									
PTFE	No	NB[a]	2–4	80–100	3	2.1	500–600	500	Yes
Glass Fiber Reinf	No	NB	1–2.5	460	–	2.9–3.6	300–400	500	Yes
FEP	b	NB	2–3.5	60–80	DNB[a]	2.1	600–600	400	Yes
CTFE	No	NB	5–6	160–190	3–7	2.6	1000	390	Yes
PVF	b	SE	10–19	195–235	–	3.0–4.1	–	225	Yes
PVF_2	No	SE	5–7	120	3.8	8.4	260–1280	340	Yes
Nylons									
Nylon, 6	No	SE	9–12	200–400	1–4	3.8	300–420	250–300	No
Glass Fiber Reinf	No	SE	20–30	1000–2000	3–4	4.4–4.6	400–580	300–400	No
Nylon, 6/6	No	SE	11–13	400–420	1–2	3.6–4.0	300–400	275–300	No
Glass Fiber Reinf	No	SE	20–30	1400–2000	2.5–3.5	4.0–4.4	480–500	300–400	No
Phenoxies	Yes	Yes	9–10	380–400	1–12	4.1	500–520	170	No
Polycarbonates	Yes	SE	9–10	345	16	3.1	400	250	No
Glass Fiber Reinf	No	SE	15–20	1000–1700	3–4.5	3.7–3.8	475–482	270	No
ABS Alloy	No	Yes	8–9	370	10	2.74	500	225	No
Polyethylenes									
Low Density	b	Yes	<1–1.8	15–20	DNB	2.3	450–700	140–175	No
High Density	b	Yes	2–3.5	76–140	<1–6	2.3	450–500	180–225	No
Glass Fiber Reinf	No	Yes	4–11	240–900	4.5	2.3	–	–	No
High Mol Wt	No	Yes	2–5.5	100	–	2.3–2.6	600–710	180–225	No
Ethylene Copolymers									
EEA[a]	b	Yes	<1	–	–	2.8	550	120	No
EVA[a]	b	Yes	<1	–	–	3.16	525	120–170	No
Ionomers	Yes	Yes	3.4–4	25–40	8–14	2.4–2.5	485	140	No
Polyimides	No	NB	10	460	<1	3.5	400	500	–
Polyphenylene Oxides	No	SE	9–11	370	2.6	2.8	500	225	No
Modified	No	SE	9–10	355	1.3	2.6	550	165	No
Polypropylenes	b	Yes	3–5	160–200	<1	2.1–2.2	450–650	250	No
Glass Fiber Reinf	No	Yes	6–9	450–900	2.5	2.3–2.5	320–475	250	No
Polystyrenes	Yes	Yes	4–7	400–500	<1	2.5–2.65	500–700	150–190	No
Glass Fiber Reinf	No	Yes	11–15	840–1200	3	2.8–3.5	350–500	190–200	No
Impact Grade	No	Yes	2–5	200–400	<1–4	2.5–4.8	300–600	120–160	No
Polysulfones	Yes	SE	10	360	1.3	3.1	425	300	No
Glass Fiber Reinf	No	SE	16–18	1000–1600	1.7	–	–	300	No

[a]EEA: Ethylene ethyl acrylate. EVA: Ethylene vinyl acetate, NB: Nonburning, SE: Self-extinguishing, DNB: Does not break. [b]Transparent in thin films. [c]Many of the flammable plastics are available in self-extinguishing grades. [d]Lb-in. (notched), Izod, 1/8 in. thick sample. [e]1/8 in. sample. [f]No load. [g]Some plastics available in weather resistant grades.

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TABLE 8-2 (Cont'd)

Material	Physical		Mechanical			Electrical		Environmental	
	Transparent	Flammable[c]	Ten Str, 1000 psi	Ten mod, 1000 psi	Impact Str[d]	Dielec Constant, 60 Hz	Dielec Str, V/mil[e]	Max Use Temp[f], °F	Weather Resistant[g]
THERMOPLASTICS									
Polyurethanes	No	Yes	4.5–8	1–4	–	6–8	850–1100	190	No
Glass Fiber Reinf	No	Yes	9	70	–	–	–	200	No
Vinyls									
Flexible	Yes	SE	1–4	0.4–3	–	5–9	300–100	130	Yes
Rigid	Yes	SE	6–9	200–600	<1–18	3 4	350–370	165	Yes
Chlorinated, Rigid	No	SE	7–9	360–450	–	3.1	1200–1500	150–210	Yes
Styrene Acrylonitrile	Yes	Yes	8–12	500–600	<1	2.8–3	400–500	190	No
Glass Fiber Reinf	No	Yes	14–18	900–1850	4	3.2–3.6	510–525	200	No
THERMOSETS									
Alkyds, Mineral Filled	No	SE	9	2800	<1	5.5–6.0	300–400	275	No
Mineral/Cellulose Filled	No	SE	5.5	1900	1	5.8–6.5	300–400	250	No
Glass Filled	No	SE	8–10	2200–2800	8–12	5.2–6.0	300–400	300	No
Allyl Diglycol Carbonate	Yes	Yes	5–6	300	<1	–	–	212	No
Diallyl Phthalate									
Asbestos Filled	No	Yes	5.5	1200	<1	4.5–6.0	350–450	350–400	No
Dacron Filled	No	Yes	5	640	4.5	3.8	375–390	350–400	No
Long Glass Filled	No	Yes	10	1300	6.0	4.2	350–430	350–400	No
Short Glass Filled	No	Yes	7	1200	<1	4.4	350–430	350–400	No
Orlon Filled	No	Yes	6	710	1.2	3.7–4 0	400	300–500	No
Epoxies	Yes	Yes	4–13	3500	<1	4–5	400–500	250–550	No
Glass Fiber Reinf	No	SE	14–30	30,000	8–15	4–5	360	330–500	Yes
Glass Fabric Reinf	No	SE	25–60	35,000–40,000	40–60	–	450–550	500	Yes
Mineral Filled	No	SE	5–7	20,000–30,000	<1	4–5	330–400	300–500	Yes
Melamines									
Alpha Cellulose Filled	No	SE	7–8	1350	<1	7.9–8.2	270–300	210	No
Wood Flour Filled	No	SE	5.7–6.5	1000	<1	6.4–6.6	350–370	250	No
Rag Filled	No	SE	8–10	1400	<1	8.1–12.6	250–340	250	No
Asbestos Filled	No	SE	5 5–6.5	1950	<1	10.0–10.2	410–430	300	No
Glass Filled	No	SE	5.9	2000	<1–6	7.0–11.1	170–370	300	No
Phenolics									
Asbestos Filled	No	SE	46	500–900	<1	1–5	350	350	No
Mineral Filled	No	SE	4–7	1000–3000	<1	4.7–40.0	150–400	250–450	No
Glass Fiber Filled	No	SE	5–10	3000–3300	<1	7.1–7.2	200–370	350–450	No
Wood Flour Filled	No	SE	5–8	800–1300	<1	7.0–13.1	230–350	300–350	No
Rubber Phenolic	No	SE	5–6.5	400–600	<1–2 5	7.9–21.2	210–400	212–360	No
Cloth Filled	No	SE	5–9	9000–14,000	10–30	6.5–15 0	200–350	250–300	No
Polyesters									
Glass Fiber Reinf	No	Yes	10–20	1100–1800	5–25	3.3–4.0	300–350	250–350	No
Glass Cloth Reinf	No	Yes	9–24	800–1800	10–20	3.3–4.0	300–350	250–350	No
Mineral Reinf	No	Yes	3–3.5	50–250	<1	3.3–4.0	300–350	250–350	No
Silicone, Glass Cloth Reinf	No	NB	20–40	1800–3200	12–18	–	100–400	500	–
Ureas									
Alpha Cellulose Filled	No	SE	5.5–7	1300–1400	<1	7.7–7.9	330–370	170	No
Wood Flour Filled	No	SE	5.5–10	1300–1600	<1	7.0–9.5	300–400	170	No

[a]EEA: Ethylene ethyl acrylate, EVA: Ethylene vinyl acetate, NB: Nonburning, SE: Self-extinguishing, DNB: Does not break. [b]Transparent in thin films. [c]Many of the flammable plastics are available in self-extinguishing grades. [d]Lb-in. (notched), Izod, 1/8 in. thick sample. [e]1/8 in. sample. [f]No load. [g]Some plastics available in weather resistant grades.

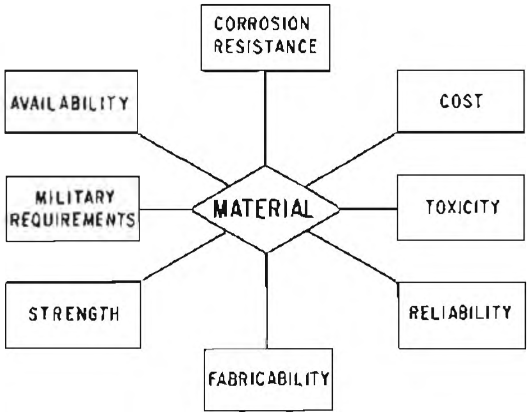


Figure 8-8.
Factors Affecting Choice of an Engineering Material

operational requirements of the pyrotechnic device, the environmental conditions that it will encounter in service, and the materials that are available in order that protective measures can be taken. Designers of military hardware must also be aware of combinations of materials, such as copper and lead azide, the reaction of which form sensitive explosive materials. It is difficult to achieve a solution that meets all requirements; therefore, it becomes necessary to balance the corrosion resistant qualities of a particular metal against other factors as illustrated in Fig. 8-8[10]. All these factors are always part of corrosion design, otherwise, the designer would use platinum which is virtually corrosion resistant.

In situations where alternate materials are being considered, it may become necessary to conduct simulated service tests to determine suitability of the material

8-1.3.1.1 CORROSION PROCESSES

Corrosion is a process involving the transformation of elemental metals to compounds of the metals through electrochemical reaction with their environment[11].

TABLE 8-3

ELECTROMOTIVE SERIES

	Metal	Standard Electrode Potential V at 25°C, volts EMF[a]
Less Noble (Anodic)	Magnesium	−2.340
	Beryllium	−1.700
	Aluminum	−1.670
	Manganese	−1.050
	Zinc	−0.762
	Chromium	−0.710
	Iron	−0.440
	Cadmium	−0.402
	Cobalt	−0.277
	Nickel	−0.250
More Noble (Cathodic)	Tin	−0.136
	Lead	−0.126
	Hydrogen	0.000
	Copper	+0.345
	Silver	+0.800
	Mercury	+0.854
	Platinum	+1.200
	Gold	+1.420

Note:
[a]These values are obtained when the specific metal is placed in a solution containing one equivalent weight of its ions per liter.

The tendency for a metal to acquire an electric potential when it is immersed in an aqueous solution can be characterized by what is known as the electromotive series of metals (see Table 8-3[12]). The metals with a very great tendency for forming ions in solution (magnesium, aluminum, manganese, zinc) are at the reactive or less noble end of the series, while metals with little tendency to form ions (platinum, gold) are at the noble or unreactive end of the series. Thus, there is a relationship between the susceptibility of a metal to corrode and its position in the series.

The electrode potential of a metal is dependent on the concentration and type of ions in solution which usually are quite different from the arbitrary conditions established for the electromotive series. Metal specimens immersed in solutions containing ions (cations) of that metal only, but of different concentrations, will have a higher potential or tendency to dissolve as the concentration of ions in the solution decreases and vice versa.

Further, the nonmetallic ions (anions) in solution also will influence the potential of the metal, depending on whether or not the anions will complex with the metal ions and promote dissolution of the metal. For example, tin is more reactive than iron in dilute citric or oxalic acid solutions owing to the fact that the concentration of tin ions is kept relatively small by the complexing power of the acid. From this it can be seen that reversals of activity of elements in the electron active series are possible under various situations encountered in practice.

Accordingly, Table 8-3 should be used only as a general guide for establishing the relative corrosion behavior of metals in a particular environment.

To account for overall and practical aspects as well as theoretical considerations, another relationship has been devised. It is referred to as Galvanic Couples, shown in Table 8-4[13]. In this table, members of groups connected by lines are considered as permissible couples. However, this should not be construed as being devoid of galvanic action. Permissible couples represent a low galvanic effect. There are several factors which influence and control galvanic action, namely, the effectiveness of the electric circuit, the ratio of anode and cathode areas, and the polarization of the electrodes.

Galvanic corrosion requires not only a conductive environment but also good electrical contact between the dissimilar metals. If this is not maintained, the galvanic action will subside. Insulation materials–such as nonwicking gaskets, paint and plastic films, and certain inorganic coatings at the mating surfaces of the dissimilar metals will prevent or reduce the galvanic current and the progress of corrosion. This, of course, brings the designer in direct conflict with accepted EMR shielding design which requires the best electrical contact possible; therefore, some compromise must be made, if electrical shielding is of concern.

Another deterrent to galvanic corrosion is polarization. This condition can occur either at the anode or cathode and is the result of deposition through electrolytic action. Corrosion products can accumulate at the anode or hydrogen deposited at the cathode. Either tends to reduce the electrochemical action. The designer must be aware of these contributing factors in order to decide their importance in his application.

8-1.3.1.2 TYPES OF CORROSION

There are a number of types of corrosion which are evidenced by uniform corrosion attack over a surface of the metal or concentrated attack at local or isolated areas. A brief discussion of types that are of concern with pyrotechnic material follows:

(1) Uniform Corrosion: simplest form of corrosion which can occur in atmosphere, liquids, or in soil. Examples are rusting of iron, tarnishing of silver, and high-temperature oxidation of iron or stainless steels.

(2) Galvanic Corrosion: previously discussed. Corrosion results from grouping of dissimilar metals in a conductive environment.

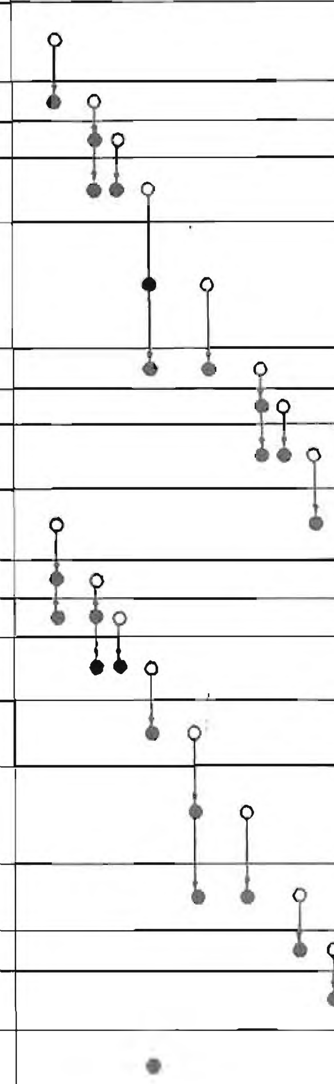
(3) Concentration-cell Corrosion: caused by nonuniformity of electrolyte or the environment. It is electrochemical in nature and ensues because of differences in ion concentration or of cracks or crevices in the metal surface which deplete electrolyte components because of reactions in confined places.

(4) Stress Corrosion: results from the combined effects of tensile stresses and corrosion. Cold-working, quenching, grinding, or welding may produce internal stresses. The most destructive type of stress is that which is

TABLE 8-4

GALVANIC COUPLES

Group	Metallurgical Category	EMF, V	Permissible Couples*
1	Gold, Solid and Plated; Gold-Platinum Alloys, Wrought Platinum	+0.15	
2	Rhodium; Graphite	+0.05	
3	Silver, Solid or Plated; High Silver Alloys	0	
4	Nickel, Solid or Plated; Monel; High Nickel-Copper Alloys; Titanium	−0.15	
5	Copper, Solid or Plated; Low Brasses or Bronzes; Silver Solder; German Silver; High Copper-Nickel Alloys; Nickel-Chrome Alloys; Austenitic Stainless Steels (301, 302, 304, 309, 316, 321, 347)	−0.20	
6	Commercial Yellow Brasses and Bronzes	−0.25	
7	High Brasses and Bronzes; Naval Brass; Muntz Metal	−0.30	
8	18% Chromium Type Corrosion-Resistant Steels 440-430, 431, 446, 17-7PH, 17-4PH	−0.35	
9	Chromium, Plated; Tin, Plated; 12% Chromium Type Corrosion-Resistant Steel, 410, 416, 420	−0.45	
10	Tin-Plate, Terneplate; Tin-Lead Solders	−0.50	
11	Lead, Solid or Plated; High Lead Alloys	−0.55	
12	Aluminum, Wrought Alloys of the Duralumin Type, 2014, 2024, 2017	−0.60	
13	Iron, Wrought, Gray, or Malleable; Plain Carbon and Low Alloy Steels; Armco Iron	−0.70	
14	Aluminum, Wrought Alloys other than Duralumin; Type 6061, 7075, 5052, 5056, 1100, 3003, Cast Alloys of the Silicon Type 355, 356	−0.75	
15	Aluminum, Cast Alloys other than Silicon Type; Cadmium, Plated and Chromated	−0.80	
16	Hot-Dip-Zinc Plate; Galvanized Steel	−1.05	
17	Zinc Wrought; Zinc-Base Die Cast Alloys; Zinc, Plated	−1.10	
18	Magnesium and Magnesium-Base Alloys Cast or Wrought	−1.60	



*Members of groups connected by lines are considered as permissible couples; However, this should not be construed as being devoid of Galvanic action. Permissible couples represent a low Galvanic effect.
○Indicates the most Cathodic member of the series, ●An Anodic member, and the arrows indicate the Anodic direction.
Refer to Table II, MIL-STD-186, for group amplification of Galvanic couples.

local and nonuniform; the stressed zones are subject to accelerated corrosion.

(5) Fretting Corrosion: term is applied to metal damage caused when two metal surfaces are in contact, under load, and subjected to vibration or relative motion. Corrosion is characterized by surface discoloration, depressions, or pits.

(6) High Temperature Oxidation: direct combination of an oxidizing agent (oxygen, sulphur dioxide, carbon dioxide) with a metal at high temperatures.

(7) Pitting: common and severe form of localized corrosive attack. Thin metal sheets and plates are especially vulnerable; corrosion may result in perforation and subsequent unserviceability.

(8) Corrosion Fatigue: fatigue failure brought about by a corrosive environment. Endurance limit of metal is lowered as it undergoes stress cycles.

(9) Dezincification: occurs with some brasses. Involves loss of zinc, leaving a residue of one or more other constituents, primarily copper. If not arrested, the entire metal will be reduced to a weak spongy mass. An example of dezincification of brass is given in Fig. 8-9[11]. A brass case was crimped over a lead projectile. In the presence of an ammonium based powder the dezincification of the brass occurred and it cracked as shown.

(10) Graphitization: occurs in grey cast iron and is similar to dezincification suffered by some brasses. This type of corrosion requires specific conditions which corrode away the iron leaving a matrix which is mostly graphite.

(11) Biological: various types of microorganisms, bacteria, yeasts, and molds influence the electrochemical reactions which cause corrosion. The most common result of this influence is pitting.

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Figure 8-9.
Case Cracking Due to Dezincification

The foregoing constitutes a list of the main corrosion hazards that a designer faces. Ways and means of overcoming these hazards are the subject of the next paragraph.

8-1.3.1.3 METHODS OF PROTECTION

In the design of pyrotechnic devices, the corrosive effect of the atmosphere and the pyrotechnic material can be minimized by proper choice of materials and use of protective coatings, encapsulation, evacuation, and hermetic seals. Materials which break down or outgas should not be used in devices which are to be evacuated and sealed.

Material selection should be based first on suitability and second on inherent resistance to corrosion. If dissimilar metals are used in contact or near one another, they should be protected against electrolytic corrosion. Preventive measures are listed in Table 8-5[14], and the specifications for metallic coatings are summarized for reference in Table 8-6[14]

Preference should be given to those metals and alloys which are resistant to both intergranular and stress corrosion. Fabrication operations such as bending, forming, and shaping should be performed on the metals in the annealed conditions.

Hydrogen embrittlement can result in a delayed fracture in those metals which can pick up hydrogen from acid cleaning or plating. If metals must be used which are susceptible to embrittlement, the following techniques can be used to minimize the damage:

TABLE 8-5

PREVENTION OF DISSIMILAR METAL CORROSION

Preventive Measure	Example
(1) Select metals which form a permissible couple in Table 8-4	Use nickel, not naval brass, in contact with silver.
(2) Interpose a metal which reduces the potential difference between the two metals.	Tin plate brass to be used next to aluminum.
(3) Design the metal contact so the relative area of the cathodic (more noble) metal is the smaller.	Stainless steel screws in aluminum chassis.
(4) Apply corrosion inhibitor such as zinc chromate primer MIL-P-8585 or zinc chromate paste MIL-P-8116.	Use zinc chromate inhibitor when assembling steel screws in aluminum.
(5) Interpose an insulating barrier or nonhygroscopic gasket between dissimilar metals	In structural joints, interpose tape MIL-T-23142 In components, use organic insulants such as conformal coating MIL-I-46058.
(6) Apply insulating organic coating to surface of each metal	Coatings such as vinyl zinc chromate primer MIL-P-15930, epoxy primer MIL-P-52192, insulating coating MIL-C-46057, MIL-V-173, MIL-I-46058.
(7) Seal joint area with moisture-proof coating or organic sealant	In structural joints, sealant such as MIL-S-7124. In components, coatings such as MIL-V-173 or MIL-I-46058.

(1) Use of organic coating, vacuum deposition.

(2) Use of low hydrogen embrittlement baths prior to plating.

(3) Embrittlement relief after plating (baking)[15]; with thermal stress relief and mechanical stress relief performed prior to plating.

(4) Elimination of acid or alkaline cathode cleaning methods.

The most effective means of preventing electrolysis, is the application of protective film or coatings. These protective coatings can be described under three main headings: chemical or anodic films, metallic coatings, and organic coatings.

(1) Chemical or Anodic Films

In chemical or anodic treatment, metals and alloys are coated with suitable solutions of chemicals under controlled conditions to form protective surface coatings. This coating is physically integrated with the underlying metal and serves as a barrier against corrosive attack. Coatings commonly used are oxides, phosphates, chromates, or complex compounds of the substrate metal and the components of the metal, and the components of the treatment solutions. These coatings may be formed on iron and steel, aluminum, magnesium, cadmium, and other metals and should be applied after fabrication or machining operations.

(2) Metallic Coatings

TABLE 8-6

SPECIFICATIONS FOR METALLIC COATINGS

Metal	Specification
Aluminum, vacuum deposited	MIL-C-23217
Cadmium, electroplated	QQ-P-416
Cadmium, electroplated, low hydrogen content	AMS 2401
Cadmium, vacuum deposited	MIL-C-8837
Chromium, electroplated	QQ-C-320
Copper, electrodeposited	MIL-C-14550
Gold, electrodeposited	MIL-G-45204
Lead, electrodeposited	MIL-L-13808
Lead, hot dip	MIL-L-13762
Nickel, electrodeposited	QQ-N-290
Nickel-cadmium, diffused	AMS-2416
Nickel-phosphorus, electrodeposited	MIL-C-26074
Palladium, electrodeposited	MIL-P-45209
Rhodium, electrodeposited	MIL-R-46085
Silver, electrodeposited	QQ-S-365
Tin, electrodeposited or hot dip	MIL-T-10727
Tin-cadmium, electrodeposited	MIL-P-23408

Metallic coatings should be selected for their suitability for the application involved, with attention to problems of aging, cracking, diffusion, and corrosion. When metallic coatings are applied by electroplating, hydrogen embrittlement should be avoided. There are recommendations (see Table 8-4) for the prevention of corrosion which should be considered and specifications (see Table 8-5) for the coatings themselves.

Metallic coatings are also applied to some metals by the process of hot-dipping. This is largely confined to the coatings of ferrous alloys with metals and alloys of low melting points. Typical hot-dipping coating materials are zinc, and tin and lead alloys including terne metal. Tinned steel. and zinc-coated or galvanized iron and steel products are the most common hot-dipped products. If corrosion-resistant steels are used, passivation should be done in accordance with QQ-P-35[15]. If steels of the 300 series are used, no further finish is required.

The noble metals (gold, palladium, platinum, and rhodium) and the corrosion-resistant metals (chromium, nickel, tin, tin-lead solder, and titanium) require no finish other than cleaning.

Applications of aluminum, copper, and magnesium require special treatment unless they are used in hermetically sealed units. Aluminum should be anodized; where this is impossible, chemical film treatment in accordance with MIL-C-5541[16] may be used. Continued exposure of aluminum at high temperatures may require the use of metallic coatings. Copper and copper alloys may be black oxide treated in accordance with MIL-F-495 or may be plated or painted. If bare copper is required, a tarnish-preventive thin silicone cured resin film may be used. Magnesium has very poor resistance to corrosion and therefore it should be anodized. Several coats of alkali resistant primer with one or more coats of compatible top coat should be applied or it may be given moisture proofing coatings such as epoxy or polyurethane. Furthermore, magnesium used with any other metal requires extreme precautions to prevent destructive corrosion.

Cladding is a process for covering one metal with another metal to utilize the superior corrosion resistant properties of the exposed metal. Cladding may be applied by working, co-rolling, pressure welding, spot welding, explosive welding, and diffusion welding. Principal clad composites produced for industrial purposes are high purity aluminum or aluminum alloys on less resistant aluminum alloys; stainless steel on steel; nonferrous metals including copper, brass, lead, nickel, and nickel alloys on steel. With the advent of explosive welding almost any desirable combination of properties is possible.

Metal coatings can also be applied by metallizing or metal spraying. Metallized coatings are porous, but they provide protection from corrosion mainly because of their thickness. They require sealing or impregnation followed by painting. Metals used to spray coat are zinc, cadmium, and aluminum.

(3) Organic Coatings

Organic coatings are used to protect metal parts, equipment, and structures primarily against atmospheric corrosion. They are applied as liquids and act chiefly as a barrier between the metal to be protected and the environment. The value of the organic coatings depends upon their ability to provide complete and uniform coverage, a good degree of impermeability, good adhesion, cohesion, resistance to mechanical damage, and good chemical inertness.

An example of such a coating employed in pyrotechnic ammunition is the asphalt compound for coating cavities prior to filling with explosives[17]. Table 8-7[18] tabulates a few of the organic coatings that are available and lists their chemical resistance characteristics.

8-1.3.2 DETERIORATION OF NONMETALLIC COMPONENTS

When a pyrotechnic material is placed inside a metal container, there may be interactions with nonmetallic parts such as spacer, gaskets, sealants, and potting compounds. The gradual change of these materials is often designated deterioration rather than corrosion. When considering materials such as plastics, ceramics, and rubbers, the number becomes extremely large—too large to list in this brief discussion. Fortunately there are documents that are readily available to aid the designer in selecting the proper choice of materials as discussed in the paragraphs that follow.

8-1.3.2.1 PLASTICS

A general listing of plastics and their resistance to external attack is shown in Table 8-2. Fluorocarbons are considreed the noble materials of the plastics, just as platinum and gold are for metals, in that they are generally resistant to most environments. Typical fluorocarbons are Teflon and Kel-F.

To obtain more specific information on a given plastic it is necessary to refer sources that gives detailed information. Good references for this purpose are Refs. 18, 19, and 20. For properties of plastics see also par. 8-1.2.8.

8-1.3.2.2 NATURAL AND SYNTHETIC RUBBERS

The outstanding characteristic of rubber and elastomers is resilence, or low modulus of elasticity. However, chemical and abrasion resistance and good insulation qualities also result in many applications. The natural rubbers have better mechanical properties while the synthetics are more resistant to deterioration. Properties are compared in Table 8-8[18].

Natural rubber is soft but can be made semi-hard or hard by vulcanizing. Synthetic rubber is available in a wide variety of materials including combinations with plastics. Plasticizer fillers and hardeners are compounded to obtain a large range of properties as illustrated in Table 8-8. Note for example that the temperature resistance of silicone rubber is 580°F. Handbook data are available in Refs. 18 and 20.

TABLE 8-7

ORGANIC MATERIALS

Type	Alkyd							Cellulose			Epoxy					
	Alkyd	Alkyd-Amine	Alkyd-Phenolic	Alkyd-Silicone	Alkyd-Urea	Styrenated Alkyd	Acrylic	Nitro-cellulose	Butyrate	Ethyl Cellulose	Epoxy-Amine	Epoxy-Ester	Epoxy Furane	Epoxy-Melamine	Epoxy Phenolic	Epoxy-Urea
CHEMICAL RESISTANCE																
Exterior Durability	E	E	E	E	E	G	E	E	E	E	G	E	E	E	E	VG
Salt Spray	E	VG	E	E	G	G	E	E	E	E	VG	E	E	E	E	E
Solvents–Alcohols	F	G	G	G	G	G	P	G	G	P	G	F	E	E	E	E
Solvents–Gasoline	G	E	E	E	E	F	G	G	G	P	E	E	E	E	E	E
Solvents–Hydrocarbons	G	E	E	G	E	F	F	F	F	F	E	VG	E	E	E	E
Solvents–Esters, Ketones	P	P	P	P	F	P	P	P	P	P	VG	F	VG	E	E	VG
Solvents–Chlorinated	P	P	P	P	P	P	P	P	P	P	G	F	E	E	E	E
Salts	VG	E	E	VG	E	E	VG	G	VG	G	E	E	E	E	E	E
Ammonia	P	P	P	P	P	P	P	P	P	G	G	P	E	P	F	P
Alkalis	P,P	VG,G	F,P	G,P	G,G	G,VG	G,F	P,P	P,P	G,G	E,E	E,E	E	E,E	E,E	E,E
Acids–Mineral	F,P,P	G,F,P	VG,G,F	G,P,P	F,P,P	G,F,P	G,F,P	E,G,F	G,F,P	G,F,P	E,VG,G	G,F,P	G	E,VG,G	E,E,E	E,VG,F
Acids–Oxidizing	P,P,P	F,P,P	G,F,P	P,P,P	F,P,P	F,P,P	F,P,P	P,P,P	P,P,P	F,P,P	G,P,P	F,P,P	F	G,P,P	E,VG,P	F,P,P
Acids–Organic (acetic, formic, etc.)	P,P,P	P,P,P	F,P,P	P,P,P	P,P,P	P,P,P	P,P,P	P,P,P	P,P,P	G,–,–	F,F,P	F,P,P	F,G	G,P,P	E,E,VG	F,P,P
Acids–Organic (oleic, stearic, etc.)	F	G	VG	G	F	F	F	F	F	–	G	E	E	E	E	E
Acid Phosphoric	P	P	P	P	P	P	P	E	P	–	G	P	E	G	E	G
Water (salt, fresh)	F	G	G	G	F	G	E	G	E	E	G	VG	E	G	E	G

Type	Chlorinated Polyether	Chlorinated Poly-propylene	Fluoro-carbon	Furane	Phenolic	Poly amide (nylon)	Poly-ester	Silicone	Poly-ethylene	Rubber				Ure-thane	Vinyl
										Chlorinated Rubber	Neoprene	Hypalon	Viton		
CHEMICAL RESISTANCE															
Exterior Durability	E	E	E	G	E	P	E	E	P	E	E	E	E	E	E
Salt Spray	E	E	E	G	E	F	E	E	VG	E	E	E	E	E	E
Solvents–Alcohols	E	E	E	E	E	G	G	F	E	E	E	–	E	VG	F
Solvents–Gasoline	E	F	E	E	E	G	E	F	P	G	G	G	E	F-G	G
Solvents–Hydrocarbons	E	F	E	E	E	–	E	G	–	–	G	G	E	E	–
Solvents–Esters, Ketones	E	P	P	G	F	–	P	P	–	P	P–F	P-F	VG,E	F-G	P
Solvents–Chlorinated	E	P	E	E	F	–	P	P	G	P	P	P	–	F	F
Salts	E	E	E	E	E	–	G	G	P	P	P	P	G	F	P
Ammonia	E	G	E	E	P	G	P	P	E	E	E	E	E	E	E
Alkalis	E	VG,VG	E,F	E	P,P	G,G	P	E,F	E	G	G	G	E	P	E
Acids–Mineral	E,E,E,	E,G,G,	E,E,E,	E	G,F,P	P,P,P	E	G,G,P	P,G	E,E	E,E	E,E	E,E	VG,F	E,E
Acids–Oxidizing	E,G,F	E,E,G	E,E,E	P	G,F,P	–	P	P,P,P	–	E,E,E	E,G,G	E,E,G	E,E,E	G,F,P	E,E,G
Acids-Organic (acetic, formic, etc.)	E,E,E	G,P,P	E,E,E	F,G	G,F,P	P,P,P	P	P,P,P	VG,VG,VG	E,E,F	F,P,P	G,G,F	E,E,E	G,F,P	E,VG,G
Acids–Organic (oleic, stearic, etc.)	E	G	E	E	E	VG	F	G	VG,F,P	G,P,P	G,F,F	G,F,F	G,G,G	G,F,F	E,P,P
Acids–Phosphoric	E	G	E	E	F	–	F	F	G	F	G	G	G	G	E
Water (salt, fresh)	E	E	E	E	E	F	G	E	VG	G	VG	G	G	G	G

Legend: E=excellent; VG=very good; G=good, F=fair; P=poor

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TABLE 8-8

PROPERTY COMPARISONS—NATURAL AND SYNTHETIC RUBBERS

Type →		Natural Rubber (Cis-polyisoprene)	Butadiene-Styrene (GR-S)	Synthetic (Polyisoprene)	Butadiene-Acrylonitrile (Nitrile)	Chloroprene (Neoprene)	Butyl (Isobutylene-isoprene)
PHYSICAL PROPERTIES	ASTM						
Specific Gravity	D792	0.93	0.94	0.93	0.98	1.25	0.90
Ther Cond, Btu/hr/sq ft/°F/ft	C177	0.082	0.143	0.082	0.143	0.112	0.053
Coef of Ther Exp (cubical), 10^{-5} per °F . .	D696	37	37	–	39	34	32
Electrical Insulation	. . . . .	Good	Good	Good	Fair	Fair	Good
Flame Resistance	. . . . .	Poor	Poor	Poor	Poor	Good	Poor
Min Rec Svc Temp, °F	. . . . .	-60	-60	-60	-60	-40	-50
Max Rec Svc Temp, °F	. . . . .	180	180	180	300	240	300
MECHANICAL PROPERTIES							
Ten Str, psi							
Pure Gum	D412	2500-3500	200-300	2500-3500	500-900	3000-4000	2500-3000
Black	D412	3500-4500	2500-3500	3500-4500	3000-4500	3000-4000	2500-3000
Elongation, %							
Pure Gum	D412	750-850	400-600	–	300-700	800-900	750-950
Black	D412	550-650	500-600	300-700	300-650	500-600	650-850
Hardness (durometer)	. . . .	A30-A90	A40-A90	A40-A80	A40-A95	A20-A95	A40-A90
Rebound							
Cold	. . . . .	Excellent	Good	Excellent	Good	Very good	Bad
Hot	. . . . .	Excellent	Good	Excellent	Good	Very good	Very good
Tear Resistance	. . . . .	Excellent	Fair	Excellent	Good	Fair to good	Good
Abrasion Resistance	. . . . .	Excellent	Good to excellent	Excellent	Good to excellent	Good	Good to excellent
CHEMICAL RESISTANCE							
Sunlight Aging		Poor	Poor	Fair	Poor	Very good	Very good
Oxidation		Good	Good	Excellent	Good	Excellent	Excellent
Heat Aging		Good	Very good	Good	Excellent	Excellent	Excellent
Solvents							
Aliphatic Hydrocarbons.		Poor	Poor	Poor	Excellent	Good	Poor

TABLE 8-6

PROPERTY COMPARISONS—NATURAL AND SYNTHETIC RUBBERS (Cont'd)

Type—	Natural Rubber (Cis-polyisoprene)	Butadiene-Styrene (GR-S)	Synthetic (Polyisoprene)	Butadiene-Acrylonitrile (Nitrile)	Chloroprene (Neoprene)	Butyl (Isobutylene-isoprene)
Aromatic Hydrocarbons	Poor	Poor	Poor	Good	Fair	Poor
Oxgenated, Alcohols	Good	Good	Good	Good	Very good	Very good
Oil, Gasoline	Poor	Poor	Poor	Excellent	Good	Poor
Animal, Vegetable Oils	Poor to good	Poor to good	—	Excellent	Excellent	Excellent
Acids						
Dilute	Fair to good	Fair to good	Fair to good	Good	Excellent	Excellent
Concentrated	Fair to good	Fair to good	Fair to good	Good	Good	Excellent
Permeability to Gases	Low	Low	Low	Very low	Low	Very low
Water Swell Resistance	Fair	Excellent	Excellent	Excellent	Fair to excellent	Excellent
USES	Pneumatic tires and tubes; power transmission belts and conveyor belts; gaskets; mountings; hose; chemical tank linings; printing press platens; sound or shock absorption; seals against air, moisture, sound and dirt		Same as natural rubber	Carburetor diaphragms, self-sealing fuel tanks, aircraft hose, gaskets, gasoline and oil hose, cables, machinery mountings, printing rolls	Wire and cable belts, hose, extruded goods, coatings, molded and sheet goods, adhesives, automotive gaskets and seals, petroleum and chemical tank linings	Truck and automobile tire inner tubes, curing bags for tire vulcanization and molding, steam hose and diaphragms, flexible electrical insulation, shock, vibration absorption

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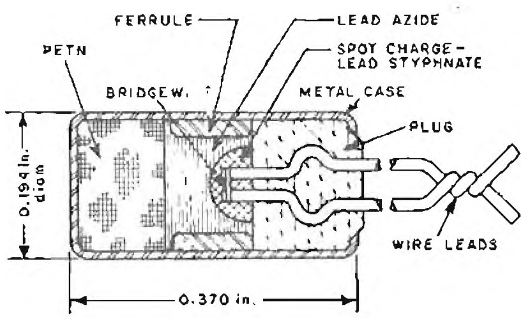

Figure 8-10.
Example of Several Mixes in One Device

8-1.3.2.3 CERAMICS

The class of materials referred to as ceramics includes brick, magnesia, fused silica, stoneware, porcelain, and glass. In general, compared to metals, these materials are inert to chemical action except for hydrofluoric acid; however, they all tend to be rather brittle, weak in tension, and subject to thermal shock.

One technique that permits the use of the chemical inertness of ceramic while overcoming its lack of strength is to coat the metal or plastic that needs to be protected with the ceramic. This is done by a process referred to as thermal-spraying, flame-spraying, or flame jet coating. Temperatures of the jet are in the order of 30,000°F.

8-1.3.3 DEGRADATION AND SENSITIZATION OF PYROTECHNIC MATERIALS

In some pyrotechnic devices, more than one mix may be used and they may be in contact with each other. As an example, consider the T24E1 Detonator shown in Fig. 8-10. A lead styphnate spot charge is covered by a lead azide charge which, in turn, is in contact with PETN. Experience has shown that these materials are compatible. Unfortunately there is no convenient source for the designer to find specific information on the compatibility of pyrotechnics. However, some limited compilations have been made[21,22].

8-2 SAFETY

Safe practices in the use, handling, storage, and manufacture of pyrotechnics are the result of the experience and knowledge of interested personnel and safety experts. Safe practices are necessary because many of the ingredients and mixtures are toxic, sensitive, and potentially explosive. A thorough knowledge of pyrotechnic ingredients, compositions, and their reactions is an absolute necessity for handling pyrotechnics in the best and safest manner. Safety cannot be delegated; it is the responsibility of each worker. Supervisors must personally assume responsibility for educating subordinates and promoting safety within their groups. The subject of pyrotechnic safety is treated fully in Ref. 23 while considerations of safety in general are covered in the *Safety Manual*, Ref. 24.

It is worth noting that there is probably a greater variety of potential hazards arising from pyrotechnics than from ordinary explosives. Some of the basic safety precautions that apply to pyrotechnics may be summarized as follows[23]:

(1) Know the characteristics of the ingredients and compositions such as toxicity, sensitivity, reactivity with other materials, safe working limits and storage, and disposal problems. In addition—when dealing with finished pyrotechnic devices such as flares, smoke screening aids, and simulators one should know the output characteristics and the method (or methods) of initiation.

(2) Recognize the dangerous situations that may arise because of potential or actual hazards.

(3) Minimize the hazards by working with or handling small quantities and observing established practices for safety equipment, processing, testing, handling, storage, and

disposal. The practices of good housekeeping are fundamental to safe practices.

8-2.1 HAZARD CLASSIFICATION

Hazardous materials are arranged into eight levels according to their storage hazard (see par. 8-2.3), and explosives are divided into three levels according to their shipping hazard (see par. 8-2.4). The proper hazard classification of each item must be known before pyrotechnic items can be made or used safely. The *Safety Manual* contains a general suide to hazard classes[24].

If the hazard level of a particular pyrotechnic item has not been established, it must be obtained by standard tests devised for this purpose[25]. Tests include the establishment of hazards within and between containers as well as the hazards due to fragmentation, blast, and fire. The minimum test criteria are summarized in Table 8-9[25]. For a description of the tests, see par. 6-7 and for detailed procedures of sensitivity, brisance, and stability tests, see Ref. 26.

Rigorously speaking, hazards can be established with precision only when we can pinpoint the environment to which ammunition containing pyrotechnics is subjected. This is a difficult task. A recent study proposed that more effort be spent to sharpen the definition[27]. In the stockpile-to-target environment—transportation, storage, and delivery-to-target phases—many of the specific environments are unknown. To make matters worse, there is also doubt as to how well the

TABLE 8-9

MINIMUM TEST CRITERIA FOR DETERMINING HAZARD CLASSIFICATION OF PYROTECHNICS

1. Type	2. Packaging, as Normally Stored and Shipped	3. Type of Info To Be Determined by Test	4. Types of Initiation To Obtain Info Outlined in Item 3
Burning	Individual Item or Unit	Propagation Within A Single Container	Simple Ignition
Detonating	More Than 1 Item Per Unit	Propagation from 1 Container to Another	Detonation
		Determination of Fragment Hazard	External Heat
		Determination of Blast Hazard	
		Determination of Fire Disbursement Hazard	

5. Minimum Test Criteria

Type test	Number items per test	Number of tests	Priming	Booster	Confinement
Test A. Detonation	1 Container	5	Normal Means of Ignition or Engr Special Blasting Cap	None	None
Test B. Detonation	2 Containers	5	Same as Above	None	None
Test C. External Heat	1 to 6 Containers Depending on Size of Unit	1	None	None	Steel Banded

tests simulate the actual environments. Further, the present approach for determining how a pyrotechnic responds is to test it in a particular hardware. This makes it difficult to predict the response for similar items in different hardware. For example, a maximum storage temperature of 165°F is widely used. If the rate of heat flow into the item were specified instead, a more meaningful tests could be performed. A small pyrotechnic tem exposed in an oven may require a heat of 130 Btu ft^{-2} hr^{-1} to reach and maintain 165°F. However, a large air-launched flare weighing 250 lb may require 450 Btu ft^{-2} hr^{-1} to reach and maintain the 165°F temperature in the same oven. Do the two oven exposures simulate identical storage conditions?

In addition to the hazards described thus far, pyrotechnics may also be toxic. Chemical agents, in particular, should be handled with the utmost care. For details, see Refs. 23 and 28.

8-2.2 HANDLING

Pyrotechnic items must be handled carefully during their entire life from the first laboratory experiments, through manufacturing, and to the stockpile-to-delivery sequence. First, personnel must be familiar with the physical and chemical properties of the pyrotechnic item or materials[29]. Next, sound safety practices must be utilized[23].

Safe handling is particularly important during manufacturing where parts are not yet fully assembled. Heat generated by friction, impact, vibration, and static electricity are major sources of hazards. See par. 8-5 for further details.

Handling during operation presents a different safety problem. Pyrotechnic items may be handled by persons who are not familiar with them. Hence, clear and precise labeling is important. Personnel should be trained in safe practices. For information on handling during

TABLE 8-10

STORAGE CATEGORIES OF TYPICAL PYROTECHNIC ITEMS AND MATERIALS

ITEM	Storage Compatability Group	Quantity-Distance Class
Black powder, in charges or containers	O	7
Bombs, photoflash (Except M122, w/o burster)	O	7
Bombs, photoflash, M122, w/o burster	C & O	2
Cartridges, illuminating	E	4
Cartridges, photoflash	O	7
Cutters, reefing line	B,E,N	1
Detonation simulator, explosive, M80	O	7
Grenades, illuminating	N	2
Grenades, practice, w/spotting charge	E	3
Grenades, smoke (except HC, WP & PWP)	N	2
Photoflash powder	A	7
Projectiles, illuminating	E & N	2
Simulators, M110, M117, M118, and M119	N	2
Simulators, M115 and XM142	O	7
Simulator, M116	B & O	3
Smoke pots	N	2
Spotting charges (cartridge for miniature practice bombs)	N	2

TABLE 8-11

EXCERPT FROM QUANTITY-DISTANCE TABLES

Material, lb	Inhabited Building bar.	Inhabited Building unbar.	Highway & or Railway bar.	Highway & or Railway unbar.	Intraline bar.	Intraline unbar.	Above Ground bar.	Above Ground unbar.
				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

storage and shipping, see pars. 8-2.3 and 8-2.4, respectively.

8-2.3 STORING

Basic information on storage is contained in the *Safety Manual*[24]. In addition, two Department of Defense safety manuals contain much of the same information but their arrangement makes them often easier to use. One of the manuals covers agencies[30] while the other covers contractors[31].

For the purpse of storage, hazardous materials are arranged into eight classes according to their level of hazard. Ammunition containing pyrotechnics are divided into classes 1 and 7 depending on their hazard level. Class 1 items are those that 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 source[31]. The storage categories of typical pyrotechnic items and materials are excerpted in Table 8-10[24]. In addition to the hazard class, the table also lists the compatibility group. Group A is the most severe; all items in this group must be stored alone. Items in groups B through Q may be stored with other items within the same group in any combination.

Pyrotechnics 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"[30].

Quantity-distance tables are contained in the safety manuals[23,30,31]; a typical excerpt is shown in Table 8-11[23]. 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 aboveground 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 material, and that a barricade of proper construction reduces by one-half the distance used for unbarricaded storage.

Dissatisfaction has recently been expressed with the degree to which safety classes suffice for pyrotechnic materials. Some pyrotechnics are quite lethal, resulting in damage due to a fire ball (radiant heat) and fragments. Damage is certainly greater than that of a Class 1 material. However, reclassification to Class 7 presents two problems: (1) the pyrotechnic does not really qualify under the criterion for detonating solids as established by the Card Gap Test (see Ref. 25), and (2) the commonly used barricades can at times enlarge the hazard by increasing the distance of thrown fragments and burning debris. Hence, a separate classification for pyrotechnic materials has been suggested[32]. It should be emphasized, however, that the personnel concerned with pyrotechnics have no choice but to comply with the existing safety regulations as a minimum.

8-2.4 SHIPPING

For the purpose of shipping, materials are divided into three classes according to their level of hazard[33]:

(1) Class A. Chemical compounds, mixtures, or devices (mass detonating, spark initiated, or shock sensitive) with maximum shipping hazard. Examples are black powder, PETN, and explosive ammunition.

(2) Class B. Explosives that function by rapid combustion rather than detonation. Examples are gun propellants and certain rocket motors.

(3) Class C. Devices that may contain Class A or Class B explosives or both, but in restricted quantities, and certain types of fireworks. Examples are electric squibs, explosive bolts, and small arms ammunition.

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 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.

Shipping regulations for specific pyrotechnic items are contained in the item specification. General regulations are covered by the Department of Transportation, Code of Federal Regulations, Title 49, Parts 100-99. For detailed information on shipping ammunition containing pyrotechnics, see Ref. 33. It identifies each item by Federal Stock Number and lists hazard class as well as the information of concern to the shipper, such as cube, weight, and labeling requirements. Transportation by rail, motor vehicle, and water carrier is also covered in Ref. 34. In addition to these regulations, state and municipal laws, local ordinances, and harbor regulations must be observed where they apply.

8-3 RELIABILITY

Reliability is the extent to which we may expect a device to perform its intended function for a specified period under stated conditions[35]. It is often expressed in statistical terms. Since reliability can be no greater than the most unreliable component of a pyrotechnic device, it is important to prove the reliability of each component. Moreover, environmental factors such as moisture and vibration, encountered during storage and transportation, can affect reliability and therefore should be taken into account.

Keep in mind that reliability and safety are closely related. While pyrotechnic devices must function as intended (reliability), they must not function under any but the right conditions (safety).

8-3.1 CONSIDERATIONS DURING RESEARCH AND DEVELOPMENT

During the research and development phase, the reliability of individual components is usually examined in detail, and the measure of reliability most often used is probability. Probability is usually expressed as a percentage and it denotes the ratio of occurrence of a given event to total number of events, e.g., if in a test of 100 aerial flares 98 function properly, the probability of proper functioning for these 100 flares is therefore 98%. The confidence interval, a function of sample size, should also be determined.

Predictions of reliability demand a knowledge of the concepts of random sampling, frequency distributions, significant differences, and methods for computing statistical parameters. All these should become a part of the designer's working vocabulary so that, at the very minimum, he can recognize those situations where a professional statistician is required. The subject of experimental statistics aimed specifically toward military application is the subject of other handbooks[36-40].

A powerful analytic technique for assessing the reliability as well as the safety of pyrotechnic ammunition is the Fault Tree Analysis[41]. Based on logic diagrams, Boolean algebra, and probability values for individual components, it helps to assess system reliability and safety by pointing out the weaknesses in design, material, manufacturing process, inspection procedure, or adverse environmental conditions. The technique also obviates the testing of a large number of samples to achieve these purposes experimentally, a task that is often prohibitively expensive.

A typical example of a fault tree is shown in Fig. 8-11. It diagrams the events and causes that could lead to the accidental ignition of the EX 48 Mod 0 flare. The fault tree analysis indicated that the most probable causes of accidental ignition are:

1. Heating to auto ignition temperature

2. Mechanical shock

3. Battery activation via an electrolytic fluid leading into the battery cavity

4. Squib initiation due to an intense radio frequency signal.

An analysis of this type is used in determining what tests must be performed to ascertain that none of the environmental conditions that the unit is likely to encounter will cause premature initiation. It also indicates which events are more or less likely to occur. In this instance, the mode of ignition least likely to occur is the accidental initiation of the flare by an RF signal because of the number of events that must occur simultaneously.

A few general suggestions can be made to the designer with regard to reliability[22]:

(1) Whenever possible, use standard components with established quality levels and other reliability criteria at least as high as those required by the application.

(2) Use redundant systems in more complex and expensive materiel but tend to keep overall systems as simple as possible.

(3) Specify materials for which the proper-

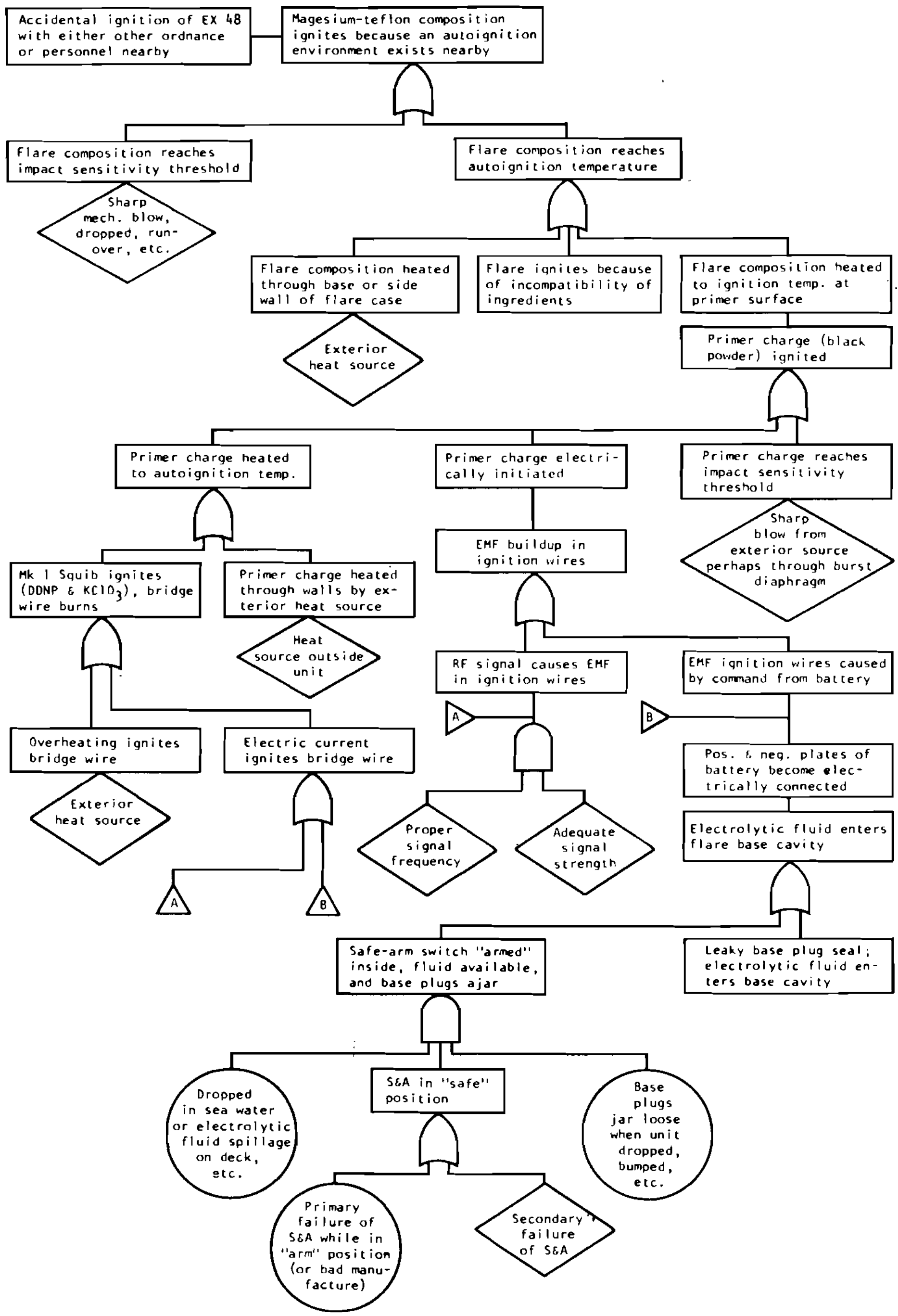

Figure 8-11. Fault Tree: Accidental Ignition of Decoy Flare, EX 48 Mod 0

ties of importance to your application are well known and reproducible. Keep in mind that the average value for a parameter may be less important for design purposes than the extreme values. Make specification changes in proven items only with great caution.

8-3.2 CONSIDERATIONS FOR THE STOCKPILE

During manufacturing, the reliability of pyrotechnic items is safeguarded by means of quality assurance procedures. When items reach the stockpile, surveillance programs are applied. Surveillance includes the observation, inspection, investigation, test, study, and classification of pyrotechnic devices and their components with respect to their serviceability, hazard, and rate of deterioration[42]. The twofold purpose of surveillance is to insure the reliability of items in storage and to provide the designer with a source of data for the improvement of future designs.

One aspect of surveillance is concerned with the order in which pyrotechnic ammunition is used. First priority is given to ammunition that is serviceable but not suited for long-term storage.

8-4 MAINTENANCE

Ideally, pyrotechnic ammunition should be completely maintenance free. It should be so designed that it can be placed on the shelf and perform perfectly when withdrawn for use 20 yr later. Every effort should be made to produce ammunition having optimum properties of handling, storage, shelf life, and serviceability. Design for maintainability requires incorporation of at least the following maintenance principles[42]:

(1) Design to minimize maintenance and supply requirements through attainment of optimum durability and service life of material.

(2) Recognition of field maintenance problems encountered in earlier designed items.

(3) Design for ease of maintenance by assuring accessibility to facilitate inspection, repair, and replacement.

(4) Consideration of field maintenance based on geographical locations and climatic conditions.

(5) Design for maximum utilization of interchangeable components.

(6) Detection of conditions that will adversely affect the conduct of maintenance operations or generate excessive maintenance and supply requirements.

(7) Design to effect maximum compatibility of maintenance operations with contemporary common tools.

(8) Evaluation for ease of packaging, car-loading, and shipment.

(9) Design to enable removal of major components as individual units.

(10) Assurance that proper materials and special treatment are used for maximum resistance to deterioration.

(11) Consideration of long term storage with a minimum of periodic checks and maintenance in storage.

8-5 MANUFACTURING

As in any specialized industry, pyrotechnic manufacturing processes involve the use of specialized tools, hardware, and assembly and control techniques. In general, many of the processes used in the manufacture of pyrotechnic ammunition are the same as those used for the manufacture of explosive items.

The production of pyrotechnic items involves a series of steps starting with the 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. 29. The processing of pyrotechnics is treated in Ref. 23, and the laboratory and plant procedures that must be followed for the safe processing of pyrotechnic items are described in Refs. 21 and 24.

8-5.1 CONTROL OF RAW MATERIALS

As in any processing of chemical materials, quality assurance starts with the selection of the proper ingredients. The physical and chemical reactions that often occur in pyrotechnic mixes are sensitive to control factors. Particle size, in particular, can have a large effect upon burn rate, light output, and efficiency of flare, smoke, and delay compositions. The various methods for determining particle size are covered in the Military Specifications for particular materials and in Ref. 23.

In addition to particle size, other factors that should be controlled are chemical purity, moisture content, and reactivity. Reactivity is a measure of the ability of a compound to react with another substance and can be influenced by grinding processes, particle shape, and the presence of trace impurities.

8-5.2 CONTROLLING PROCESSES

Pyrotechnic raw materials are mixed, ground, weighed, blended, granulated, dried, pressed, or consolidated--depending on the application[23]. For reasons of safety, processes should be controlled from behind suitable barricades with the minimum possible quantities. Often the process is controlled visually, based on experience, but sampling and subsequent measurement of particle size, moisture content, and performance characteristics are also used.

Whenever possible, processing tools of metal should be conductive nonsparking. Common nonsparking metals are bronze, beryllium alloys, lead, and monel. Certain tools may also be made from wood, plastic, and rubber. It should be kept in mind, however, that these nonsparking metals can occasionally produce sparks under certain conditions.

When strength or dimensional stability is needed, as in pressing, tool steel is required. Here it is particularly important that the tools are designed in such a manner that the pyrotechnic being worked is not pinched between sharp edges. In addition, vent holes or other means to prevent pressure buildup in the event of accidents should be provided in molds used in pressing operations.

8-5.3 LOADING

After blending, the pyrotechnic composition is loaded into its container. All loading operations should be performed by remote control with operating personnel behind reinforced protective barricades. For purposes of loading, compositions may be classified into three groups[23].

(1) Illuminants and Smokes. These compositions usually contain a binder, and are loaded by consolidating into a case by a hydraulic press. Incremental consolidation is often used.

(2) Delay Compositions. These are usually loaded in the same manner as illuminants and smokes, except that higher pressures are used (except where binders are present). Dies are normally used to support the delay body.

(3) Flash and Spotting Compositions. Flash and spotting compositions, because they do not usually contain a binder, are likely to be more sensitive to friction than compositions containing a binder. For this reason such compositions are usually loaded by vibrating the item on a vibrating table.

Flash and spotting compositions are usually loaded dry. In the other two groups, wet loading and cast loading techniques may also be used.

The desire is always to load a specific weight of pyrotechnic. For small test quantities or for some premium quality production, direct reading, one-pan balances are used that provide an accuracy within one percent. 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. In hand operations, scoops are filled and leveled against a rubber band. Careful scooping is accurate within 4%. Charging plates lend themselves to production rates[22].

Production pressing tools are hardened tool steel (60 Rockwell C is common) and the die is lapped and polished. Cups are supported by close fitting loading tools while the charge is being pressed. A quantity of pyrotechnic can be pressed either to a controlled height (stop laoding) 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 pyrotechnic charges is 3 or 4%. In stop loading, if the height of an increment is exactly reproduced, the density may vary as much as 7%. In either type of loading, the density should be checked for each production lot.

Loading pressure varies with the material being pressed. For delays, the pressure is as high as 10,000 psi. Charges may be pressed directly into their containers or, sometimes, pressed into molds and ejected as pellets. When a container of length greater than its diameter is used, the pyrotechnic is usually loaded in increments that are one diameter long[22].

8-5.4 ASSEMBLY

Assembly methods are many and varied because of the wide variety of pyrotechnic end items. During the assembly operations, the pyrotechnic charge is brought together with the necessary hardware. Whether common or specialized, hardware is produced by means of conventional manufacture. Different metals, wood, cardboard, paper, and plastics have all been employed. The design and selection of hardware is based on such factors as chemical compatibility, storage life, strength, cost, availability, and reliability.

When pyrotechnic devices are assembled, controlled operations are desirable. The temperature and humidity should be carefully controlled and dusting of the composition should be kept at a minimum. The least practical number of items should be kept in the working area.

While assembled pyrotechnic items are usually safer to handle than the pyrotechnic material itself, safe practices are nevertheless mandatory. To protect the pyrotechnic material from deterioration, special sealing or welding techniques are often employed in assembly, such as ultrasonic welding.

8-6 PACKAGING

Pyrotechnic ammunition – such as flares, signals, fusees, igniters, and illuminants – is packed in much the same way as other types of conventional ammunition. The primary function of any military package is to provide protection against induced environmental factors (shock and vibration) and natural environmental factors (humidity, temperature, rain, dust, etc.), and to provide for ease and safety of handling that may be encountered during world-wide handling, shipping, and storage.

Since packaging of the ammunition may affect its design, a packaging handbook should be consulted[43]. The first concern in packaging is to establish the Level (degree) of protection desired, namely:[44]

(1) Level A military packages are for unknown overseas destinations and storage conditions. The gross weight of a Level A military

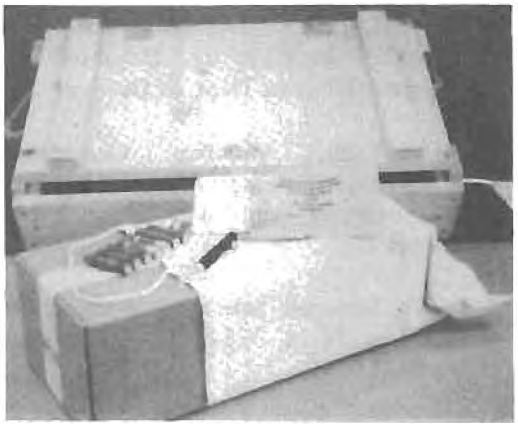

Figure 8-12.
Distress Signal Packaging for Level A Protection

package could be either 65 or 130 lb depending on handling expected during field operations (one or two man portability).

(2) Level B military packages are for known overseas destinations and storage conditions, and may provide a slightly lower level of protection than Level A, but for all intents and purposes, the package is generally designed similar to Level A.

(3) Level C military packages are used to package metal parts or component subassemblies of pyrotechnic items. They provide the least amount of protection but adequate enough to insure high end-item reliability during domestic and interplant shipments.

For Level C, less expensive water-vapor materials are used and the wooden boxes are simpler (no rope handles, wood preservative, or metal hardware). Corrugated fiberboard cartons are acceptable in place of the wooden boxes.

A typical Level A package for pyrotechnic items would be seven distress signals and one ejector packaged in a set-up box (small carton) and individually wrapped in a waterproof barrier bag. Ten of these boxes fit into a corrugated fiberboard box and each fiberboard box is enclosed in a barrier bag (for water and moisture proofing). The total military package (see Fig. 8-12) contains four bagged cartons per nailed wooden or wirebound box. If moisture proofing is not required and the item is large, such as a parachute flare, packaging would be one flare per spirally wound fiber container with two or four fiber containers per nailed wooden or wirebound box.

Packaged ammunition, especially that providing Level A protection should be subjected to a series of environmental tests (shock, vibration, temperature, humidity, etc.) prior to field release to verify the effectiveness of the package to meet all logistic requirements imposed by the military. In addition to the packaging requirements set forth in Refs. 43 and 44, Department of Transportation as well as state and local regulations have to be met (see par. 8-2.4).

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APPENDIX A

FLARE DESIGN INFORMATION

This Appendix contains the available design aids for flares. Figs. A-1[1] and A-2[1] are nomograms from which the burning rate and candlepower, respectively, can be obtained for $Mg/NaNO_3$ flares. The efficiency of various light sources for flares is compared in Table A-1[2].

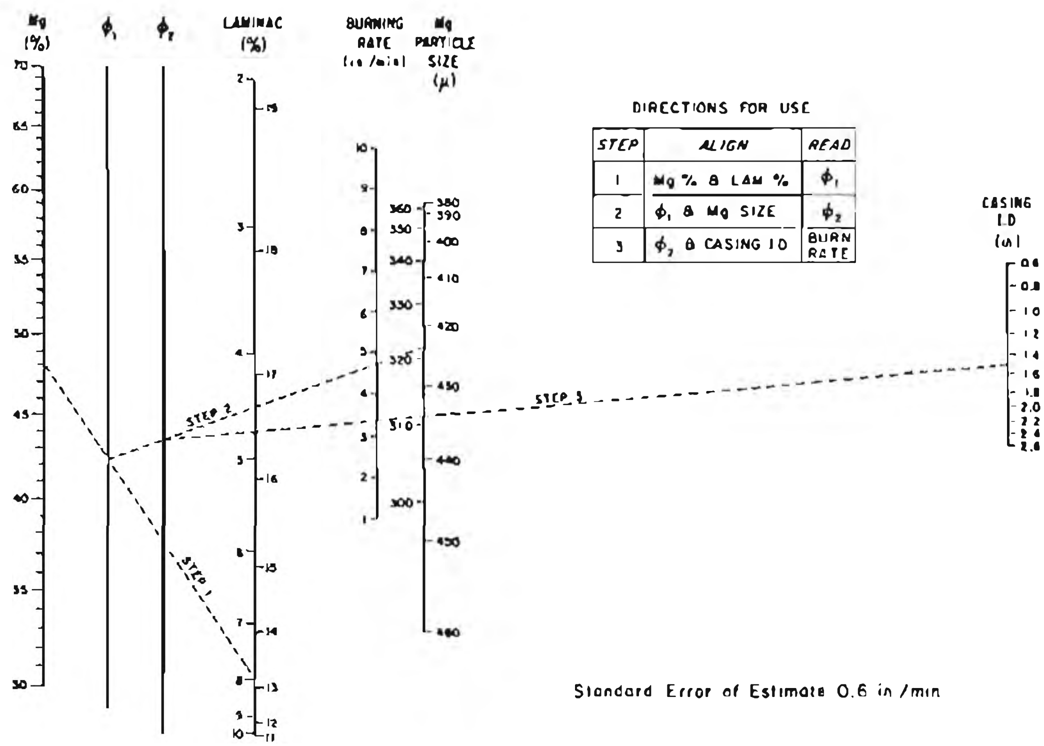

Figure A-1. Nomogram – Burning Rate of $Mg/NaNO_3$ Flares With Laminac Binder and Paper Cases

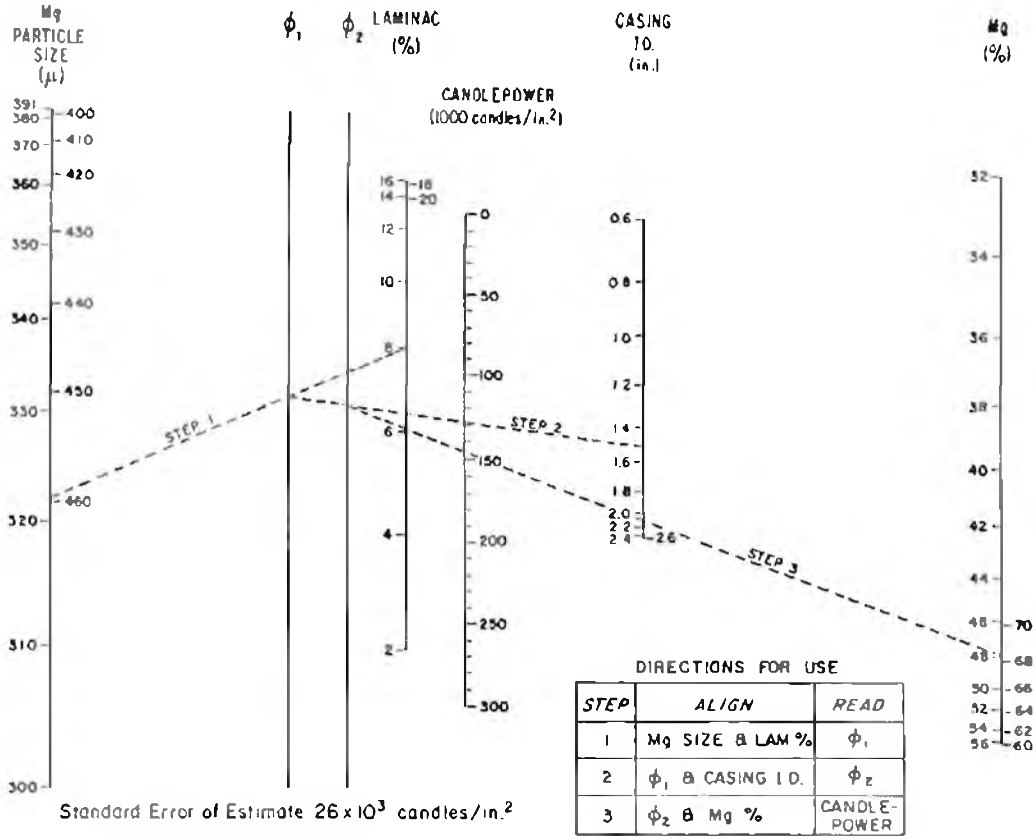

Figure A-2. Nomogram – Candlepower of $Mg/NaNO_3$ Flares With Laminac Binder and Paper Cases

TABLE A-1

COMPARISON OF EFFICIENCIES OF VARIOUS LIGHT SOURCES

Item	Luminous Flux, to Radiant Flux, %	Efficiency, lm W^{-1}	Efficiency, c-sec·(gram metal)$^{-1}$
Ideal Yellow-Green Line 556	100	680	
Sun	16.1	100	
Tungsten Lamp 5000 W	4.7	29	
Sodium Vapor Lamp	16.4	102	
M112 Photoflash Cartridge	1.14	7.1	16,700
M123 Photoflash Cartridge	1.11	6.9	16,200
M120A1 Photoflash Bomb	0.98	6.1	14,500
Al + Liquid Oxygen	1.3-1.6	8.1-9.8	20-24,000
X-52	0.65	4.05	10,000
T86E5	0.55	3.4	8,200
T10E3-4 Flare	10.1	63	110,000
T10E5-6 Flare	8.4	52	94,000
T90 Photoflare	7.2	45	82,500

Two empirical equations predict the performance of magnesium flares (within the limits of 48-60% magnesium content and diameters from 1 to 2.25 in.)[3]. The mean burning time is

$$
\begin{aligned}
t = {} & 523.29604 - 7.5126000x \\
& - 156.71800A + 2.247600Ax \\
& + 12.250900A^2 - 0.17302000A^2x
\end{aligned}
\qquad \text{(A-1)}
$$

and the output is

$$
\begin{aligned}
r = {} & 14685.430 - 217.29000x \\
& - 5658.9000A - 14332.500d \\
& + 4893.1000Ad + 301.92181A^2 \\
& - 235.21764A^2d + 41.963000Ax \\
& + 225.86000dx - 37.095000Adx
\end{aligned}
\qquad \text{(A-2)}
$$

where

t = mean burning time, sec

r = output, dimensionless

A = surface area of magnesium, $10^{-2}\ cm^2\ g^{-1}$

d = diameter, in.

x = magnesium content, %

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APPENDIX B

PYROTECHNIC COMPOSITIONS

(1) Stab Primer Compositions[1]:

Ingredients	Composition, % by weight PA100	NOL130
Lead Azide	5	20
Potassium Chlorate	53	–
Antimony Sulfide	17	15
Basic Lead Styphnate	–	40
Lead Thiocyanate	25	–
Tetracene	–	5
Barium Nitrate	–	20

(2) Friction Primer Compositions[2]:

Ingredients	Composition, % by weight A	B	C
Potassium Chlorate	63	53	42
Antimony Sulfide	32	22	42
Sulfur	–	9	3
Calcium Carbonate	–	1	2
Meal Powder	–	–	3
Ground Glass	–	10	3
Gum Arabic	5	5	5

(3) Percussion Primer Compositions:

Ingredients	M39 (Ref. 3)	Composition, % by weight PA101 (Ref. 1)	FA70 (Ref. 1)	NOL60 (Ref. 1)	FA959 (Ref. 3)*
Lead Styphnate	–	–	–	–	35.0
Basic Lead Styphnate	–	53	–	60	–
Tetracene	–	5	--	5	3.1
Potassium Chlorate	37.05	–	53	–	–
Barium Nitrate	8.68	22	–	25	31.0
Antimony Sulfide	–	10	17	10	10.3
Lead Thiocyanate	38.13	–	25	–	–
Powdered Glass	10.45	–	–	–	–
Powdered Aluminum	–	10	–	–	–
Powdered Zirconium	–	–	–	–	10.3
Lead Dioxide	–	–	–	–	10.3
TNT	5.69	–	5	–	–

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(4) Electric Primer Compositions[3]:*

Ingredients	Composition, % by weight			
	A	B	C	D
Diazodinitrophenol (DDNP)	20	75	–	–
Potassium Chlorate	60	25	55	8.5
Lead Thiocyanate	–	–	45	–
Lead Mononitro Resorcinate (LMNR)	–	–	–	76.5
Charcoal	15	–	–	–
Nitrocellulose	–	–	–	15.0
Nitrostarch	5	–	–	–

(A) Used as primer and fire transfer.
(B) Used in Mk1 Mod 0 Squib.
(C) Used in M59 Electric Igniter.
(D) Used for various electric matches.

(5) Conductive Primer Mixes[3]:*

Ingredients	Composition, % by weight		
	A	B	C
Zirconium (<5μ)	7.5	6-9	15.0
Zirconium (>10μ)	32.5	30-35	–
Zirconium Hydride	–	–	30.0
Lead Dioxide	25.0	18-22	20.0
Barium Nitrate	25.0	15-25	15.0
PETN	–	15-23	20.0

(6) High Intensity White Flares[3]:*

Ingredients	Composition, % by weight			
	A	B	C	D
Magnesium (30/50)	58±2	45.5	53	55
Sodium Nitrate	37±2	45.5	39	36
Laminac	4±½	9.0	8	9

(7) Mild White Light Source (used in M118 Booby Trap Simulator)[3]:*

Ingredients	Composition, % by weight
Potassium Perchlorate	73
Red Gum	21
Detxrin	6

(8) White Star[3]:*

Ingredients	Composition, % by weight
Magnesium	25
Aluminum	14
Barium Nitrate	42
Strontium Nitrate	11
Asphaltum	5
Linseed Oil	3

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(9) High Altitude Flash Charges[3]:*

Ingredients	Composition, % by weight			
	A	B	C	D
Aluminum (<17μ)	40	31	20	—
Calcium Metal	—	—	30	80
Sodium Perchlorate	—	—	—	20
Calcium Flouride	—	20	—	—
Potassium Perchlorate	60	49	50	—

(10) Photoflash Powders:

Ingredients	Composition, % by weight			
	A (Ref.3)*	B (Ref.4)	C (Ref.4)	D (Ref.4)
Aluminum	40	—	—	26
Magnesium/Aluminum Alloy	—	60	45.5	—
Magnesium	—	—	—	34
Potassium Perchlorate	30	40	—	40
Barium Nitrate	30	—	54.5	—

(11) Simulator Mixes[3]:*

Ingredients	Composition, % by weight	
	A	B
Magnesium	45	34
Aluminum	—	26
Potassium Perchlorate	35	60
Barium Nitrate	15	—
Barium Oxalate	3	—
Calcium Oxalate	1	—
Graphite	1	—

(A) Used in M110 Gunflash Simulator.
(B) Used in M115 Projectile Ground Burst Simulator.

(12) Underwater Flare Mix[3]:*

Ingredients	Composition, % by weight
Magnesium	16
Aluminum	12
Barium Sulfate	40
Barium Nitrate	32

(13) Intensity Flare (Fl), Star (St), and Star Tracer (Tr) Mixes[3]:*

Ingredients	Composition, % by weight								
	Red			Green			Yellow		
	Fl	St	Tr	Fl	St	Tr	Fl	St	Tr
Magnesium	29	23	46	26	15	48	26	19	49
Gilsonite	2	8	3	2	—	3	2	9	5
Oil	2	—	—	2	2	—	2	—	—
Hexachlorobenzene	4	6	4	7	15	6	5	7	—
Powdered Copper	—	—	—	—	2	2	—	—	—
Cupric Oxide	—	—	—	2	—	—	—	—	—

(continued)

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Ingredients	Red Fl	Red St	Red Tr	Green Fl	Green St	Green Tr	Yellow Fl	Yellow St	Yellow Tr
Barium Nitrate	–	–	–	45	66	16	29	–	–
Strontium Nitrate	34	41	18	–	–	–	–	–	–
Potassium Perchlorate	29	22	29	16	–	25	23	50	31
Sodium Oxalate	–	–	–	–	–	–	13	15	15

(14) Artillery Tracer Mixes[3]:*

Ingredients	Composition, % by weight: Red		Green	Yellow		White
Magnesium	28	28	41	33	43	34
Barium Nitrate	–	–	28	–	41	60
Strontium Nitrate	40	55	–	40	–	–
Potassium Perchlorate	20	–	–	–	–	–
Barium Oxalate	–	–	16	–	–	–
Strontium Oxalate	8	–	–	–	–	–
Sodium Oxalate	–	–	–	17	12	–
Sulfur	–	–	–	–	2	–
Polyvinyl Chloride	–	17	–	–	–	–
Binder and Fuel	–	–	15	10	2	6
Calcium Resinate	4	–	–	–	–	–

(15) Flare Mixes[3]:*

Ingredients	Composition, % by weight: A	B	C	D	E	by parts: F
Magnesium	21	17.5	30	3-5	8	8
Strontium Nitrate	45	45	42	68-70	52	38
Potassium Perchlorate	15	25	9	–	–	–
Ammonium Perchlorate	–	–	–	–	–	15
Strontium Oxalate	–	–	–	–	8	10
Hexachlorobenzene	12	–	–	–	18	–
Polyvinyl Chloride	–	5	12	23	–	17
Calcium Silicide	–	–	–	–	–	2
Charcoal	–	–	–	–	1	–
Stearic Acid	–	–	–	–	13	6
Gilsonite	7	7.5	–	–	–	–
Laminac	–	–	7	–	–	–
Linseed Oil	–	–	–	8	–	–

(A) (B) (C) Used in red signal flares.
(D) (E) Slow burning red flare.
(F) Used in Mk 43 and Mk 44 Mods O Drill Mine Signal.

(16) Green Flare Mixes[3]:*

Ingredients	Composition, % by weight: A**	by parts: B
Magnesium	35	20
Barium Nitrate	22.5	50
Potassium Perchlorate	22.5	10
Polyvinyl Chloride	13	16

(continued)

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**Error in not adding up to 100% occurs in Ref. 3.

	% by weight	by parts
	A**	B
Laminac	5	--
Asphaltum	–	4

(A) Typical mix.
(B) Used in Mk 39 Mod O Drill Mine Signal.

(17) Yellow Flare Mixes[3]:*

Ingredients	Composition, % by weight A**	Composition, by parts B
Aluminum	3.5	3-20
Magnesium	–	0-11
Potassium Nitrate	15.5	–
Strontium Nitrate	15.5	–
Barium Nitrate	–	63-67
Sodium Oxalate	64	8-17
Sulfur	–	4-5
Castor Oil	2	2-3
Rosin	5	–

**Error in not adding up to 100% occurs in Ref. 3.

(18) Blue Flare Mixture (used in Mk 1 Mod 1 Blue Distress Signal)[3]:*

Ingredients	Composition, % by weight**
Potassium Perchlorate	38.9
Barium Nitrate	19.5
Paris Green	32.6
Stearic Acid	8.2

**Error in not adding up to 100% occurs in Ref. 3.

(19) Blue Flare Mixture[3]:*

Ingredients	Composition, % by weight
Ammonium Perchlorate	74.2
Copper Dust	11.1
Stearic Acid	11.1
Paraffin	3.7

(20) White Smoke Mixtures:

Ingredients	Composition, % by weight A (Ref.4)	B (Ref.3)*	C (Ref.4)	D (Ref.4)	E (Ref.5)	F (Ref.4)
Hexachloroethane	45.5	45.5	–	–	30.5	–
Hexachlorobenzene	–	–	34.4	–	–	–
Dechlorane	–	–	–	33.9	–	–
Zinc Oxide	47.5	45.5	27.6	37.4	31.5	–
Ammonium Perchlorate	–	–	24.0	20.5	27.0	–
Aluminum	7.0	–	–	–	4.0	–

(continued)

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	A (Ref.4)	B (Ref.3)*	C (Ref.4)	D (Ref.4)	E (Ref.5)	F (Ref.4)
Calcium Silicide	–	9.0	–	–	–	–
Zinc Dust	–	–	6.2	–	–	–
Laminac	–	–	7.8	8.2	3.5	–
Styrene	–	–	–	–	3.5	–
White Phosphorus	–	–	–	–	–	65
Plasticizer	–	–	–	–	–	35

(A) HC, Type C
(B) HC, Type B
(C)(D) Modified HC
(E) HCM8P Plastic-bonded White
(F) Plasticized White Phosphorus (PWP)

(21) Black Smoke Mixtures:

	Composition, % by weight	
Ingredients	A (Ref.4)	B (Ref.3)*
Potassium Chlorate	52.0	–
Anthracene	48.0	19
Magnesium	–	19
Hexachloroethane	–	62

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(22) Red Smoke Mixtures

	Composition, % by weight				Parts by weight
Ingredients	A (Ref.2)	B † (Ref.4)	C (Ref.4)	D (Ref.4)	E (Ref.2)
Potassium Chlorate	23	30.2	35.0	–	–
Sugar	23	–	17.0	–	–
Sulfur	–	11.8	–	–	–
1-methylamino (AQ)*	–	36.0	45.0	–	–
1,4-di-p-toluidino (AQ)*	–	–	3.0	–	–
1-(methoxyphenylazo)-2-naphthol	–	–	–	80.0	–
9-diethylaminorosindone	54	–	–	–	–
Rhodamine Red	–	–	–	–	10
Sodium Bicarbonate	–	18.0	–	–	–
Dextrin	–	4.0	–	–	–
Potassium Perchlorate	–	–	–	–	5
Gum Arabic	–	–	–	–	1
Antimony Suflide	–	–	–	–	4
Sodium Chloride	–	–	–	20.0	–

† Standard red used in the M18 Smoke Grenade.

*(AQ) Anthraquinone

(23) Green Smoke Mixtures:

Ingredients	Composition, % by weight A (Ref.4)	Composition, % by weight B† (Ref.5)	Parts by weight C (Ref.2)
1,4-di-p-toluidine (AQ)*	28.0	28.3	–
Indanthrene GK (Golden yellow)	12.0	–	–
Auramine	–	11.7	–
Malachite Green	–	–	10
Potassium Chlorate	35.0	26.0	–
Potassium Perchlorate	–	–	6
Sugar	23.0	–	–
Sulfur	–	10.0	–
Sodium Bicarbonate	2.0	24.0	–
Antimony Sulfide	–	–	5
Gum Arabic	–	–	1

† Standard green used in the M18 Smoke Grenade.

*(AQ) Anthraquinone

(24) Yellow Smoke Mixtures:

Ingredients	Composition, % by weight A (Ref.4)	B (Ref.4)	C† (Ref.5)
Bezanthrene	32.0	–	–
Indanthrene GK	15.0	–	–
Auramine Hydrochloride	–	40.0	–
Potassium Chlorate	30.0	–	22.0
Sugar	20.0	–	–
Sodium Bicarbonate	3.0	–	31.5
Sulfur	–	–	8.5
Auramine	–	–	38.0
Sodium Chloride	–	60.0	–

† Standard yellow used in M18 Smoke Grenade

(25) Tracer and Igniter Mixtures[6]:

	Composition, % by weight															
	R256	R284	R20C	R403	R321	I280	I276	I508	I136	IM11	S200W	CS-49	LCA #1	LC No. 1	LC No. 2	LC No. 3
Aluminum	–	–	–	–	–	–	–	–	–	–	–	–	35	–	–	–
Magnesium	26.7	28.0	21.6	25.2	26.0	15.0	15.0	14.1	–	–	–	–	–	–	15.0	25.0
50/50 Magnesium - Aluminum Alloy	–	–	–	–	–	–	–	–	–	50	–	–	–	–	–	–
Strontium Nitrate	33.3	55.0	–	49.5	52.0	–	–	–	–	–	–	–	–	–	–	40.9
Strontium Peroxide	26.7	–	65.6	–	–	76.5	–	–	90.0	–	70	–	–	76.5	65.0	–
Strontium Oxalate	5.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Barium Peroxide	–	–	3.4	–	–	–	83.5	79.0	–	–	–	–	–	–	–	–
Barium Nitrate	–	–	–	–	–	–	–	–	–	50	–	–	–	–	–	–
Potassium Perchlorate	–	–	–	–	–	–	–	–	–	–	–	73.0	–	–	–	–
Lead Dioxide	–	–	3.4	–	–	–	–	–	–	–	–	–	–	–	–	–
Oxamide	–	–	–	10.0	–	–	–	–	–	–	–	–	–	–	–	8.9
Polyvinyl Chloride	–	17.0	–	15.3	16.0	–	–	–	–	–	–	–	–	–	–	15.2
Perlon	–	–	–	–	6.0	–	–	5.5	–	–	–	–	–	–	–	–
Calcium Resinate	8.3	–	6.0	–	–	8.5	–	–	10.0	–	15	–	–	23.5	20.0	10.0
Zinc Stearate	–	–	–	–	–	–	1.0	.9	–	–	–	–	1	–	–	–
Toluidine Red Toner	–	–	–	–	–	–	.5	.5	–	–	–	–	–	–	–	–
1-Methylamine Anthraquinone	–	–	–	–	–	–	–	–	–	–	15	–	–	–	–	–
Lucite	–	–	–	–	–	–	–	–	–	–	–	17.0	–	–	–	–
Asphaltum	–	–	–	–	–	–	–	–	–	–	–	5.0	–	–	–	–
Silver Iodide	–	–	–	–	–	–	–	–	–	–	–	5.0	–	–	–	–
RDX	–	–	–	–	–	–	–	–	–	–	–	–	64	–	–	–

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APPENDIX C

METHODS FOR INTERIOR BALLISTIC CALCULATIONS FOR SMALL ARMS

C-1 EMPIRICAL METHOD

A set of graphs prepared by Frankford Arsenal for use in small arms design is shown in Fig. C-1[1]. These normalized graphs were obtained empirically by reducing experimental data from eleven different small arms weapon systems. Least-square curves were generated to give the best fit to the data. They can be used to relate maximum pressure, propellant weight, projectile weight, expansion ratio, muzzle velocity, and breech pressure at a given projectile travel while the projectile remains in the gun barrel.

Example Given the Cartridge, Caliber .30, Ball with the following characteristics:

W = projectile weight = 150 gr

W_p = propellant weight = 49.9 gr

A = bore area = 0.0732 in^2

V_o = case volume (initial free volume) = 0.25 in^3

x = bullet travel = 21.9 in. (barrel length)

P_m = maximum pressure = 51.2 kpsi

Find: Exit muzzle velocity v_m, ft sec^{-1}.

Calculations.

1. First determine the ratio of propellant weight W_p to projectile weight W

$$\frac{W_p}{W} = \frac{49.9}{150} = 0.333 \qquad \text{(C-1)}$$

2. For the first approximation, the expansion ratio is assumed to be 5, i.e., $V_m/V_o = 5$ where V_m is the free volume at the muzzle, and the maximum breech pressure 60 kpsi. Then from Fig. C-1(A), the muzzle velocity is read as 2610 ft sec^{-1}.

3. This velocity must be corrected for the actual expansion ratio and breech pressure as follows. The actual expansion ratio is

$$\frac{V_m}{V_o} = \frac{xA + V_o}{V_o} = \frac{21.9 \times 0.0732 + 0.25}{0.25}$$

$$= 7.41 \qquad \text{(C-2)}$$

4. From Fig. C-1(B) at $V_m/V_o = 7.41$, a value for v_x/v_5 is read as 1.06.

5. To correct for the difference in breech pressure, use is made of Fig. C-1(C). At 51.2 kpsi a velocity ratio v_m/v_{60} is read as 0.981

6. The true exit muzzle velocity v_m is then

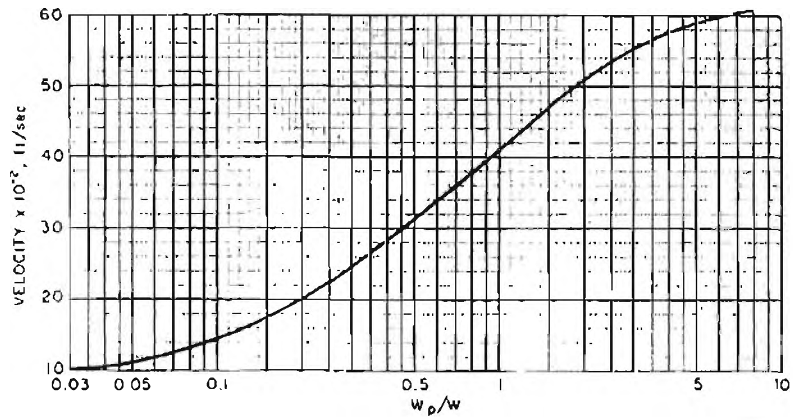
$$v_m = v_{5,60}\left(\frac{v_x}{v_5}\right)\frac{v_m}{v_{60}} \qquad \text{(C-3)}$$

$$= 2610 \times 1.06 \times 0.981 = 2720 \text{ ft/sec}$$

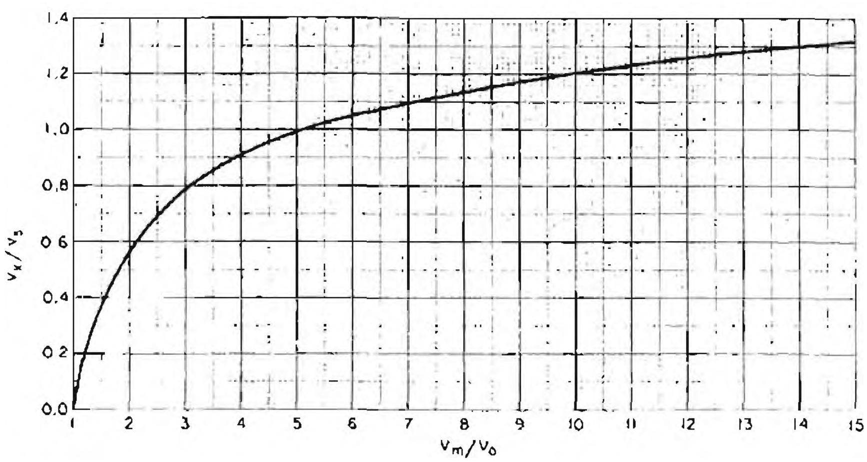
It should be noted that these figures work well for a nearly optimum propellant and primer. In order to select the best propellant for a given system, use is made of the relation

$$\text{web} \propto \frac{Wv_b}{A} \qquad \text{(C-4)}$$

where W and A are projectile weight and bore



(A) Velocity at V_m/V_o = 5 and P_m = 60 kpsi as a Function of W_p/W



(B) Relative Velocity Normalized to Unity at an Expansion Ratio of 5 as a Function of Expansion Ratio

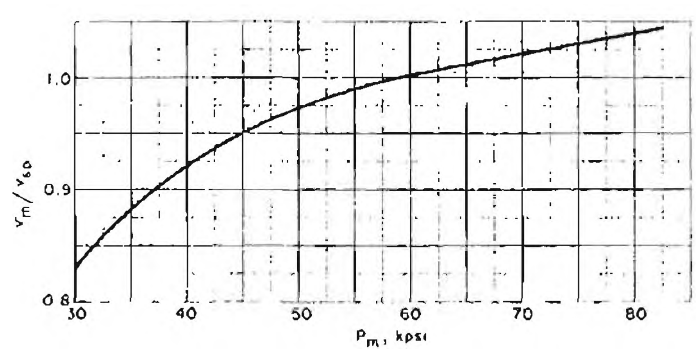


Figure C-1. Empirical Curves for Small Arm Design area, respectively, and v_b is the projectile velocity at "all burnt". This generally occurs in small arms systems at an expansion ratio of about 3.5. For purposes of estimation, the velocity at burnout may be replaced by muzzle velocity, and a new system compared to an existing, well-performing one. This process allows a constant to be established for the given relation so that the web dimension can be determined.

C-2 GRAPHICAL METHOD

Numerous schemes have been devised by ballisticians for making fast approximate calculations of certain interior ballistic variables. These schemes utilize a set of parameters chosen so that their form does not involve a knowledge of unknown quantities, such as starting pressures or burning rates. The charts are based in part on simplified theory such as that of Mayer and Hart[2], and adjusted to their final form by fitting to numerous firing records. Such a scheme is that formulated by Strittmater[3] which utilizes a single working chart that shows the interrelationship of five dimensionless ballistic parameters:

(1) e = thermodynamic efficiency

(2) z = piezometric efficiency

(3) x = volume expansion ratio

(4) r = energy ratio

(5) y = pressure ratio

If one knows any two of these initially, then the other three can be found. The theory employed is that of Mayer and Hart with an additional assumption that bore friction varies proportionally with chamber pressure. This assumption is used to improve the agreement between the chart and experiment by adjusting the effective projectile weight. The effective weight W_e is defined by

$$W_e = W + 5\times 10^5 d x_m / v_m^2 \text{, lb} \quad \text{(C-5)}$$

where

W_e = effective projectile weight, lb

W = projectile weight, lb

d = bore diameter, in.

x_m = travel to muzzle, in.

v_m = muzzle velocity, ft sec^{-1}

The five parameters are presented in Fig. C-2[3]; The ballistic parameters are defined by the following equations:

$$e = \frac{(r-1)(W_e + W_p/3)v_m^2}{2gFC} \quad \text{(C-6)}$$

$$z = \frac{(W_e + W_p/3)v_m^2}{2g P_m V_m} \quad \text{(C-7)}$$

$$x = V_m / V_o \quad \text{(C-8)}$$

$$r = \frac{FW_p}{P_m V_o} \quad \text{(C-9)}$$

$$y = \frac{P_f}{P_m} \quad \text{(C-10)}$$

where

W_p = propellant weight, lb

g = acceleration due to gravity, 386 in. sec^{-2}

F = specific energy of the propellant, in.-lb/lb

P_m = space mean peak pressure, lb in.$^{-2}$

V_m = free volume at the muzzle, in.^{3}

V_o = initial free volume, in.^{3}

P_t = pressure when the projectile is at the muzzle, lb in.$^{-2}$

If the maximum chamber pressure P_c (lb in.$^{-2}$) is given, the space mean peak pressure P_m is calculated by

$$P_m = \left(\frac{W + W_p/3}{W + W_p/2} \right) P_c, \text{ lb in.}^{-2} \qquad \text{(C-11)}$$

If Eq. C-5 is substituted into Eqs. C-6 and C-7, assuming the numerical value of 1.30 for r and expressing the gravitational acceleration g as 386 in. sec^{-2}, the ballistic e and piezometric z efficiencies, respectively, may be expressed as

$$e = 3.89 \times 10^{-4} \left[\frac{(W + W_p/3) v_m^2 + 5 \times 10^5 d x_m}{F W_p} \right] \qquad \text{(C-12)}$$

$$z = \frac{(W + W_p/3) v_m^2 + 5 \times 10^5 d x_m}{772 P_m V_m} \qquad \text{(C-13)}$$

Solving Eq. C-12 for v_m gives

$$v_m = \sqrt{\frac{2574 F W_p e - 5 \times 01^5 d x_m}{144 (W + W_p/3)}}, \text{ ft sec}^{-1} \qquad \text{(C-14)}$$

The initial free volume V_o is defined by

$$V_o = V_c - W_p V \qquad \text{(C-15)}$$

The free volume at the muzzle V_m is defined by

$$V_m = V_o + A x_m \qquad \text{(C-16)}$$

where

V_c = chamber volume, in.^{3}

V = specific volume, in.^{3} lb^{-1}

A = bore area, in.^{2}

x_m = travel to muzzle, in.

Now, if any two of the ballistic parameters are known, the other three can be evaluated by means of the chart (Fig. C-2).

Sample Calculation

The data that follow are from the firing records for a cal .30 rifle firing a 150.5-gr projectile, propelled by 50 gr of a certain lot of propellant. The characteristics of the propellant and rifle, that constitute part of the given data, are:

Characteristic	Symbol	Value	Unit
Propellant weight	W_p	0.00714	lb
Specific energy	F	4.023×10^6	in.-lb lb^{-1}
Specific volume	V	17.5	in.^{3} lb^{-1}
Chamber volume	V_c	0.258	in.^{3}
Area of bore	A	0.0735	in.^{2}
Bore diameter	d	0.30	in.
Travel to muzzle	x_m	21.79	in.
Projectile weight	W	0.0215	lb

To calculate at least two of the parameters from the given data, one also needs to know either the muzzle velocity or the mean pressure. One or both of these will normally be specified in any gun design problem. In the present problem, the maximum breech pressure P_c will be assumed to be given and equal to the measured value 35,890 lb in.$^{-2}$. Now we can calculate the following parameters:

Characteristic	Symbol	Value	Unit	Calculated by
Initial free volume	V_o	0.133	in.^{3}	Eq. C-15
Muzzle free volume	V_m	1.735	in.^{3}	Eq. C-16
Space mean peak pressure	P_m	34,180	lb in.$^{-2}$	Eq. C-11

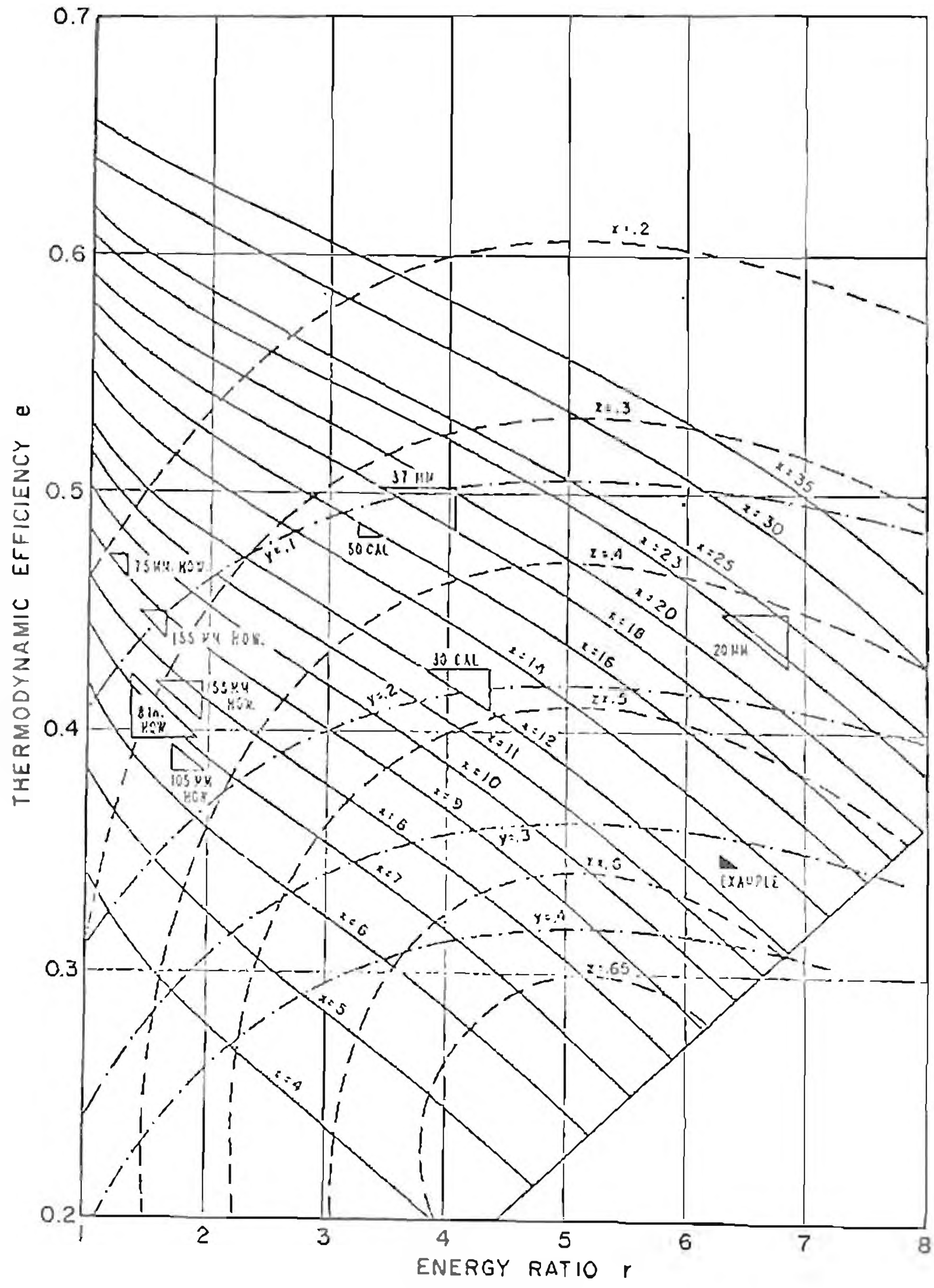


Figure C-2. Chart for Interior Ballistic Calculations by the Scheme of Strittmater

Characteristic	Symbol	Value	Unit	Calculated by
Volume expansion ratio	x	13.05	–	Eq. C-8
Energy ratio	r	6.32	–	Eq. C-9

Then e, z, and y are read from Fig. C-2:

(1) Thermodynamic efficiency $e = 0.352$

(2) Piezometric efficiency $z = 0.566$

(3) Pressure ratio $y = 0.316$

The muzzle pressure P_f can now be found by use of Eq. C-10. The muzzle pressure is 10,800 lb in^{-2}. The muzzle velocity v_m can be solved with Eq. C-14. The muzzle velocity is 2572 ft sec^{-1}. The actual observed velocity for this firing was 2565 ft sec^{-1}.

If the theory represented by Fig. C-2 were exact, the lines representing the five different parameters for any gun-ammunition system would all intersect at a point. When experimental values for the quantities defining the parameters are substituted into the corresponding equations, the lines so determined do not cross at a single point but form a polygon. If the experimental values are not subject to serious error, the dimensions of this polygon are a measure of the discrepancies involved in using the chart. The triangles shown on the chart are the result of using experimental values to determine e, x, and r for the weapons indicated—as was done for the given example. A similar set of nomograms has been constructed by Kravitz[4].

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