ENGINEERING DESIGN HANDBOOK
PROPELLANT ACTUATED DEVICES

ARMY MATERIEL COMMAND
ALEXANDRIA, VIRGINIA

SEPTEMBER 1975

DEPARTMENT OF THE ARMY
HEADQUARTERS UNITED STATES ARMY MATERIEL COMMAND
5001 Eisenhower Ave., Alexandria, VA 22333

AMC PAMPHLET
NO. 706-270

30 September 1975

ENGINEERING DESIGN HANDBOOK
PROPELLANT ACTUATED DEVICES

TABLE OF CONTENTS

*Supersedes AMCP 706-270, August 1963.

TABLE OF CONTENTS (Con't.)

TABLE OF CONTENTS (Con't.)

TABLE OF CONTENTS (Con't.)

TABLE OF CONTENTS (Con't.)

CHAPTER 7. PERFORMANCE EVALUATION

TABLE OF CONTENTS (Con't.)

TABLE OF CONTENTS (Con'd.)

TABLE OF CONTENTS (Con't.)

TABLE OF CONTENTS (Con't.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Con't.)

LIST OF ILLUSTRATIONS (Con't.)

LIST OF TABLES

PREFACE

This handbook—containing basic information and fundamental data useful in the design and development of Army materiel—is one in the Engineering Design Handbook series of the US Army Materiel Command. The handbook is a revision of the existing handbook published in 1963. The revision updates the material and design methodology, and introduces the application of computer techniques. Also, the revision reorganizes the material and presents the design information in a more logical sequence.

The handbook is a guide to design engineers engaged in the development of propellant actuated thrust devices and gas generators for various applications. The text—written by the Propellant Actuated Devices Branch—is based on the experience of Frankford Arsenal, which has been engaged in the development of these devices for aircraft escape systems since 1945. It is interesting to note that more than 3200 US pilots have been saved by using the Frankford designed propellant actuated devices (PAD); also, there is no record of a known failure.

Chapter 1 presents a brief history of PAD's, their application to various types of aircraft, and possible future applications. Chapter 2 describes the specific components of PAD's and their function. Chapter 3 considers the basic design parameters such as time and motion functions, load, size, and environmental factors.

Chapters 4 and 5 deal with the mechanical and ballistic design of the various PAD components. Chapter 6 illustrates the component design techniques of the previous chapters by integrating the methodology into the design of PAD systems. Realistic examples are used throughout.

Chapter 7 describes the instrumentation, text fixtures, and various test and evaluation programs used in the design process.

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 in accordance with current DOD Directive 7230.7, dated 18 September 1973. All unclassified Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

a. All Department of Army activities having need for the Handbooks must submit their request on an official requisition form (DA Form 17, dated Jan 70) directly to:

Commander
Letterkenny Army Depot
ATTN: AMXLE-ATD
Chambersburg, PA 17201

(Requests for classified documents must be submitted, with appropriate "Need to Know" justification, to Letterkenny Army Depot.) DA activities will not requisition Handbooks for further free distribution.

b. All other requestors, DOD, Navy, Air Force, Marine Corps, nonmilitary Government agencies, contractors, private industry, individuals, universities, and others must purchase these Handbooks from:

National Technical Information Service
Department of Commerce
Springfield, VA 22151

Classified documents may be released on a "Need to Know" basis verified by an official Department of Army representative and processed from Defense Documentation Center (DDC), ATTN: DDC-TSR, Cameron Station, Alexandria, VA 22314.

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

Commander
US Army Materiel Command
ATTN: AMCRD-TV
Alexandria, VA 22333

(DA Forms 2028, Recommended Changes to Publications, which are available through normal publications supply channels, may be used for comments/suggestions.)

CHAPTER 1

INTRODUCTION

1-1 PURPOSE AND SCOPE

This design handbook is intended for the dissemination of such general and technical information concerning propellant actuated devices as may be necessary for their care, handling, and utilization. It also serves as a convenient reference of fundamental and practical information as well as analytical procedures necessary to aid in the design, performance estimation, and test evaluation of these devices. Only the basic theory and principles underlying the functioning and design of most devices in the class are discussed; no attempt is made to treat the mechanical details or operating procedures that differentiate one model from another. General reference is only made to specific models to give the reader an overall picture of the development of propellant actuated devices from the conception and to serve as examples in the design and ballistic analysis chapters.

1-2 HISTORY

Prior to World War II, escape from a disabled aircraft in flight occurred in environments and at speeds that were physiologically tolerable; therefore, muscular effort usually was sufficient to separate the man from his plane. As speeds increased, it became more difficult to leave the aircraft safely in the event of an emergency. The technique of inverting the plane, opening the canopy, releasing one's safety belt, and falling out was no longer feasible.

In 1943, the US Army Air Corps made a survey of emergency bail-outs that had occurred in 1942. The results showed that 12.5 percent had been fatal and 45.5 percent had resulted in injury. A similar study of bail-outs from fighter aircraft for the year 1943 showed that 15 percent had been fatal and 47 percent had resulted in injury.

The Germans, who probably had similar experience, were the first to take corrective action. A German directive was issued in 1944 requiring that all fighter aircraft be equipped with ejection seats. The British followed with a directive in 1945 requiring that all fighter aircraft with speeds greater than 400 mph be equipped with ejection seats.

The problems of escape from pusher-type aircraft were studied by the Aircraft Laboratory at Wright Field as early as 1940. At least one experimental airplane made during World War II is reported to have been equipped with an escape mechanism, but it was not until 1945 that our Air Force and Navy began serious development work on ejection seats. In August 1945, the Pitman-Dunn Laboratories of the Frankford Arsenal were requested to develop ejection devices under the cognizance of the Special Projects Branch, Aircraft Laboratory, Engineering Division, Air Materiel Command. Initial performance requirements of the ejection devices were established on the basis of data and information from the Aircraft and Aero-Medical Laboratories of Engineering Division, Air Materiel Command. With the passage of time the organization now charged with this responsibility is the Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base.

Before gas-type devices could be used on personnel ejection seats, it was necessary to determine tolerable acceleration levels for the human body and the minimum separation velocity necessary for ejected personnel to clear the aircraft structure. The Aerospace Medical Research Laboratories have been conducting a continuing study to determine the physiological limitations of the human body when subjected to the ejection environment. Recent studies have led to the specification of a parameter called the Dynamic Response Index (DRI) instead of the previously specified limitations of maximum acceleration and rate of change of acceleration as the criterion for determining the physiological limitations for personnel escape systems[1]. The DRI which is a measure of human spine compression – and, therefore, probability of injury – is intended to be a more meaningful determinant in that it is a measure of the stresses actually experienced by the ejectee. A nominal value of 18 for the average 50 percentile flying population has been specified for this parameter for ejection systems conditioned at 70°F.

The first ejection seat catapult was standardized in 1947 and designated the M1 Personnel Catapult. The design and development of the M1 and M2 Canopy Removers followed in quick succession. These early devices were initiated mechanically; i.e., cocked firing pins were released by rotating or withdrawing a sear. The "choke coil", bell-crank rod, and cable-actuated system left much to be desired from a reliability, simplicity, and maintenance standpoint.

In 1949, Frankford Arsenal developed a propellant gas pressure source that was designated an initiator. Concurrently, the Arsenal redesigned the existing devices to incorporate a pressure operated firing mechanism. The propellant gas was transmitted by MS-28741 hydraulic hose assemblies from the initiators to the firing mechanisms.

With the advent of the B-52 airplane and its requirements for multicrew, multifunction, integrated escape system, it was realized that new forms of propellant actuated devices (PAD) would be required for such functions as positioning ejection seats, unlocking hatches, and stowing control columns. With the support of the airframe contractors, Wright-Patterson Air Force Base and Frankford Arsenal commenced the design and development of the first series of Thrusters, designated M1, M2, M3, and M5 in 1951. Since that time many new and varied applications for PAD have been found in aircraft escape, aerial delivery, and other systems.

Ever since the advent of powered ejection seats, Frankford Arsenal has supported the US Air Force in their requirements for Government-furnished (GFE) PAD in these systems throughout their life cycle. With the advent of the weapon system concept of procurement, and the subsequent development of much of the PAD used in newer escape systems as contractor-furnished equipment (CFE), Frankford Arsenal procures and remanufactures many of the CFE as well as GFE items for all services.

Over 200 GFE propellant actuated devices have been developed and standardized. An engineering manual is published by Frankford Arsenal listing about 175 propellant actuated devices[2]. In addition to the devices listed in this reference, a nomenclature list for standardized propellant actuated devices as well as those under development[3], and a publication listing propellant actuated device patents and technical reports covering the period 1946 through 1969[4] are available.

1-3 USES

Although propellant actuated devices originally were developed for emergency escape from aircraft, their use has proliferated to a growing number of nonescape system applications. These include applications to large bore gun scavenging, support of Army concepts for advanced aerial delivery systems, applications to devices for explosive ordnance disposal, settable time delay mechanisms, deployment kits for retardation systems used in the delivery of special stores, and cool gas generators for inflation and rigidization applications.

Propellant actuated devices are useful in these and other applications because of their reliability, simplicity, light weight, small size, and ability to withstand long periods of storage under extremes of environment without impairment of reliability.

REFERENCES

1. MIL-S-9479A (USAF), *Seat System Upward Ejection, Aircraft, General Specification for*, 30 December 1969.

2. IEP 65-6370-8 REV A, *Propellant Actuated Devices Engineering Manual*, 15 June 1969, AD-872 430.

3. *Nomenclature List for Cartridge and Propellant Actuated Devices*, Dept. of the Army, Frankford Arsenal, July 1969, AD-872 429.

4. *Summary of Statistics for Cartridge and Propellant Actuated Devices*, Dept. of the Army, Frankford Arsenal, February 1970, AD-872 426.

CHAPTER 2

DESCRIPTION OF PROPELLANT ACTUATED DEVICES

2-1 GENERAL

The first aircraft personnel escape catapults and associated devices powered by solid propellants were called "Cartridge Actuated Devices" (CAD), a name which arose from the similarity in appearance between their propellant containers and cartridge cases for conventional small arms munitions. As new applications were developed, this similarity disappeared, but the name continued to be used. Many of the older records will show this name. Ordnance Corp Technical Minutes 37418, 12 April 1960, was published to change the name of future developments of these items to "Propellant Actuated Devices" (PAD), this name more nearly expressing their principal characteristic.

The propellant actuated devices described in this chapter have been divided arbitrarily into three categories, gas-generating devices, stroking devices, and special purpose devices. Although special purpose devices could, for the most part, be classified in either of the first two categories, they have been separated because of their specific applications.

Stroking devices may be further classified as direct or high-low. Direct systems are devices in which the propellant is consumed in the working chamber. In high-low devices the propellant is burned in a separate, or high pressure chamber, and the resultant gases are then bled through an orifice or nozzle into the working chamber. Only direct systems will be considered in this chapter. High-low systems will be considered in Chapter 4.

Various sources list information on the physical and performance characteristics of propellant actuated devices which have been developed. These data and that listed in this publication are presented to aid the design engineer and to serve as a reference in determining the feasibility of proposed devices.

Escape systems are discussed and a specific escape system application is described in order to illustrate the use of propellant actuated devices and to demonstrate their interrelationship in an actual system. Energy transmission in systems also is discussed.

2-2 PROPELLANT ACTUATED DEVICES

Propellant actuated devices will be discussed according to three categories: gas generating devices, stroking devices, and special purpose devices.

2-2.1 GAS GENERATING DEVICES

There are two basic types of gas-generating devices: short duration "initiators" and long duration "gas generators". These devices consist of vented chambers containing cartridges and firing mechanisms. The method of actuation may be either electrical, mechanical, or ballistic (gas pressure).

2-2.1.1 INITIATORS

Initiators are short duration gas generating devices designed primarily to supply gas pressure to operate the firing mechanisms of other propellant actuated devices, but they also may be used as sources of energy for operating piston-type devices such as lap-belt releases, personnel restraint systems, and safety-pin extractors. Since they eliminate cumbersome and difficult to maintain cable-pulley systems and provide a more reliable method of actuation. Initiators are used extensively in aircraft to operate the firing mechanism of other propellant actuated devices. In systems where the propellant actuated device is remote from the initiator, intermediate gas actuated initiators are used as boosters. For applications where propellant actuated devices are fired in sequence, initiators or other PAD's may contain a combustion train or delay element to delay propellant ignition for a specific time to permit completion of another operation.

The development of the gas-actuated ejection system has paved the way for sophisticated transmission systems that program, sequence, and automate a complex array of PAD devices during the entire personnel ejection cycle. Initiator charges are sized for a given length of transmission line. Early initiators, such as the M5A2, weighed 0.9 lb and occupied 6.5 in.^{3}; more recently, miniature initiators, of which the M28 is typical, weigh 0.33 lb and occupy 4.0 in.^{3} [3]

A need has existed for many years for a small lightweight initiator that would further reduce their size and weight. This need apparently has been filled by the M104-type Initiator. The M104 weighs only 0.083 lb. In the F-104 aircraft, for example, 3.46 lb of weight may be saved by using M104-type Initiators for the 14 initiators now carried. In addition, supply and resupply can be accomplished at considerable cost savings[3].

Fig. 2-1 shows a cross-sectional drawing of a typical mechanically actuated delay initiator. Table 2-1 lists comparative data for several existing initiators.

2-2.1.2 GAS GENERATORS

Gas generators primarily are designed to supply gas pressure for a longer period of time than initiators and are used to inflate, pressurize, or otherwise serve as a self-contained propellant gas generating system. They can be designed to deliver propellant gas for a range of times from seconds to minutes. The delivered gas also may be filtered and cooled as required for a specific application.

Fig. 2-2 is a partial cross-sectional drawing

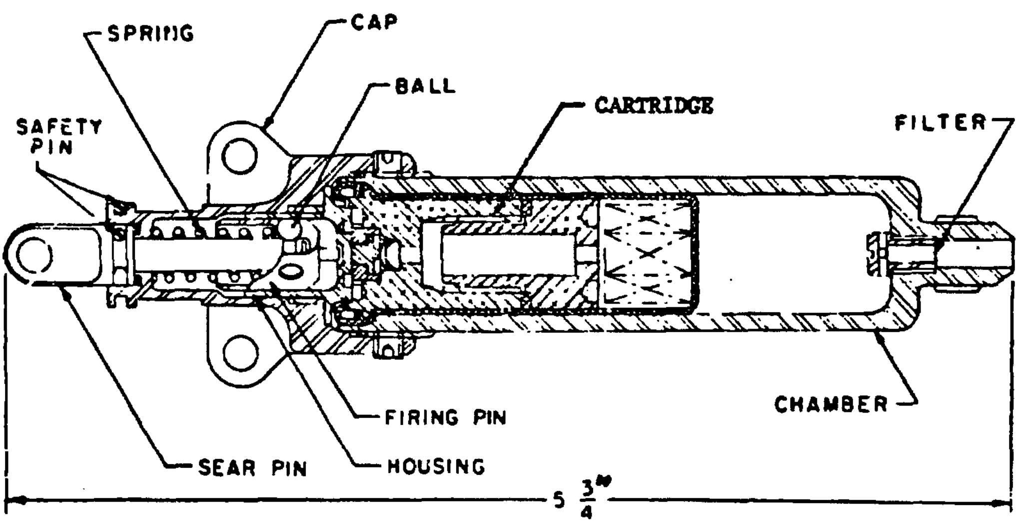


Figure 2-1. Mechanically Actuated Delay Initiator

TABLE 2-1

COMPARATIVE DATA FOR INITIATORS

Device	Weight, lb	Delay, sec	Peak Pressure, psi [1]
MECHANICALLY ACTUATED [2]			
M4A1	1.0	2.0	750(10)
M12A1	1.0	1.0	750(10)
M14	0.39	3.0	750(10)
M16	0.39	3.0	1000(15)
M27	0.33	–	1000(15)
M52	0.39	5.0	1000(15)
M88	0.3	–	750(10)
M98	0.9	–	1000(15)
GAS ACTUATED [3]			
M5A2	0.9	–	1000(15)
M10	0.9	2.0	1000(15)
M15	0.39	3.0	750(10)
M28	0.33	–	1000(15)
M29 [4]	1.75	–	1000(15)
M42	0.9	3.0	1000(15)
M51	0.39	2.0	1000(15)
M72	1.0	0.5	1000(15)
M104	0.083	–	1500(15)

[1] Peak pressure in 0.062 in.^{3} gage located at end of a length of MS-28741-4 hose. The number following the pressure indicates the hose length in feet.
[2] Actuation force 20-35 lb
[3] Actuation pressure 750 psi minimum
[4] Actuation – gas pressure with manual override

of the M17 Gas Generator. It is gas initiated and is designed to pressurize a 27-in.^{3} chamber to 7000 psi in 0.22 sec. and is used to operate the parachute ejector mechanism for the BDU-12/B Practice Bomb.

2-2.2 STROKING DEVICES

Stroking devices, for purposes of this discussion, include catapults, removers, and thrusters. These devices can be further divided into two groups: (1) open devices or those which separate and allow the escape of the propellant gas, usually upon completion of function, and (2) closed devices that retain the gas after completion of function.

Closed devices must be designed to an additional constraint since a method of arresting the stroking member at the completion of its travel is required.

2-2.2.1 CATAPULTS

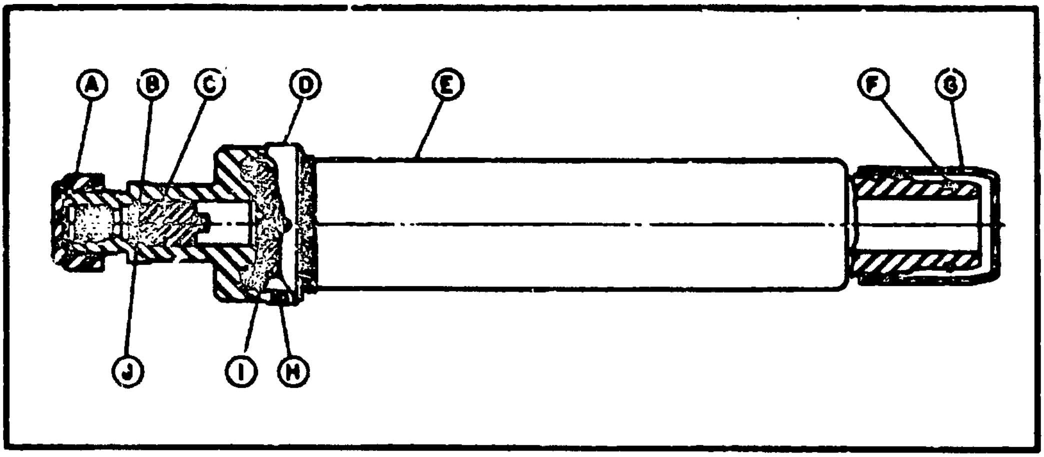
The ballistic catapult was developed for emergency escape of personnel from aircraft. In this application it serves as a connecting member between the crewman's seat and the aircraft structure.

2-2.2.1.1 CONVENTIONAL CATAPULTS

The conventional catapult or ballistic catapult as it is sometimes known is a two- or three-tube telescoping open device which is mounted in the aircraft on trunnions. The firing mechanism is mounted in one end of the catapult along with a cartridge containing a primer, igniter, and propellant charge. When the cartridge is actuated, the propellant gas fills the catapult and causes it to extend (Fig. 2-3). As the catapult extends, it ejects the seat-man from the aircraft. Table 2-2 lists typical conventional catapults and presents performance data for these devices.

2-2.2.1.2 ROCKET-ASSISTED CATAPULTS

Rocket-assisted catapults combine the operation of conventional catapults with those of a rocket to sustain thrust and thus increase ejection height. These devices are of two basic designs. In the M8, M9, and M10, for example, the launch tube surrounds the rocket motor, while in the XM38 and XM39 the launch tube is housed within the perforation of the rocket grain. As the launch tube strokes out and separates from the rocket, which is attached to the ejection seat, the gas evolved during the launch phase is used to ignite the sustainer rocket. For stability in the pitch plane, the rocket nozzle is angled to allow the resultant thrust vector to pass through the seat-man center of mass. In the M8, M9, M10, and XM39 the nozzle is fixed at a predetermined angle, while in the XM38 the nozzle angle is variable to allow for



CROSS SECTION DRAWING

Component		Component	
A	Cap, Shipping	F	"O" Ring
B	Pin, Firing	G	Cap, Shipping
C	"O" Ring	H	Setscrew
D	Cap, Initiator	I	Cartridge Assembly, M37
E	Body, Chamber	J	Pin, Shear

Figure 2-2. M17 Gas Generator

variations in the location of the center of mass.

The catapult portion of the XM38 and XM39 Rocket-assisted Catapults are small bore high-pressure devices which, because of their concentric configuration, maximize the impulse delivered for a unit of a given size. Also, their high operating pressure, about 5000 psi as compared to about 1500 psi for conventional catapults, tends to reduce the spread in performance over the temperature range −65° to +200°F.

Table 2-3 lists the performance data for several existing rocket-assisted catapults. Fig. 2-4 is a cross-sectional drawing of the XM39 Rocket-assisted Catapult.

2-2.2.2 REMOVERS

Removers are two- or three-tube telescoping devices which are designed to jettison the canopy from high speed aircraft prior to personnel ejection. They are either mechanically or ballistically actuated. A third type, the electromechanical-ballistic remover, is designed to permit normal opening and closing of the canopy as well as emergency jettisoning. Comparative data for these devices are presented in Table 2-4.

Removers are similar in design to conventional catapults with one important exception: they are designed to be capable of retaining the maximum pressure produced by the burning propellant in the event of

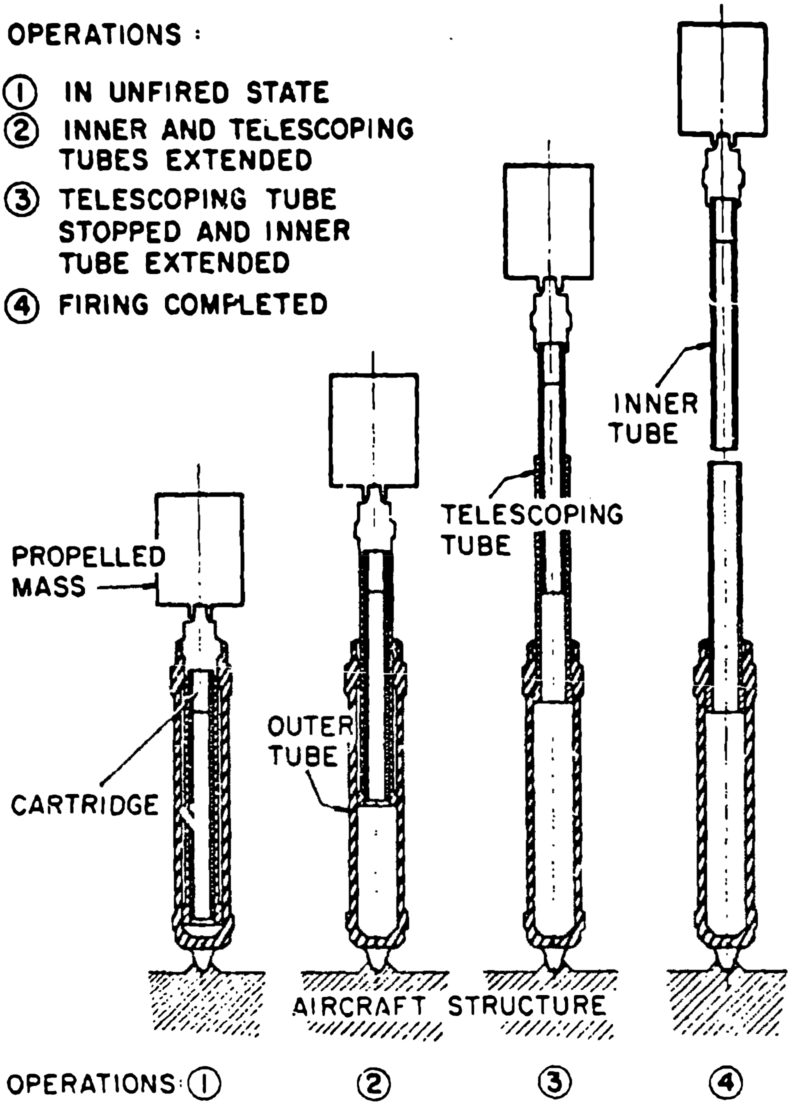


Figure 2-3. Operation of a Conventional Catapult

restricted motion of the propelled load[4]. This feature is described as being able to withstand "locked shut" firings. Also, greater acceleration is permissible with removers since human physiological limitations are not a factor. The only limiting factor is the strength of the aircraft structure. Fig. 2-5 is a sketch of a typical gas actuated remover.

2-2.2.3 THRUSTERS

A thruster is a propellant actuated device

TABLE 2-2

COMPARATIVE DATA FOR CONVENTIONAL CATAPULTS

Device	Stroke, in.	Propelled Weight, lb	Velocity at 70°F, fps	Maximum Acceleration at 70°F, g	Maximum Rate of Change of Acceleration at 70°F, g/sec	Weight of Device, lb
M1A1	66	300	60	20	170	8.2
M2[1]	60	300	38	12	150	13.0
M3A1	88	350	77	20	180	24.9
M4A1	45	325	38	12.5	100	6.7
M5A1	66	300	60	20	170	8.2
M6A[1]	21	300	28	8.5	150	31.5

[1] Multishot training catapult

primarily developed to serve as a source of energy or exert a thrust, through a short stroke, to move a weight and probably overcome a resistive force. Thrusters are used for operations such as seat positioning, storage of equipment, hatch or canopy unlock and canopy ejection. They generally are designed as a closed ballistic system so that the piston does not separate under any operational condition including "locked shut" and "no load" firings. Each thruster is designed to operate against a specific mass and a constant or varying forces.

Buffer or oil damper mechanisms are used occasionally in conjunction with thrusters and, in these instances, are made as integral parts of the thruster. These buffering mechanisms are used to restrict the velocity and acceleration of the propellant load because of structural or human physiological limitations. Fig. 2-6 depicts the M16 Oil Buffered Thruster.

Thrusters have been developed which function in the usual manner, except that at the end of the stroke, they bypass gas through high pressure flexible hose to initiate other propellant actuated devices. An example is the M19 Thruster in the F-106B aircraft escape system. This thruster unlocks the canopy and, at the completion of stroke

TABLE 2-3

COMPARATIVE DATA FOR ROCKET-ASSISTED CATAPULTS

Device	Catapult Stroke, in.	Weight Propelled, lb	Separation Velocity at 70°F, fps	Maximum Acceleration at 70°F, g	Rocket Impulse at 70°F, lb-sec	Rocket Action Time at 70°F, sec	Weight of Device, lb
M8	40	350	40	12	1200	0.40	27
M9	35.75	350	40	12	1100	0.35	24
M10	34	400	40	12	1100	0.40	26
XM38	34	363	47	18	1350	0.41	33
XM39	34	415	52	18	1140	0.40	19.5

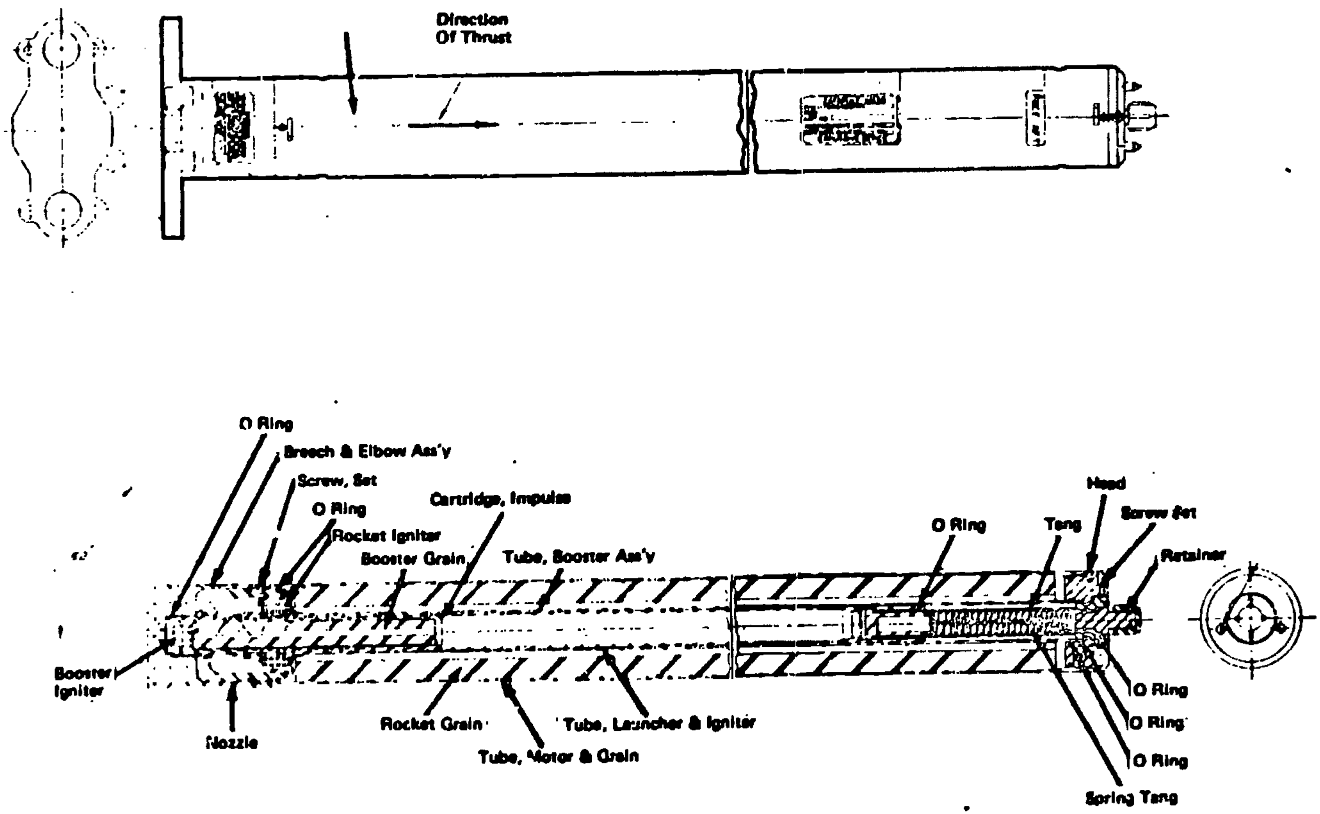


Figure 2-4. XM39 Rocket-assisted Catapult

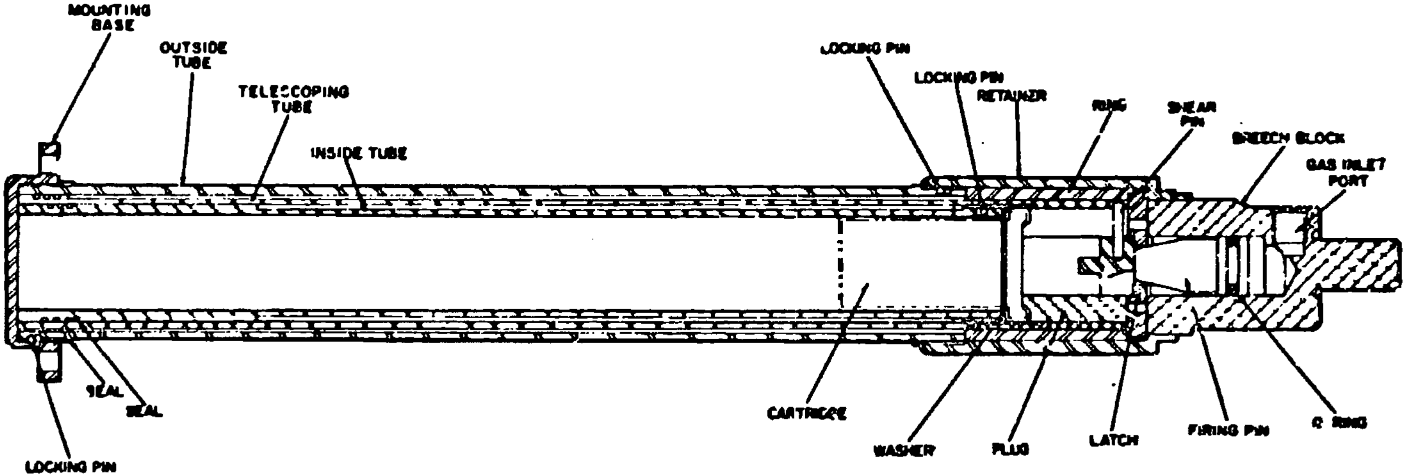


Figure 2-5. Gas Actuated Remover

TABLE 2-4

COMPARATIVE DATA FOR REMOVERS

Device	Stroke, in.	Propellant Weight, lb	Thrust at 70°F, lb	Velocity at 70°F, fps	Stroke Time at 70°F, sec	Method of Initiation	System Weight, lb
M1A3	23.3	300	2800	20.0	0.135	Gas	2.1
M2A1	26.0	300	2600	20.5	0.150	Mech	4.4
M3A1	26.0	300	2600	20.5	0.150	Gas	4.4
M4	18.0	300	2900	20.0	0.114	Gas	3.84
M5	18.0	1000	4500	10.0	–	Gas	3.84
M8A1[1]	12.0	350	5400	24.0	0.150	Gas	22.5
M9[1]	27.0	300	6000	33.0	0.090	Gas	35.0

[1] Electromechanical-ballistic canopy remover actuator

(after the canopy is unlocked), bypasses gas to actuate the canopy remover.

2-2.3 SPECIAL PURPOSE DEVICES

A number of propellant actuated devices have been developed for special applications that do not fall into the previously mentioned categories. These devices include cutters, releases, electric ignition elements, pulse generators, and ejectors.

2-2.3.1 CUTTERS

Cutters have been developed for a number of specific applications including the severing of electrical connections and reefing lines that restrain a parachute from opening initially to full size.

2-2.3.1.1 CABLE CUTTERS

Cable cutters have been designed to sever electrical cables prior to the removal or ejection of an aircraft canopy or ejection seat. Although most cable cutters were developed to sever a single cable, the M8 Cable Cutter was designed to sever a bundle of 41 electrical wires prior to the removal of the aircraft canopy. The M8 has a blade attached to the

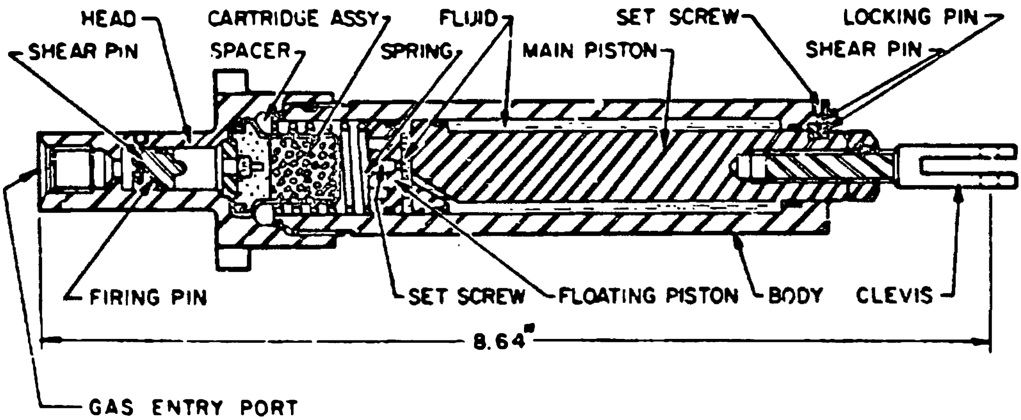


Figure 2-6. M16 Oil Buffered Thruster

forward end of a piston. Gas produced by the burning propellant in the cartridge propels the piston forward, driving the blade into the wires to be severed. The blade of the cutter may be coated to prevent electrical shorting as it passes through the current carrying wires.

2-2.3.1.2 REEFING LINE CUTTERS

2-2.3.1.2.1 Conventional Type

Reefing line cutters are designed to sever the reefing lines of parachutes[5]. Unlike cable cutters that may be electrically or gas initiated, reefing line cutters are initiated mechanically. Fig. 2-7 shows a typical reefing line cutter. The firing mechanism of the cutter is attached by lanyard to the shroud of a parachute. When the shroud lines are pulled taut by the opening of the parachute, the cable (sear) is pulled out of the end of the cutter, cocking and releasing the firing mechanism. The firing pin strikes the primer in the cartridge which ignites a pyrotechnic delay element. After a predetermined delay, the cartridge is fired and the propellant gas propels the cutter blade forward. The blade shears the reefing line that is passed through the hole in the end of the cutter. A whole family of cartridges has been developed to provide a range of different delay times (2-, 4-, 6-, 8-, and 10-seconds). The sear-type firing mechanism may be operated by pulling the cable (sear) from any angle up to and including 180 deg to the cutter main axis.

2-2.3.1.2.2 Settable Delay Reefing Line Cutter

Present technology for aerial delivery of cargo by parachute is hampered by inaccuracies due to variables such as drop height and prevailing winds. To improve delivery accuracy and reduce vulnerability, the parachute is reefed during the initial portion of the descent trajectory. Present technology uses a fixed pyrotechnic delay reefing line cutter to disreef the parachute and allow for soft cargo landing. However, this arrangement limits the effectiveness of aerial cargo delivery systems to performance prescribed by a fixed time delay and a corresponding preselected drop height.

A prototype settable Mechanical Delay Reefing Line Cutter, the XM31, has been developed. This device is a combination of a modified M9 Mechanically Initiated Reefing Line Cutter and the M564 Mechanical Artillery Time Fuze. The XM31 is settable and resettable in 0.1-sec increments from 2 to 100 sec[6].

By use of this device it is possible to compensate for variables that are identified in flight and that otherwise might detract from the accuracy of the drop.

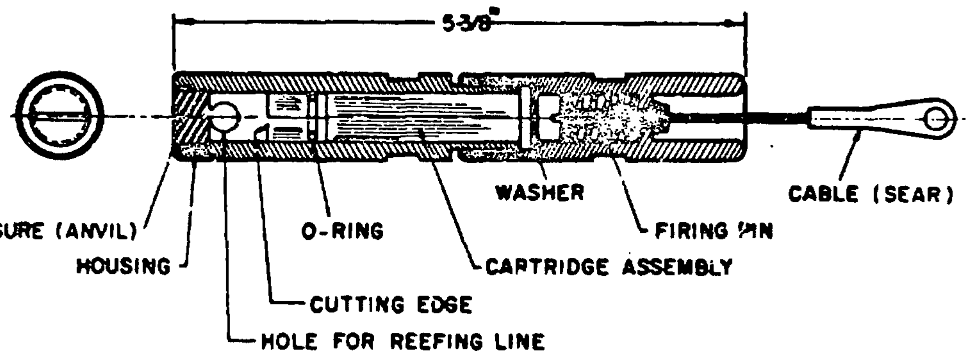


Figure 2-7. Typical Reefing Line Cutter

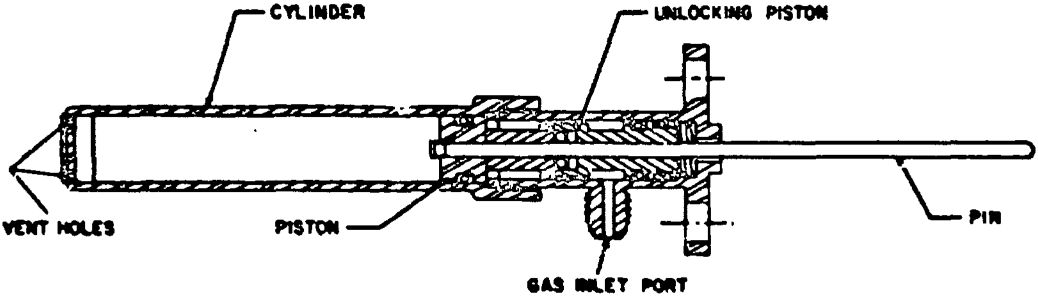


Figure 2-8. Release

2-2.3.2 RELEASES

Releases have been developed to perform a variety of functions including releasing external stores from aircraft and extracting the safety pins from other propellant actuated devices. Fig. 2-8 shows a device designed to accomplish this latter function. It consists of a cylinder (body), piston with integral pin, and locking mechanism. The release pin replaces the safety pin in the firing mechanism of a propellant actuated device. The release contains no cartridge, but rather uses gas supplied by another device. The supplied propellant gas unlocks the piston and causes it to withdraw its pin from the device to be armed.

This type of device has been used in aircraft escape systems. For instance, the M1A1 Release is used to release a spring-loaded firing pin in the M1A3 Canopy Remover. For this application, the release is actuated automatically during the pre-ejection cycle. This prevents personnel ejection prior to canopy removal.

2-2.3.3 ELECTRIC IGNITION ELEMENTS

2-2.3.3.1 CONVENTIONAL TYPE

The electric ignition element is a device designed to replace the firing pins and percussion primers used with gas or mechanically actuated propellant actuated devices. Ignition elements have been developed that are capable of being fired by an electrical power source such as an aircraft 28-V supply. The first ignition elements developed were designed to pass 0.5 A without firing and to fire when the current was 1.0 A. This early series of ignition elements used the body of the element for a ground. A latter series was designed with four internal pins insulated from the body of the device (Fig. 2-9). Two pins are interconnected and provide a testing circuit separate from the firing circuit. The other pins are connected to the firing circuit. These units are designed to a 1-A, 1-W, 5-min no fire and a 5-A, 50-msec all fire specification[7].

The two pins in the firing circuit are connected to a wire filament in the element. This wire is coated with an ignition bead that is ignited when the filament is heated by passage of the required current. Ignition of the bead sets off the main charge. The gas generated exerts a force against the firing pin of the device to be actuated.

2-2.3.3.2 ELECTROMAGNETIC IMPULSE GENERATORS

To improve the reliability of electrically initiated systems, auxiliary firing sources such as electromagnetic impulse generators have been developed[8]. These devices are composed of several magnets and a coil of wire. They are operated manually and automatically reset, and are designed to generate sufficient

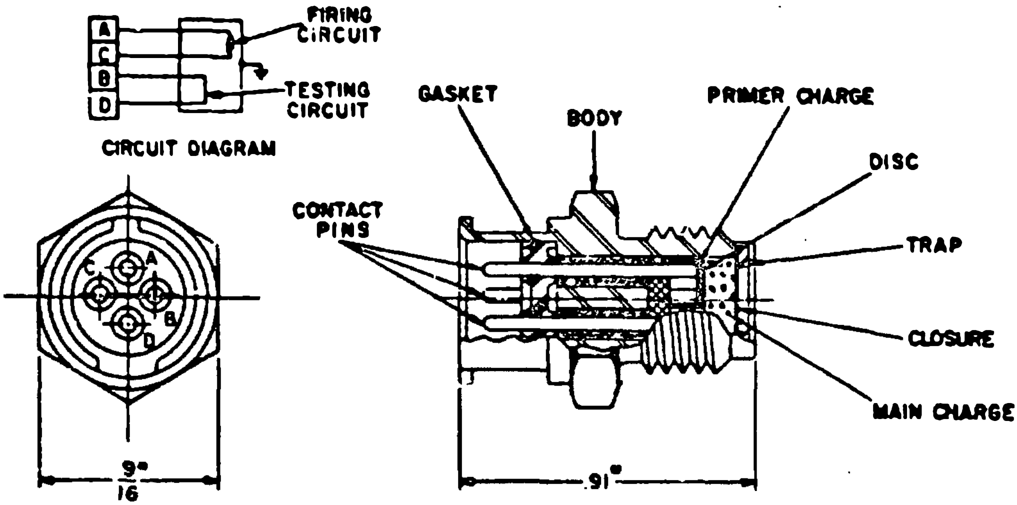


Figure 2-9. Electric Ignition Element

electrical energy to fire specified electric ignition elements. Movement of the handle or trigger on the generator changes the reluctance in the magnetic circuit, generating a current in the coil. These units may be designed to have an indefinite life and to be unaffected by environmental extremes.

2-2.3.4 EJECTORS

A number of ejectors or launching devices have been developed for a number of specific applications including stores and munitions launchers, drogue guns, and parachute ejectors. One such device is the XM7 Reserve Parachute Ejector. This cartridge actuated parachute ejector is a device used to insure deployment of the paratrooper reserve parachute in the event of main chute malfunction. The deployment bag and parachute are chest mounted on the paratrooper and are actuated manually. The parachute and canopy with ballistic components are ejected laterally. As the shroud lines become taut, the parachute is separated from the deployment bag and ballistic launcher. The deployment bag and launcher in turn deploy their own 36-in. chute to arrest their descent.

A ballistic rarity that occurs with the XM7 Ejector is the variation of the effective load. The ejector travels nearly 60 percent of its stroke with almost no load while absorbing the elasticity of the parachute container; thereupon, it abruptly picks up the entire parachute mass and continues to accelerate it until the end of stroke.

2-3 ESCAPE SYSTEMS

Escape systems are only one of the many possible systems applications of propellant actuated devices. This application will be discussed, however, because of its relative importance not only in military but also commercial applications.

2-3.1 CONVENTIONAL AIRCRAFT ESCAPE

Initially, relatively simple systems for canopy removal and seat ejection were provided for escape of personnel from fighter aircraft. In these systems, two separate operations – canopy removal followed by seat ejection – were required; mechanical interlock insured the order of actuation. As the operation of aircraft became more complex, escape systems were expanded to include pre-ejection operations, such as positioning the ejection seat and restraining the ejectee. The development of escape systems for bomber aircraft necessitated that initiation be possible from several points and provision be made for the escape of many crewmen.

The sequence of events which make up a complete emergency egress trajectory is depicted in Fig. 2-10.

As an example of the application of propellant actuated devices to conventional escape systems, the escape system for the F-104A and F-104C aircraft is presented.

2-3.2 ESCAPE SYSTEM FOR THE F-104A AND F-104C AIRCRAFTS

A schematic of the C2 seat ejection system for the F-104A and F-104C aircrafts (single-place fighters) is presented in Fig. 2-11. When the "D" ring is pulled, three cables attached to it are pulled actuating four initiators. One M27 Initiator supplies gas pressure to actuate the M13 Thruster that unlocks the aircraft canopy and then supplies gas to a remover to jettison the canopy.

Concurrently, a second M27 Initiator, actuated by pulling the "D" ring, supplies gas pressure to initiate an M15 Thruster that positions the pilot's legs by tightening cables attached to the spurs of his flight boots. As the piston of the thruster retracts, it actuates an M27 Initiator that supplies gas pressure to initiate the M10 Catapult that ejects the pilot from the aircraft.

The third initiator, actuated by pulling the "D" ring, is an M32 Delay Initiator that supplies gas pressure to fire the M10 Catapult after a 1-sec delay. This initiator is insurance against a maintenance failure or malfunction of the pre-ejection portion of the system; when the catapult is actuated by the M32 Delay Initiator, the pilot is ejected through the canopy.

The fourth initiator actuated by the original pull of the "D" ring is an M30A1 Delay Initiator that contains a 2-sec delay element. After the 2-sec delay, the initiator is fired and gas is supplied to cable cutters that release the pilot's legs. To insure that the pilot's legs are released, a mechanical tripper ignites an M32 Initiator containing a 1-sec delay element that is supplied to the cable cutters. Gas from the M32 Initiator is also supplied to the M28 Initiator which acts as a booster and supplies gas to operate the pilot's lap belt release and rotary actuator that separates the pilot from the seat.

To summarize, the pilot pulls the "D" ring, the canopy is unlocked and ejected, his legs are positioned, and the seat ejected. His legs are then freed, the lap belt opened and he is separated from the seat. All this is accomplished in the proper sequence, and backed up by parallel systems to insure operation of the catapult and leg release cable cutters.

2-3.3 CAPSULE ESCAPE SYSTEMS

With the development of higher performance flight aircraft operating at supersonic speeds and extreme altitudes, it became necessary to develop escape systems whose performance envelopes would be compatible with those of the advanced vehicles. The ejection seat escape system is effective in the region below 600 kt indicated air speed. Above 600 kt the probability of a safe escape with this system rapidly decreases*. One of the systems selected for study was the separable nose capsule. Such an escape system would allow the crewmen to separate safely from the aircraft throughout its altitude and speed range. Air Force Specifications require that escape capsules with protective and survival equipment be used in all aircraft with speeds exceeding 600 kt equivalent air speed and operational altitudes exceeding 50,000 ft.

A design study as well as the fabrication

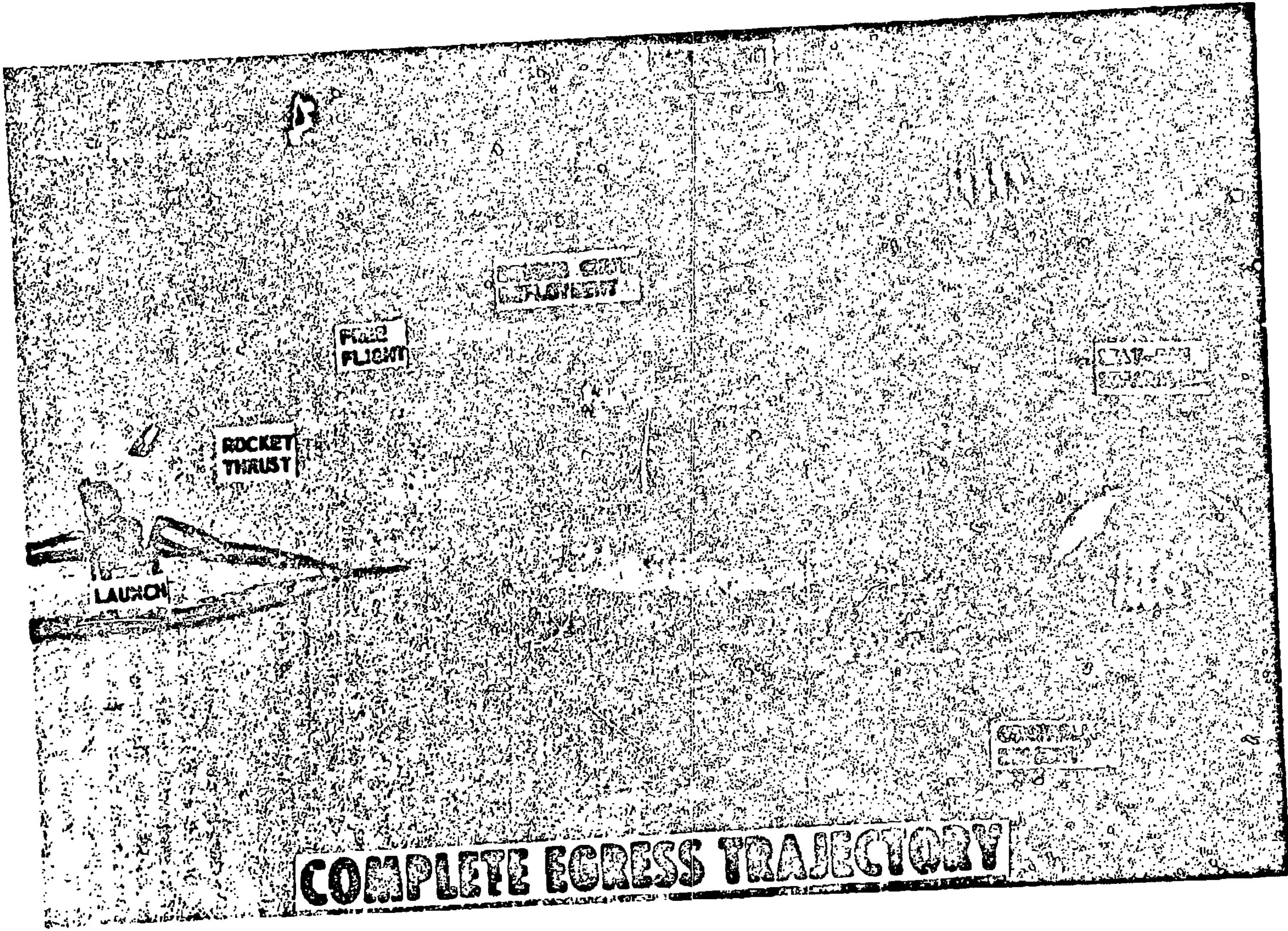


Figure 2-10. Egress Trajectory

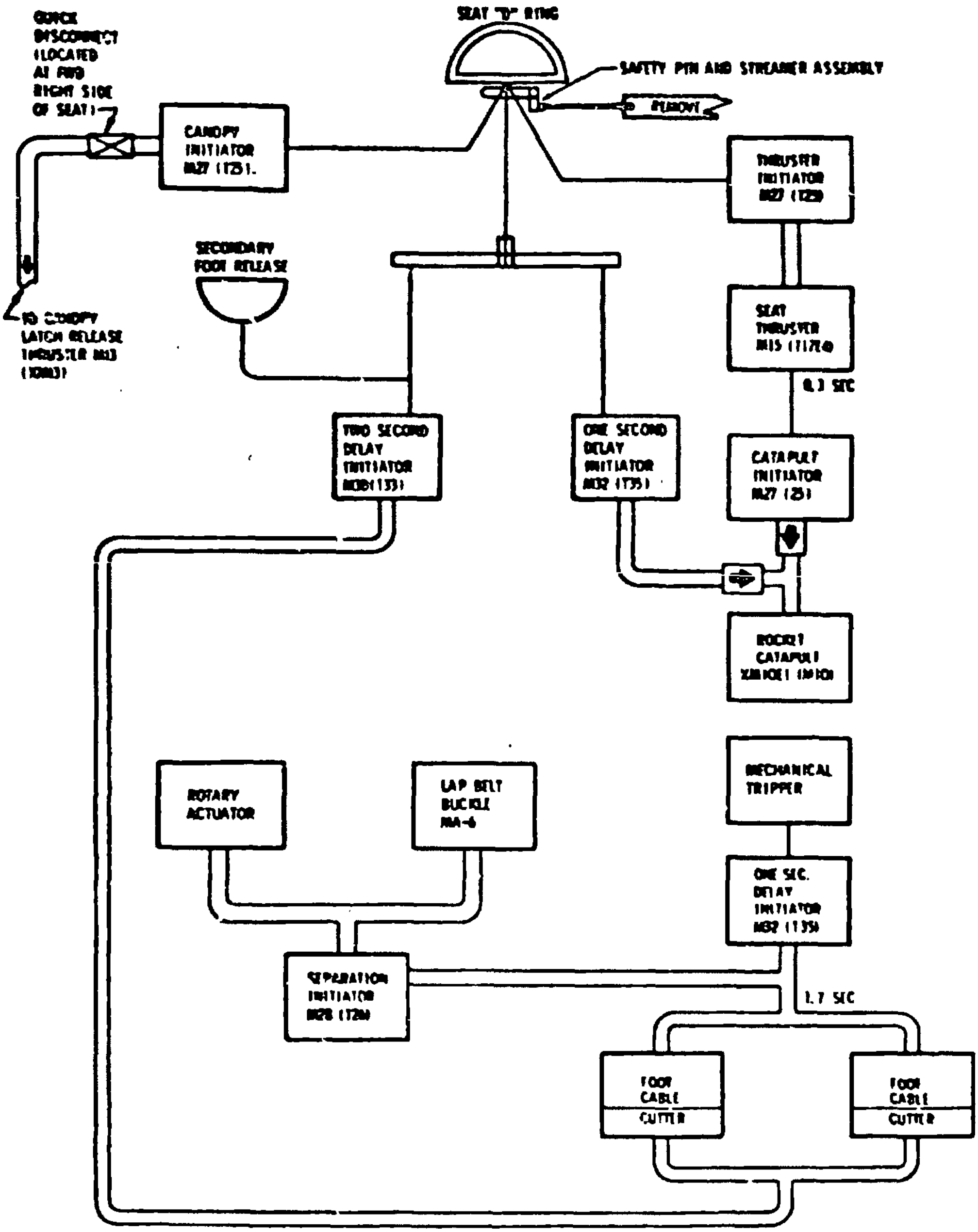


Figure 2-11. F-104A and F-104C Aircraft Ejection System

and testing of a rocket for a separable nose capsule escape system was conducted by Frankford Arsenal[10]. The test capsule (Fig. 2-12), based on the F-104 aircraft configuration, was designed to operate in the performance envelope of 0 to 900 kt equivalent air speed and an altitude range from sea level to 100,000 ft.

2-3.4 HELICOPTER ESCAPE SYSTEMS

The need for emergency escape from disabled aircraft is not limited to fixed-wing aircraft. Recent emphasis and the increased usage of helicopters for military and commercial applications have pointed out the necessity of equipping these aircraft with emergency escape systems. The presence and location of the rotor blades above the helicopter fuselage, however, prevent the use of the conventional upward escape trajectory.

Current concepts for effecting rescue include: the capsule concept in which the rotor blades and either all or a portion of the fuselage are separated ballistically from the crew or passenger compartments and the helicopter descends by parachute; ballistic separation of the rotor blades followed by conventional upward egress; and lateral ejection to a point beyond the rotor blades and then an upward rocket impulse to a safe recovery altitude[11].

2-3.5 EMERGENCY ESCAPE FROM COMMERCIAL AIRCRAFT

Emergency escape or means of providing for rapid evacuation from commercial aircraft in the event of a crash landing is a serious and vexing problem. This situation is even more critical in the event of a fire. Under these circumstances it is essential to provide for multiple exits for maximum safety of the passengers. One possible solution to this problem is shown in Fig. 2-13 and involves a concept using linear shaped charges to create emergency exits.

According to this concept, empty shaped charge tubing and a two-part liquid explosive system are provided for the creation of emergency exits. At the time of emergency and only when the aircraft is on the ground, the two liquid components are introduced into the shaped charge tubing by an initiator and are then detonated. The separate storage of these liquid components, each of which is nonexplosive, eliminates the hazards associated with the day-in and day-out transport

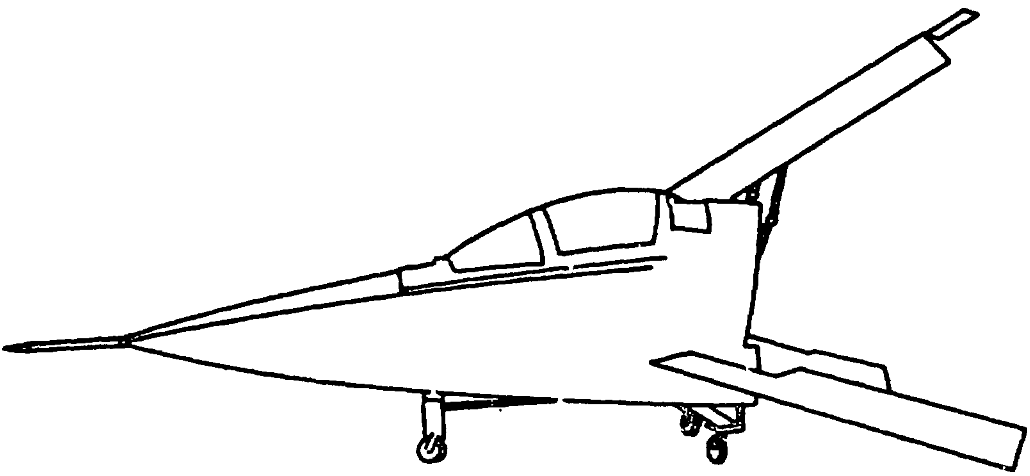


Figure 2-12. Separable Nose Capsule

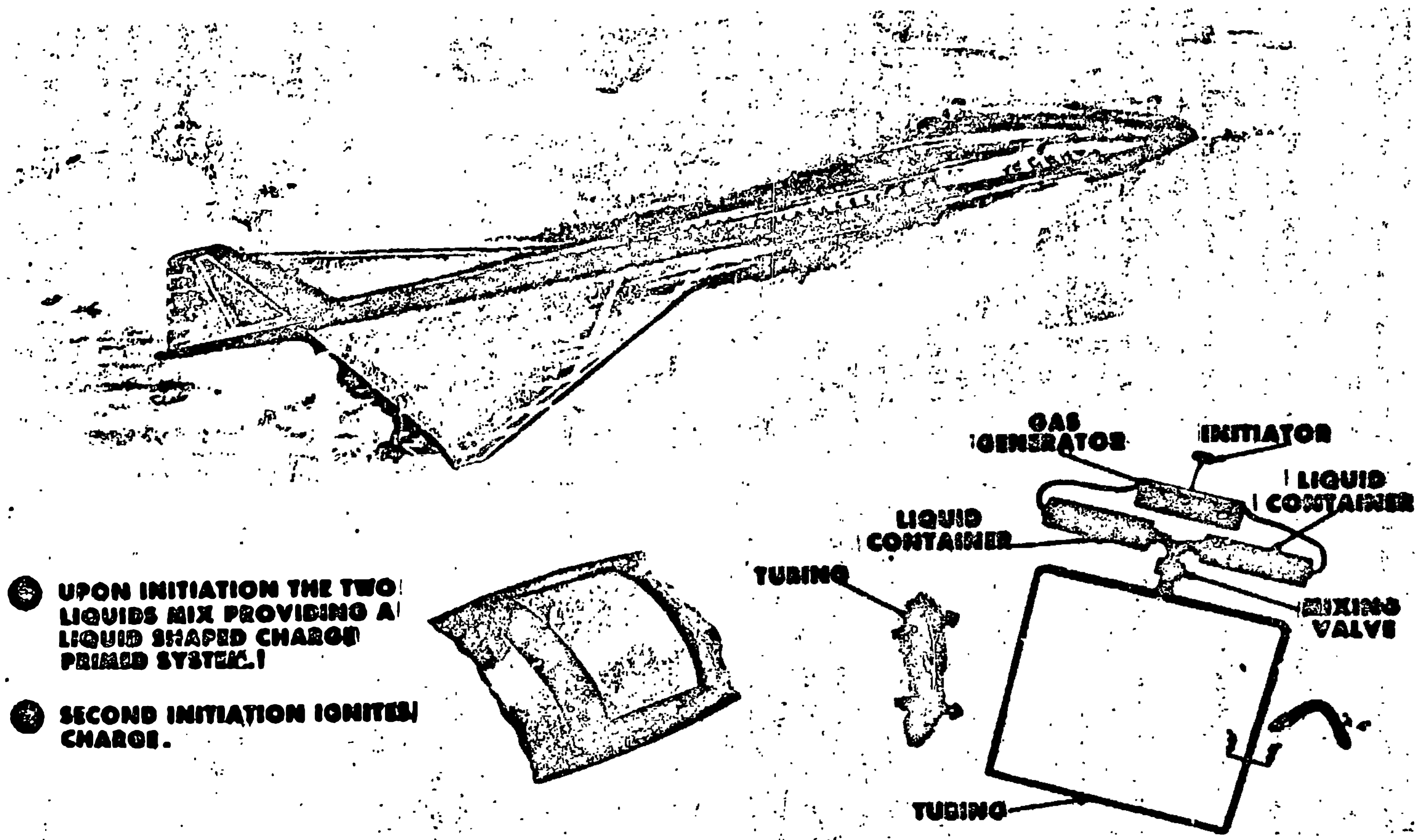


Figure 2-13. Emergency Egress System from Commercial Aircraft

of an explosive ordnance system on the aircraft.

This concept has been evaluated by the Federal Aviation Agency.

2-4 ENERGY TRANSMISSION IN SYSTEMS

In early aircraft escape systems all propellant actuated devices were initiated mechanically. This mechanical initiation required elaborate cable pulley arrangements to release cocked or precocked firing pins by rotating or withdrawing sears. The drawbacks of this system include cable routing and tensioning, and crash safety problems.

Gas initiated systems gradually replaced these early systems. Gas systems use steel-braided hose lined with Teflon and stainless steel tubing to transmit the gas from the gas-generating device to the propellant actuated device to be operated. The gas initiated systems not only provide a more reliable means of initiating a system of devices, but also permit the use of delay initiators and bypass thrusters to sequence operations in the system.

Electrically initiated systems have reliability comparable to gas initiated systems. The weight of electrical systems is less than gas systems since all initiators, couplings, check valves, and high pressure hose can be eliminated; however, an auxiliary power source must be provided. Where the propellant actuated device and the initiating device are some distance apart, booster initiators are required. Electrical systems offer the advantage of economy, smaller size, easier installation, and less maintenance, as well as permitting continuity checks by pilot or ground crews. The disadvantages of electrical systems lie in their need for an external power source and the possible danger of accidental initiation by stray electromagnetic radiation or static electricity.

Hybrid systems such as those used in the F-111 and F-14A aircraft incorporate gas operated and electrical components together with mild detonating cord (MDC).

REFERENCES

1. IEP 65-6370-8 REV A, *Propellant Actuated Devices Engineering Manual*, 15 June 1969, AD-872 430.

2. *Nomenclature List for Cartridge and Propellant Actuated Devices*, Dept. of Army, Frankford Arsenal, July 1969, AD-872 429.

3. H. D. MacDonald, *Low Cost Energy Transmission System*, Frankford Arsenal Technical Note TN-1146, March 1970.

4. MIL-C-25918 (USAF), *Cartridge Actuated Devices, Aircraft Crew Emergency Escape, General Specification for*, 27 September 1957.

5. *USAF Parachute Handbook*, WADC Technical Report 55-265, December 1956.

6. Nimylowycz, et al., *XM31 Reefing Line Cutter, Propellant Actuated with Settable Mechanical Time Delay*, Frankford Arsenal Technical Report No. R-1944, January 1970.

7. MIL-I-23658, *Initiators, Electric, General Design Specification for*, 3 June 1966.

8. A. E. White, *Development of Electrically Initiated Escape System Components, Ignition Elements T14E2, T19E1, T14E3, T19E2, XM21, XM22, and*

XM42; Pulse Generators XM10, XM11, and XM15, Frankford Arsenal Technical Report No. R-1725, June 1964.

9. J. Goodrich, *Escape from High Performance Aircraft*, WADC (now Wright-Patterson Air Force Base) Report No. TN 56-7, January 1956.

10. H. D. MacDonald, Jr., *Development of the XM15 Escape Rocket*, Frankford Arsenal Technical Report No. R-1817, February 1967.

11. M. Weinstock, *Emergency Escape For Army Helicopters*, paper presented at the 35th Aerospace Medical Association Meeting, 11-13 May 1964.

CHAPTER 3

BASIC DESIGN CONSIDERATIONS

3-1 GENERAL CONSIDERATIONS

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

Constant awareness of basic concepts must be maintained when designing propellant actuated devices, the most important being reliability. Determination of how these devices will operate in conjunction with other components in a system must be established along with a reliable method of initiation and a simple but sure method of installation.

Standard parts are used wherever possible, and when special parts are necessary, they are designed for ease of manufacture. All components of propellant actuated devices are interchangeable between similar units, *and under no conditions may the functional reliability of a device be dependent upon the selective fit of any or all parts.* Propellant actuated devices are designed for ease of proper assembly and, wherever possible, parts are made nonreversible to preclude improper assembly.

3-2 MOTION OR TIME FUNCTIONS

The functioning time for propellant actuated devices is the time interval between initiation and completion of function, e.g., end of stroke for a stroking device or termination of effective thrust or pressure output for rockets or gas-generating devices. This interval may vary from as little as a few milliseconds for initiators to as much as minutes for gas generators. This is illustrated by two examples: a stroking device and a solid propellant rocket.

3-2.1 PROPELLANT ACTUATED STROKING DEVICES

In the system shown in Fig. 3-1, a mechanically operated initiator is connected to a thruster by a length of hose. When the lanyard is pulled, the initiator cartridge is fired. The burning propellant in the initiator generates gas that flows through the hose to the thruster. When sufficient gas pressure is exerted on the thruster firing mechanism, the thruster cartridge is fired. As the propellant burns in the thruster, the pressure generated causes the thruster piston to extend and move the load. A curve showing the interrelationship of pressure and time in the thruster is presented in Fig. 3-2. Point A represents the point in time when the lanyard was pulled; point B, the pressure rise at the thruster firing mechanism; point C, initiation of the thruster firing mechanism; point D, the maximum delivered pressure from the initiator; point E, the rise in pressure in the thruster; point F, the first of a series of pressure wave reflections in the thruster firing mechanism; point G, the maximum pressure in the thruster; and point H, the completion of thruster stroke.

If it is assumed that the piston motion starts at time E, the actual work cycle of the device extends from points E to H. However,

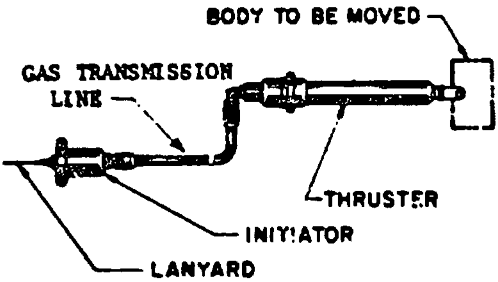


Figure 3-1. Simple PAD System

thrusters normally have internal locking mechanisms to prevent the piston from extending prior to thruster cartridge actuation, and the initial lock is released when the pressure reaches some intermediate point between E and G.

Every effort is made to minimize the time from point A to point E. The exception to this is in the design of the delay initiator where the time from point A to point B is increased intentionally to establish a specific sequence of operations. The delay function of the initiator is a major consideration in the design of elaborate systems. The interval of time from C to E, the time between initiation and the beginning of a sustained pressure rise, is referred to as the ignition delay. The interval E to G affects the selection of propellant, propellant geometry, internal volume, and expansion ratio (ratio of final internal volume to initial internal volume). The time from E to G varies from a few milliseconds for releases and initiators to 100 msec or more for some catapults.

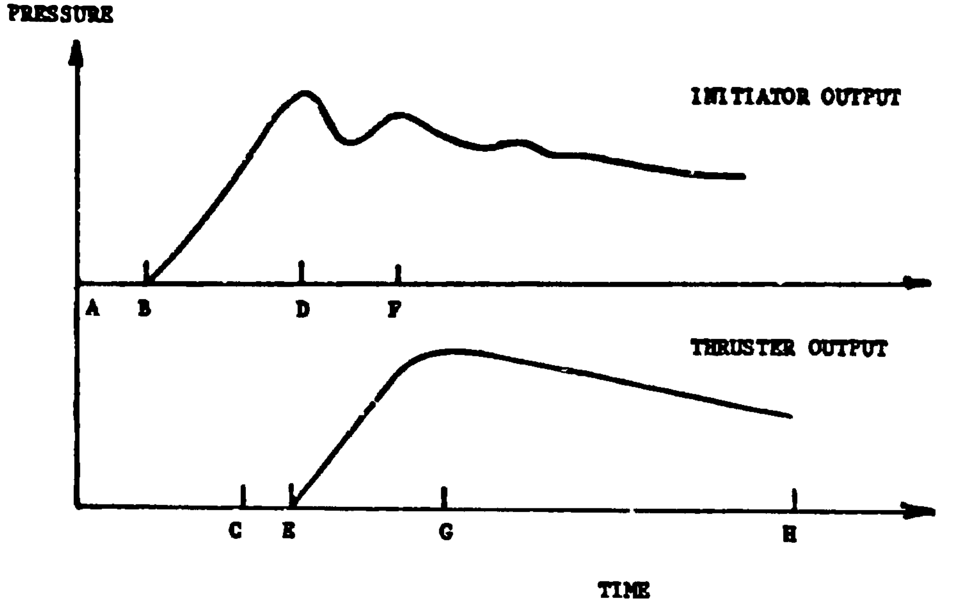
Peak pressure, point G, also is important since it determines the maximum acceleration and working pressure the unit must withstand. This working pressure affects the selection of piston size, the wall thickness, material selection, and overall weight.

Finally, the interval from point G to point H represents the remaining time required to complete the piston stroke. Most of the piston movement occurs during this interval, and so it is during this time that velocity and acceleration can be controlled most effectively. Without acceleration control, the maximum velocity normally occurs at time H, the end of stroke.

Acceleration and rate of change of acceleration of a device are controlled by selection of the interior ballistic parameters such as grain design. Occasionally, further control is effected by the addition of a buffer or damper. External dampers were used in earlier propellant actuated devices. Internal dampers have been used successfully in several newer thruster designs. Fig. 2-6 illustrates the operation of an oil damped thruster. The spring acting against the floating piston is compressed or extended as the buffer fluid reacts to temperature changes. When the thruster is fired, the expanding gas drives the floating piston against the fluid, exerting pressure on the main piston. The main piston begins to stroke when the pressure buildup is sufficient to shear the locking pin. The fluid surrounding the main piston then is forced through the orifice into the volume between the floating piston and the main piston. The velocity of the main piston is a function of the viscosity of the buffer fluid, the orifice area, and the difference in force due to the same pressure acting against a large area on one side of the main piston and on a considerably smaller area on the opposite side.

Motion not only is controlled by grain design and the addition of dampers but also may be regulated ballistically by metering the flow of propellant gas through an orifice. A high-low system is an example of such ballistic control. In a high-low system, the propellant is burned in one chamber and the gas is bled through an orifice into a second chamber. The propellant is burned at a high pressure which is conducive to effective combustion while the stroke is controlled by the low pressure gas in the second chamber.

A pressure relief valve also can be used to control the motion of a propellant actuated



A Initiator Firing Pulse
B Pressure Rise at Thruster Firing Mechanism
C Thruster Initiation
D Peak Pressure Output of Initiator
E Pressure Rise in Thruster
F First Pressure Wave Reflection
G Maximum Thruster Pressure
H End of Thruster Stroke

Figure 3-2. Pressure-time Curve for PAD System in Fig. 3-1

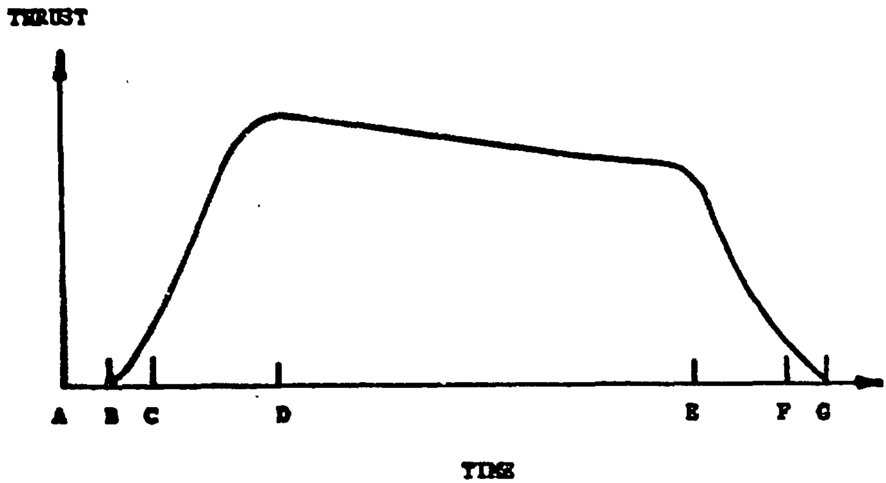
device by porting the gas that would cause excessive acceleration. Throughout the stroke, the valve opens and closes to maintain a nearly constant pressure within the device[1].

3-2.2 GAS-GENERATING PROPELLANT ACTUATED DEVICES

For gas-generating devices where stroke is not a consideration, the output of a propellant actuated device can be thought of as a peak pressure at the end of a given length of hose (initiators), volume of gas delivered (gas generators), or impulse (rockets).

Consider the case of a rocket. A typical thrust-time output is represented in Fig. 3-3. Point A represents the point of the applied ignition pulse; point B, the point of sustained thrust or pressure rise; point C, the point at which the thrust attains a value of 10 percent of its maximum; point D, the point of maximum thrust; point F, the point at which the thrust declines to 10 percent of maximum; and G, the point of effective zero thrust level.

As with the stroking device, every attempt is made to minimize the ignition interval A to



A Firing Pulse
B Thrust Rise
C 10% Maximum Thrust
D Maximum Thrust
E Propellant Burnout
F 10% Maximum Thrust
G Zero Thrust Level

Figure 3-3. Thrust-time Curve

B. The interval E to F is called the tail off or sliver burning portion of the curve. For most applications it is also desirable to keep this interval to a minimum.

The output of a rocket is measured in terms of the impulse or integral of the thrust-time curve. The total impulse is simply the integral over the interval B to G. The impulse also may be given in terms of the 10 percent points, C to F. For practical considerations, however, the effective impulse usually is stated in terms of the interval C to E, the 10 percent thrust level to the grain burnout point. The cutoff point E usually is taken to be the intersection of the slopes defining the burning and tail off portion of the curve.

The maximum thrust level (point D) and operating time, which are specified by the grain and nozzle parameters, determine the maximum working pressure, rocket size, and corresponding system weight.

The ballistic equations governing the operation of stroking and gas-generating devices will be covered in detail in Chapter 4.

3-3 LOAD

The load experienced by a propellant actuated device is the total of all forces acting on the device. These loads may assist as well as resist motion. They include the inertia forces of the body being propelled and the moving parts of the device itself, initial and final locks (if used), friction forces, and damping forces. In aircraft installations, friction and bending forces may be present as a result of aircraft maneuvers and aerodynamic loading. In addition, aircraft maneuvers may result in variations of "g" loading. Such variations may either resist or, depending on the device and loading level, increase the output level[3].

3-4 WEIGHT AND SIZE

Weight and size, although subordinate to reliability, generally are critical considerations in aircraft and other applications. The design of the propellant actuated device is dependent upon a specific space allocation, which can result in mounting problems, insufficient actuator stroke for the task, and complicated mechanical and ballistic designs. As an example, space limitations can cause a device – which could be fabricated easily from a single tube with piston, chamber, and end connections all on the same axis – to be designed with telescoping tubes or in a folded or stacked configuration as for example the M15 Thruster depicted in Fig. 3-4.

To reduce weight, the designer operates with working stresses that approach the yield stresses of the materials used. The size of the parts are adjusted and readjusted to provide safety factors that experience has indicated will produce a reliable item. The safety factors used are covered in Chapter 6 of this handbook.

Some propellant actuated devices are used integrally as structure of force linkage in aircraft, e.g., the M25 Thruster is a force link in the canopy operating mechanism of the T-38 and F-5 aircraft. In addition to firing loads, the M25 has been designed for long term service life as a highly stressed force member capable of repeated actuation cycles.

The selection of materials for propellant actuated devices entails more than just strength and weight consideration. Resistance to corrosion, ease of fabrication, and resistance to erosion and chemical action with propellants or damper fluids also are factors.

3-5 ENVIRONMENT

The environment (temperature, humidity, dirt, vibration, shock, etc.) in which propellant actuated devices are required to operate, is discussed in detail in Ref. 3. A summary explanation of some of these factors is presented here.

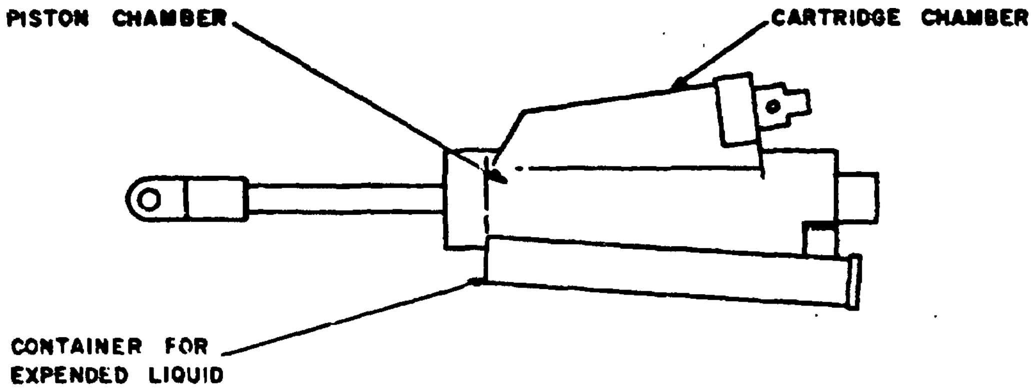


Figure 3-4. Thruster With Stacked Configuration

3-5.1 TEMPERATURE

In aircraft applications propellant actuated devices are exposed to temperatures within the range of −65° to +200°F. A maximum upper limit of only +160°F is imposed on catapults and rocket catapults in view of their normal position in a cockpit (behind the seat and mostly shielded from the direct radiant energy of the sun). Nonpropulsive systems as well as igniters or firing mechanisms, however, will be qualified to +200°F. Propellant, primers, and all mechanical components must be selected so that they operate throughout this range with minimum variation in performance. Particular attention must be given to the selection of nonmetallic materials that may age and cease to function properly. The coefficient of expansion and viscosity of damping and buffing fluids are also important considerations because of this wide temperature range.

In addition to meeting these specification temperature limits, various propellant actuated devices are designed to operate at temperature levels in excess of +200°F; the primary limiting factor for temperature extremes being the stability of the primer and propellant formulations.

Many devices can operate up to +350°F and the operational range of others may be extended to +400°F. It is recommended, however, that Frankford Arsenal be consulted for use at temperatures above +200°F.

3-5.2 HUMIDITY AND DUST

Propellant actuated devices are supplied as sealed units to prevent moisture or dirt entry during long storage periods (as long as 5 yr either on a shelf or mounted in a system). As added insurance, cartridges are hermetically sealed and are replaced periodically to prevent propellant aging from adversely affecting performance.

3-5.3 VIBRATION

Threaded connections must be capable of withstanding torque tests in accordance with Ref. 3 as insurance against loosening when exposed to vibration encountered in handling, shipment, or installation. A thread locking agent – such as a Nylock pellet or Loctite inserted in the threaded joint – creates sufficient friction to prevent loosening, yet the device may be disassembled by applying sufficient torque. Staking the threads is not considered an acceptable way of meeting vibration (torque) requirements of a device contains a cartridge, since the device may require disassembly.

3-5.4 SHOCK

If a propellant actuated device can survive a specified drop in a variety of attitudes and in accordance with Ref. 3 onto concrete, it can withstand the maximum shock that will occur in service. Devices, therefore, are designed to withstand this drop test, which means that the propellant grains will not shatter and the firing mechanism will not function as a result of this shock. The design of shear pins used to retain the firing pins in gas actuated devices is critical; the pins must withstand the shock of the drop test and yet shear when the pin is subjected to a specific gas pressure. The design of shear pins is presented in Chapter 6.

3-6 HEAT LOSS

A highly theoretical discussion of heat loss in the design of propellant actuated devices considering conductive, convective, and radiant processes is both tedious and, from the practical standpoint, unnecessary. Propellant actuated devices tend to have an efficiency (percent of mechanical energy to total propellant energy) of about 10 percent. For ballistic analyses a simplified energy balance has been derived which suffices for most applications. A derivation of this equation as well as a discussion of the analytical techniques used for propellant actuated devices is presented in Chapter 5.

It is important, however, that several

factors be understood. To minimize heat loss, the metal surface in contact with the hot propellant gas should be kept to a minimum, consistent with hardware requirements. Heat loss, which can account for over 50% of the available energy, reduces the performance of devices that retain or produce hot gas over an extended period.

In transferring hot gas from one device to another, as with initiators, Teflon-lined hose is used primarily because it absorbs less heat than stainless steel tubing and introduces less friction loss than rubber hose.

REFERENCES

1. M. Weinstock and W. Boaz, *Investigation of the Principle of Controlled Acceleration Operation of Personnel Escape Catapults*, Frankford Arsenal Memorandum Report No. MR-712, October 1958.

2. R. Gelman and J. L. Helfrich, *Performance of Catapults in Various Force Fields*, Frankford Arsenal Memorandum Report No. MR-594, October 1954.

3. MIL-C-83124, *Cartridge Actuated Devices/Propellant Actuated Devices General Specification for*, 30 October 1969.

CHAPTER 4

PRELIMINARY DESIGN TECHNIQUES

4-0 LIST OF SYMBOLS

a = acceleration, ft/sec^2

$\dot{a}$ = rate of change of acceleration, ft/sec^3

$\bar{a}$ = average acceleration, ft/sec^2

a_m = maximum acceleration, ft/sec^2

A_p = piston area, in.^{2}

A'_p = port area of rocket grain, in.^{2}

A_s = instantaneous propellant burning surface, in.^{2}

A_t = gas generator orifice area, in.^{2}

A'_t = nozzle throat area, in.^{2}

b = burning rate coefficient, in./sec-psi^n

C = propellant charge weight, lb

C = rocket grain weight, lb

$\dot{C}$ = gas generator discharge rate, lb/sec

C_D = propellant discharge coefficient, lb/lb-sec

C_f = thrust coefficient, dimensionless

d = minor diameter of male threads (min), in.

E_m = mechanical energy, ft-lb

E_p = propellant energy, ft-lb

F = propellant impetus, ft-lb/lb

$\mathfrak{F}$ = thrust, lb

F_r = resistive force, lb

$\bar{F}_r$ = average resistive force, lb

g = acceleration due to gravity, ft/sec^2

h_t = heat loss per unit hose area, ft-lb/in.^{2}

I = impulse, lb-sec

I_{sp} = specific impulse, lb-sec/lb

J = ratio A'_t/A'_p, dimensionless

K_n = ratio of propellant burning surface to generator orifice required to maintain a specified generator pressure, dimensionless

L = length of thread engagement, in.

n = burning rate exponent, dimensionless

P = gas pressure, psi

P_c = gas generator pressure, psi

P'_c = rocket chamber pressure, psi

P_m = maximum pressure, psi

P_t = pressure at end of hose, psi

r = propellant burning rate, in./sec

R = major radius of female thread (max), in.

s = stroke, ft

S_s = shear strength, psi

S_t = hose surface area, in.^{2}

t = time, sec

t_b = burn time, sec

t_s = stroke time, sec

T = gas temperature, °R

T_o = adiabatic isochoric flame temperature, °R

v = terminal velocity, ft/sec

V = gas volume, in.^{3}

V_c = initiator volume, in.^{3}

V_t = hose volume, in.^{3}

w_m = propellant web, in.

W = propelled weight, lb

W' = wall ratio (OD/ID), dimensionless

x = displacement, ft

Y = yield strength of material, psi

β = heat loss factor, dimensionless

γ = propellant ratio of specific heats, dimensionless

ρ = solid propellant density, lb/in.^{3}

σ_e = equivalent yield strength, psi

σ_1 = radial stress, psi

σ_2 = tangential stress, psi

σ_3 = axial stress, psi

4-1 INTRODUCTION

4-1.1 GENERAL

This chapter provides the designer with a basic knowledge of the preliminary design of propellant actuated devices. Methods of approximating parameters not generally given in design requirements are presented. Materials, safety factors, and methods of calculating wall strengths and selecting tube sizes to be used are discussed. The design of individual components is described, and the use of protective finishes and dissimilar metals is outlined.

4-1.2 DESIGN REQUIREMENTS

The customary starting point in the design of propellant actuated devices is the list of requirements which detail the size, weight, strength, and performance of the device. A typical list of design requirements might include all or some of the following: maximum envelope dimensions and weight, external loading, method of initiation and ignition delay, open or closed type system, initial and/or final locking requirements, maximum acceleration, rate of change of acceleration, terminal velocity, stroke, propelled load, gas generation rate, total impulse, action time, and physiological considerations.

4-2 FIRST-ORDER BALLISTIC APPROXIMATIONS

4-2.1 GENERAL

All significant parameters may not be

defined for a particular device. The design requirements might specify maximum acceleration and velocity but not the stroke necessary to satisfy these requirements. Stroke and velocity but not acceleration may be specified for thrusters or removers. The envelope specifications may give exterior dimensions but not the interior volume and expansion ratio. The unspecified parameters must be determined by the designer in conjunction with the ballistician. Methods of approximating stroke, operating time, pressure, acceleration, and propellant charge are presented here. More sophisticated analytical and simulation techniques are treated in Chapter 5.

4-2.2 STROKING DEVICES

The performance requirements for stroking devices might specify all or some of the desired kinematic system variables: terminal velocity, maximum acceleration and maximum time rate of change of acceleration, stroke, and action time. With a knowledge of these parameters the maximum operating pressure and required propellant charge weight can be approximated. When only three of these variables are specified, the remaining two can be determined based on the construction of an assumed acceleration time curve for the device.

4-2.2.1 KINEMATIC VARIABLES

Consider that the performance requirements specify only three of the five kinematic variables. By assuming an acceleration-time curve for the device the remaining two can be determined by applying the equations for the terminal velocity v and stroke s:

$$v = \int_0^{t_s} a\,dt, \text{ ft/sec} \tag{4-1}$$

and

$$s = \int_0^{t_s} \int_0^{t} a\,dt, \text{ ft} \tag{4-2}$$

where

a = acceleration, ft/sec^2

s = stroke, ft

t = time, sec

t_s = stroke time, sec

v = terminal velocity, ft/sec

For the assumed acceleration-time curve (Fig. 4-1), which is characteristic of those produced by propellant actuated stroking devices, Eqs. 4-1 and 4-2 give:

$$v = a_m t_s - \frac{a_m^2}{2\dot{a}}, \text{ ft/sec} \tag{4-3}$$

and

$$s = \frac{a_m t_s^2}{2} - \frac{a_m^2 t_s}{2\dot{a}} + \frac{a_m^3}{6\dot{a}^2}, \text{ ft} \tag{4-4}$$

where

a_m = maximum acceleration, ft/sec^2

$\dot{a}$ = rate of change of acceleration, ft/sec^3

Therefore, if the maximum acceleration, rate of change of acceleration, and terminal velocity are specified, the stroke time and stroke can be determined by rearranging Eqs. 4-3 and 4-4 to give:

$$t_s = \frac{v}{a_m} + \frac{a_m}{2\dot{a}}, \text{ sec} \tag{4-5}$$

and

$$s = \frac{v^2}{2a_m} + \frac{a_m^3}{24\dot{a}^2}, \text{ ft} \tag{4-6}$$

If only two kinematic variables are specified in the performance requirements, the engineer has additional latitude in the selection of the remaining ones.

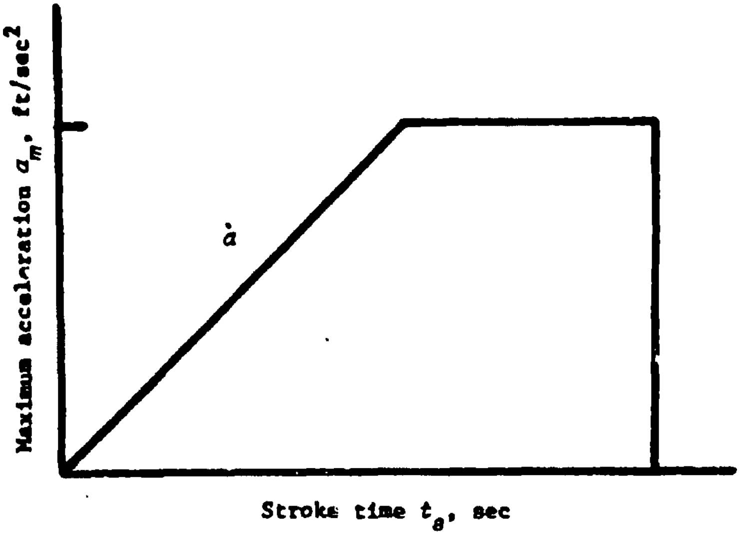


Figure 4-1. Acceleration-time Curve for Propellant Actuated Stroking Device

As an example on the use of this equation consider the M38 Rocket Catapult, which will be discussed in greater detail in Chapter 6. The catapult portion of this device has the following characteristics when fired at 70°F:

v = 46 ft/sec

a_m = 13.8 g (444 ft/sec^2)

$\dot{a}$ = 117 g/sec (3770 ft/sec^3)

Substituting these values into Eqs. 4-5 and 4-6

$$t_s = \frac{(46)}{(444)} + \frac{(444)}{(2)(3770)} = 0.163 \text{ sec}$$

and

$$s = \frac{(46)^2}{(2)(444)} + \frac{(444)^3}{(24)(3770)^2} = 2.64 \text{ ft} = 32 \text{ in.}$$

The actual values for these parameters are s = 34 in. and t_s = 0.165 sec.

4-2.2.2 MAXIMUM PRESSURE

The maximum pressure may be obtained from the maximum acceleration by the relation

$$P_m = \frac{Wa_m}{gA_p}, \text{ psi} \tag{4-7}$$

where

A_p = piston area, in.^{2}

g = acceleration due to gravity, ft/sec^2

P_m = maximum pressure, lb/in.^{2} (psi)

W = propelled weight, lb

Again using the M38 Rocket Catapult as an example, where

A_p = 0.7854 in.^{2}

g = 32.2 ft/sec²

W = 383 lb

from Eq. 4-7

$$P_m = \frac{(383)(444)}{(32.2)(0.7854)} = 6720 \text{ psi}$$

The actual measured peak pressure at 70°F is 6930 psi. Eq. 4-7 also may be used to determine the piston area of a specific pressure if desired.

4-2.2.3 PROPELLANT CHARGE WEIGHT

It should be noted that the numerical coefficients for the equations presented in this paragraph will vary with the value of the impetus and ratio of specific heats of the propellant chosen for a particular application. The purpose of this paragraph is more to demonstrate a technique than to generate relations that are valid for all propellant actuated stroking devices.

A first-order approximation of the propellant charge weight required by stroking propellant actuated devices may be made by assuming that these devices have an efficiency of about 10%; the realized mechanical output is 10% of the propellant energy.

$$E_m = 0.1E_p \text{, ft-lb} \tag{4-8}$$

where

E_m = mechanical energy, ft-lb

E_p = propellant energy, ft-lb

The energy content of solid propellant is given by the expression

$$E_p = \frac{FC}{\gamma - 1} \text{, ft-lb} \tag{4-9}$$

where

C = propellant charge weight, lb

F = propellant impetus, ft-lb/lb

γ = propellant ratio of specific heats, dimensionless

Eq. 4-9 can be derived by using the equation of state for the propellant gas, i.e.,

$$PV = \frac{12\,FTC}{T_o} \text{, psi} \tag{4-10}$$

where

P = gas pressure, lb/in.²

T = gas temperature, °R

T_o = adiabatic isochoric flame temperature, °R

V = gas volume, in.³

and 12 is a conversion from feet to inches.

Assuming an adiabatic expansion to infinity and assuming the initial gas temperature equal to the adiabatic isochoric flame temperature

$$E_p = \int_{V_i}^{\infty} P\,dV = \frac{FC}{\gamma - 1} \tag{4-11}$$

Using typical values of propellant impetus F and ratio of specific heats γ, 3.4×10^5 ft-lb/lb and 1.23, respectively; substituting these values into Eqs. 4-8 and 4-9; and solving for the charge weight gives

$$\left.\begin{aligned} C &= \frac{E_m(\gamma - 1)}{0.1F} \\ C &= 6.76 \times 10^{-6}\,E_m \text{, lb} \end{aligned}\right\} \tag{4-12}$$

The charge for propellant actuated devices is usually specified in grams. Making this conversion, Eq. 4-12 becomes

$$C = 3.07 \times 10^{-3}\, E_m \text{, gram} \tag{4-13}$$

For catapults, removers, and other stroking devices in which the mechanical energy is primarily kinetic, Eq. 4-13 becomes

$$C = 4.9 \times 10^{-5}\, Wv^2 \text{, gram} \tag{4-14}$$

Fig. 4-2 is a plot of Eq. 4-14, with the ratio of charge weight to propelled weight vs velocity.

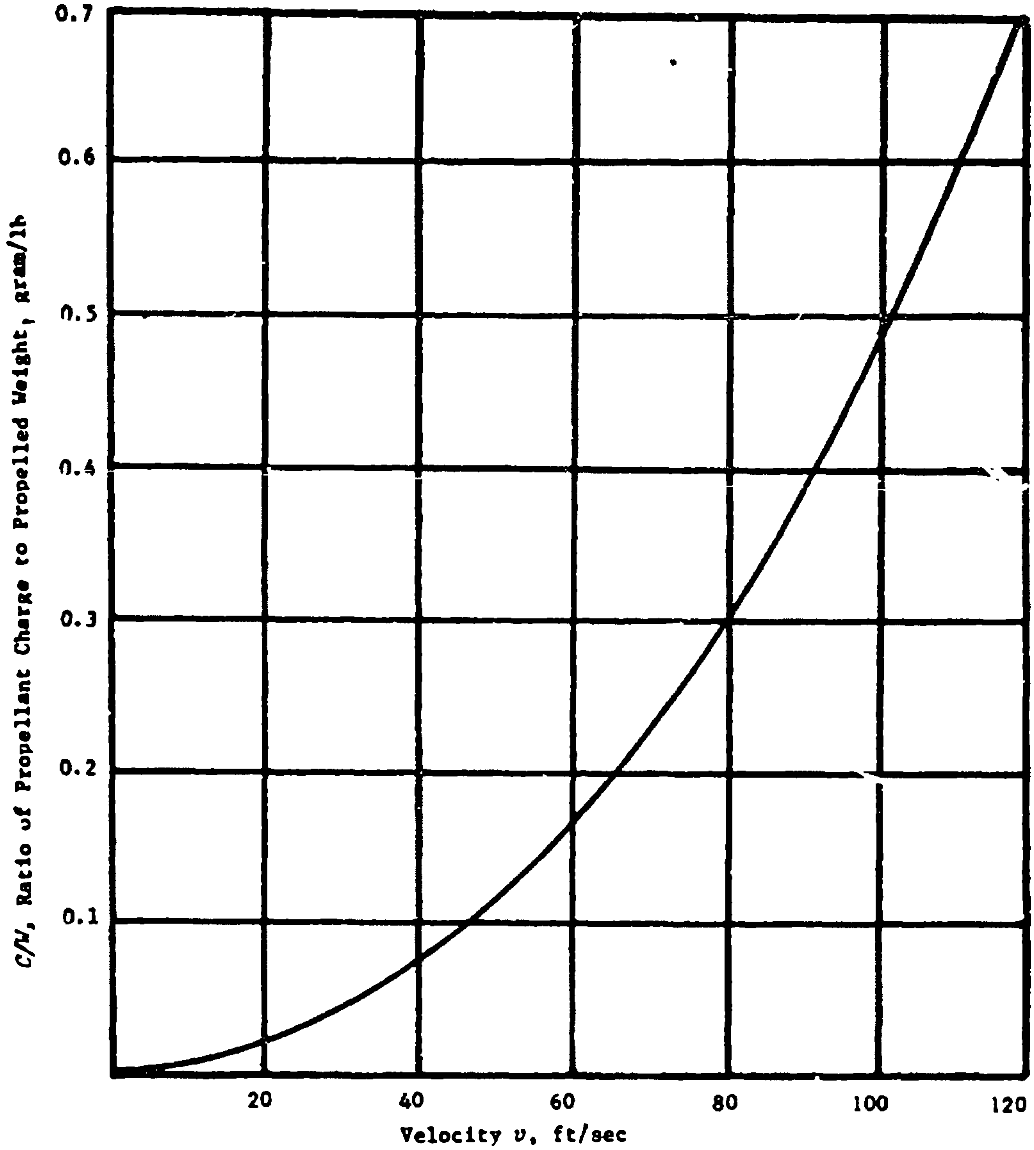


Figure 4-2. Ratio of Propellant Charge Weight to Propelled Load for Propellant Actuated Stroking Devices

For thrusters and those devices where the energy is primarily expended in overcoming a resistive force and the kinetic energy imparted to the load is insignificant in comparison, Eq. 4-13 becomes

$$C = 3.07 \times 10^{-3} \int_0^s F_r dx, \text{ gram} \qquad (4\text{-}15)$$

where

F_r = resistive force, lb

x = displacement, ft

or

$$C = 3.07 \times 10^{-3} \bar{F}_r s, \text{ gram} \qquad (4\text{-}16)$$

where

$\bar{F}_r$ = average resistive force, lb

Using the M38 Rocket Catapult as an example – W = 383 lb and v = 46 ft/sec – the charge weight for the catapult portion may be estimated from Eq. 4-14.

$$C = (4.9 \times 10^{-5})\ (383)(46)^2 = 39.9 \text{ grams}$$

The actual charge weight used in this device was 40 grams.

4-2.2.4 PROPELLANT WEB

The propellant web w_m, which is the maximum burn distance before grain integrity is destroyed, may be estimated from the relation

$$w_m = \int_0^{t_s} r dt, \text{ in.} \qquad (4\text{-}17)$$

where

r = propellant burning rate, in./sec

The burning rate for most propellants can be approximated closely over the applicable pressure range by the expression

$$r = bP^n, \text{ in./sec} \qquad (4\text{-}18)$$

where

b = burning rate coefficient, in./sec-psi^n

n = burning rate exponent

Utilizing the form of the acceleration-time curve given in Fig. 4-1, setting the pressure P equal to

$$P = \frac{Wa_m}{gA_p} \qquad (4\text{-}19)$$

and substituting into Eq. 4-17 gives

$$w_m = b\left(\frac{Wa_m}{gA_p}\right)^n \left[t_s - \left(\frac{n}{n+1}\right)\frac{a_m}{\bar{a}}\right], \text{ in.} \qquad (4\text{-}20)$$

Estimating the average acceleration $\bar{a}$ by the relation

$$\bar{a} = \frac{v}{t_s} \qquad (4\text{-}21)$$

and noting that as a approaches infinity (zero to rise time to constant acceleration level a_m) Eq. 4-20 becomes

$$w_m = b\left(\frac{Wv}{gA_p}\right)^n t_s^{1-n}, \text{ in.} \qquad (4\text{-}22)$$

4-2.2.5 CARTRIDGE CASE VOLUME

The cartridge case volume usually is estimated in one of two ways – depending upon the size of the individual propellant grains that make up the complete charge. If the grains are "small" and will be oriented randomly when loaded in the cartridge, the loading density is taken to be about 0.066 in.^{3}/gram of propellant. For example, if 20 grams of propellant are required for a particular application the required case volume would be estimated as:

$$(0.066 \text{ in.}^3/\text{gram}) \times 20 \text{ grams} = 1.32 \text{ in.}^3$$

Additional volume also must be provided for a case, cap, and igniter charge retainer. This must be determined after estimation of the igniter charge volume by a preliminary design of the head cap.

If "large" grains are used, they may be loaded in some definite geometrical arrangement. The grains then are stacked in the cartridge case with their centerlines parallel to the centerline of the case. The case volume then is estimated by the size and number of the grains and their geometrical arrangement.

4-2.2.6 IGNITER CHARGE

The igniter charge used in most propellant actuated devices has been black powder. A rule of thumb that has evolved to estimate the igniter charge is to use about 40 grams of black powder per pound of propellant. This estimated igniter charge may have to be adjusted depending on the results of firings between $-65°$ and $+200°F$. More recently B-KNO_3 (boron potassium nitrate) and a magnesium-Teflon mixture have been used to achieve other characteristics relating to the ignition process such as longer duration, greater heat, and gas output.

4-2.3 GAS-GENERATING DEVICES

Gas-generating devices are designed to produce a given pressure output (initiators), generate a specified quantity of gas (gas generators), or deliver a specified impulse (rockets).

4-2.3.1 INITIATORS

Initiators are devices which produce a specified pressure output at the end of a selected length of transmission line and commonly are used to actuate other devices. An empirical relation which specifies the maximum pressure at the end of a given length of transmission line is (Ref. 2).

$$P_t = \frac{12FC}{V_c + V_t}\left[1 - \beta - \frac{h_t S_t(\gamma - 1)}{FC}\right], \text{psi} \tag{4-23}$$

where

P_t = pressure at end of hose, psi

h_t = heat loss per unit hose area, ft-lb/in.^{2}

S_t = hose surface area, in.^{2}

V_c = initiator volume, in.^{3}

V_t = hose volume, in.^{3}

β = heat loss factor, dimensionless

The value of β has been determined experimentally to be between 0.25 and 0.35, and h_t for aircraft hose is about 25 to 30 ft-lb/in.^{2}. Eq. 4-23 was applied to the M3 Initiator to calculate the pressure in 0.062 in.^{3} and 0.558 in.^{3} end blocks. The computed and measured pressures as functions of hose length are depicted in Fig. 4-3.

4-2.3.2 GAS GENERATORS

Gas generators are devices which are designed to produce an output in the form of a specified amount of propellant gas at a preselected rate of delivery. A rule of thumb used in gas generator design is that one pound of propellant will produce approximately 15 ft^3 of gas at standard conditions.

The gas generator output rate $\dot{C}$ for sonic flow through the orifice is equal to

$$\dot{C} = C_D A_t P_c, \text{ lb/sec} \tag{4-24}$$

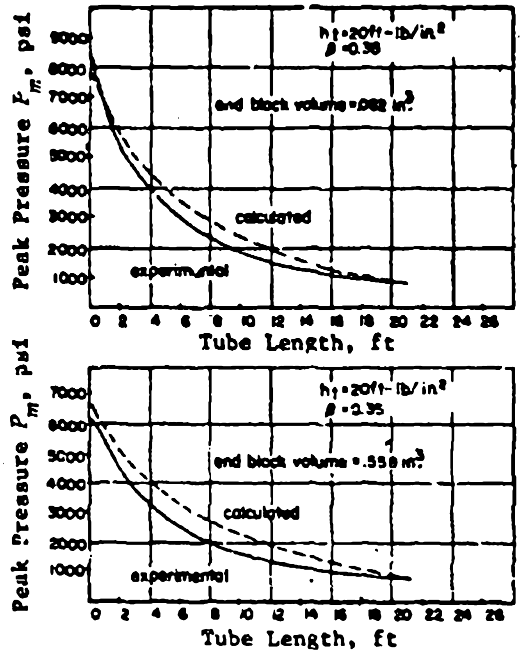


Figure 4-3. Hose Length vs Pressure P_m for M3 Initiator

where

A_t = gas generator orifice area, in.²

C_D = propellant discharge coefficient, lb/lb-sec

P_c = gas generator pressure, lb/in.²

Eq. 4-24 is derived in Appendix C of Ref. 1. The propellant discharge coefficient, although differing for each propellant, has a value on the order of 0.007 lb/lb-sec.

The gas generator pressure P_c for the propellant burn rate, as given in Eq. 4-18, is given by

$$P_c = \left(\frac{\rho b A_s}{C_D A_t}\right)^{1/(1-n)}, \text{psi} \qquad (4\text{-}25)$$

where

ρ = solid propellant density, lb/in.³

A_s = instantaneous propellant burning surface, in.²

Eq. 4-25 can be derived by equating the gas discharge rate, Eq. 4-24, to the rate of gas production ($\rho A_s b P_c^n$).

A parameter used in gas generator ballistics is the factor K_n

$$K_n = \frac{A_s}{A_t}, \text{ dimensionless} \qquad (4\text{-}26)$$

Or in terms of Eq. 4-25

$$K_n = \frac{C_D}{b\rho} P_c^{1-n} \qquad (4\text{-}27)$$

This factor K_n is important in that it defines the ratio of the propellant burning surface to generator orifice required to maintain a specified generator pressure. Conversely, it allows for a prediction of the generator pressure for a given grain geometry and orifice.

As an example, consider the following values for various parameters:

b = 0.04 in/sec-psi^n

n = 0.4

C_D = 0.0072 lb/lb-sec

ρ = 0.06 lb/in.^{3}

The propellant burn rate by Eq. 4-18 is

$$r = 0.04 P_c^{0.4}$$

where by Eq. 4-27

$$K_n = \frac{0.0072 P_c^{0.6}}{(0.04)(0.06)} = 3 P_c^{0.6}$$

Thus for P_c = 1000 psi and A_t = 0.05 in.^{2}, by Eq 4-26,

$$A_s = K_n A_t = 3 P_c^{0.6} A_t = 3\,(1000^{0.6})\,(0.05) = 9.45 \text{ in.}^2$$

A plot of the burning rate of K_n vs pressure is plotted in Fig. 4-4 for the numerical values considered in the preceding example.

If the propellant surface area is not constant but varies with the burn distance, then the pressure will vary accordingly. Although the preceding relations will not yield a time dependent history of the generator pressure for a varying surface area, they will provide the pressure extremes.

4-2.3.3 ROCKETS

The interior ballistics of solid propellant rockets is similar to that for gas generators. Their output, however, is measured in terms of thrust and impulse delivered rather than in the production of gas. A detailed analysis of rocket ballistics is not presented here as there are many excellent references available (e.g., Refs. 3 and 4). Only a listing of the basic equations are given here.

The thrust $\mathfrak{F}$ developed by a solid propellant rocket is given by the relation

$$\mathfrak{F} = C_f A_t' P_c', \text{ lb} \qquad (4\text{-}28)$$

where

$\mathfrak{F}$ = thrust, lb

C_f = thrust coefficient, dimensionless

A_t' = nozzle throat area, in.^{2}

P_c' = rocket chamber pressure, lb/in.^{2}

The thrust coefficient C_f is a function of the nozzle geometry, rocket operating pressure, propellant rates of specific heats, and pressure into which the nozzle is exhausting. Values of the thrust coefficient are tabulated for these varying parameters in Refs. 2 and 3.

The total impulse I delivered by a rocket is the time integral of the developed thrust $\mathfrak{F}$

$$I = \int_0^{t_b} \mathfrak{F}\, dt, \text{ lb-sec} \qquad (4\text{-}29)$$

where

t_b = burn time, sec

For a constant chamber pressure

$$I = C_f A_t' P_c' t_b, \text{ lb-sec} \qquad (4\text{-}30)$$

Another expression for the total impulse I is given by

$$I = I_{sp} C, \text{ lb-sec} \qquad (4\text{-}31)$$

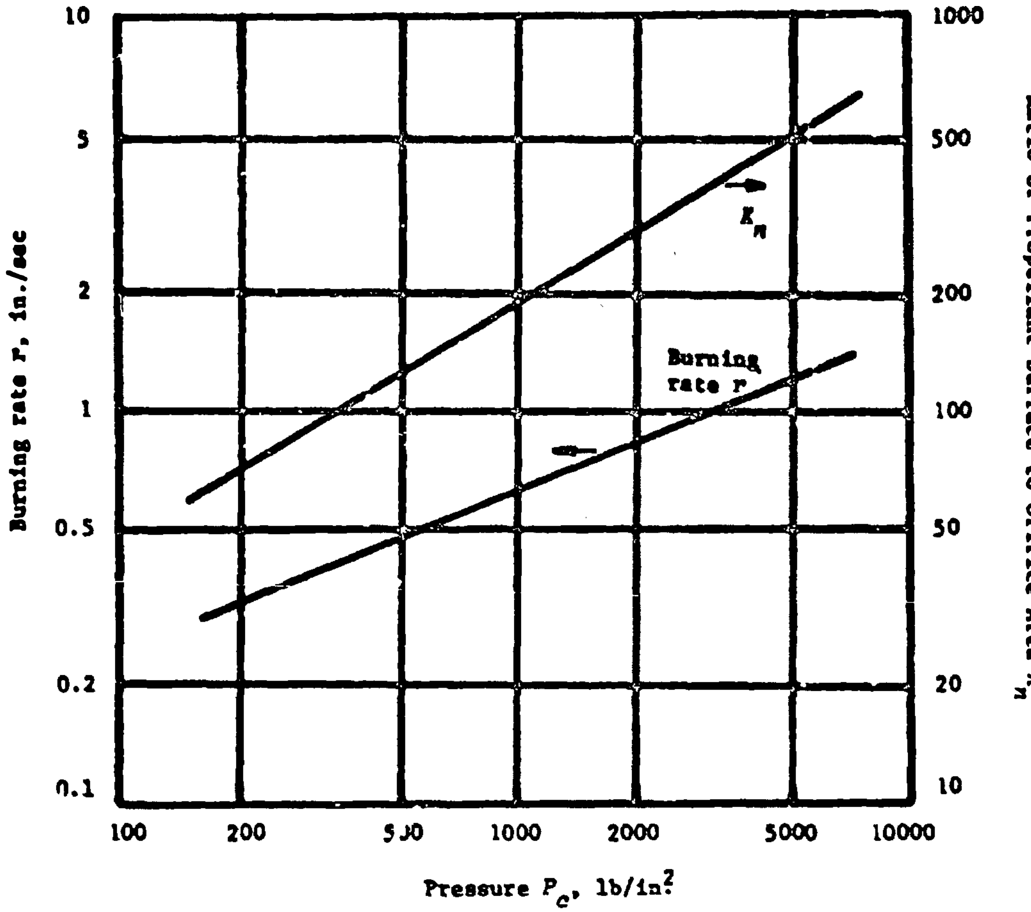


Figure 4-4. Burning Rate r and K_n vs Pressure P_c

where

I_{sp} = specific impulse, lb-sec/lb

C = rocket grain weight, lb

The specific impulse of the propellant usually is listed as one of the specified propellant parameters. It is to an extent dependent on motor design and usually is given in conjunction with a specific set of operating conditions. Eq. 4-31 also serves as a means of estimating the grain weight given the impulse requirements. In practice, the specific impulse has a value on the order of 200 lb-sec/lb.

For the rocket portion of the M38 Rocket Catapult the impulse delivered at 70°F is 1325 lb/sec. The rocket grain weight is 6.75 lb thus the specific impulse for this device is 196 lb-sec/lb.

A factor of importance in the design of

solid propellant rockets is the J factor.

$$J = \frac{A_t}{A_p'} \text{, dimensionless} \tag{4-32}$$

where

A_p' = port area of rocket grain, in.^{2}

For stable rocket operation it is desirable to keep the J factor below 0.7. For values greater than this, flow through the port from the head to nozzle end of the grain tends to induce erosive burning which increases the burning rate and can lead to catastrophic failure.

The preceding relations together with those in the paragraph on gas generator ballistics (par. 4-2.3.2) are sufficient to make first-order estimates of solid propellant rocket ballistics.

4-3 DESIGN STRENGTH CALCULATIONS

4-3.1 GENERAL

In most propellant actuated device applications, minimum weight is a primary consideration. For this reason materials that possess a high strength-to-weight ratio, such as heat-treated alloy steels and high strength aluminum, commonly are used. Critically stressed portions of propellant actuated devices should be designed so that material is used efficiently. Resulphurized steels never are used since they contain iron sulfide "stringers" (microstructural sulfide inclusions oriented in the direction of working and normal to the most critical stress) and are thus inadequate in devices with high internal pressures.

4-3.2 SAFETY FACTORS

Safety factors used in the design of propellant actuated devices may appear low, but they are consistent with aircraft practice and are adequate because these devices are subjected only to controlled loads. Cylindrical parts that must withstand internal pressure are designed using the yield strength as the design base and safety factor of 1.15. Parts subjected to repetitive external loads – such as locking keys, trunnions, and other similar mechanical parts – are designed with a safety factor of 2.0.

4-3.3 TEMPERATURE EFFECTS

Temperature has a marked effect on the mechanical properties of metals at high temperatures. However, the burning of propellant in the device is for so short a time that the metal parts are unable to absorb and retain sufficient thermal energy to affect their strength. In addition, propellant actuated devices are not exposed to ambient temperatures exceeding 200°F, and the change in strength at 200°F is negligible. The exception to this is in gas generator and certain long burning rocket applications. In these cases the effects of elevated temperatures must be taken into account in the design of load carrying components.

4-3.4 STRESSES

When calculating the sizes of metal parts to withstand the internal pressures in propellant actuated devices, it is necessary to consider the stresses at the weakest part of the tubes, commonly at the undercut at the end of the threads. The gas pressure inside the devices produces a direct radial compressive stress that is greatest on the inside wall, and induces a tangential or hoop stress that is also greatest at the inside wall. In undamped stroking devices, the stresses are biaxial (radial and tangential), but occasionally a longitudinal stress is introduced in the tube due to axial loading and the stresses become triaxial. Biaxial stresses put greater strains on materials than triaxial stresses when the directions of strain are directed as they are in cylindrical pressure vessels.

4-3.4.1 DISTORTION-ENERGY THEORY

The distortion-energy theory of failure (Von Mises-Hencky) is the accepted criterion for the design of ductile materials under combined loads. This theory defines an equivalent stress that exists for a combined loading. The distortion-energy equation for triaxial stresses (Ref. 5) is given in Eq. 4-33.

$$2\sigma_e^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 \tag{4-33}$$

where

σ_e = equivalent yield stress, lb/in.^{2}

σ_1 = radial stress, lb/in.^{2}

σ_2 = tangential stress, lb/in.^{2}

σ_3 = axial stress, lb/in.^{2}

Eq. 4-33 may be transformed into more useful forms, Eqs. 4-34 and 4-35.

$$\frac{P_m}{Y} = \frac{1}{\sqrt{3}}\ \frac{(W'^2 - 1)}{W'^2}\text{, dimensionless} \tag{4-34}$$

and

$$W' = \sqrt{\frac{1}{1 - \sqrt{3}\left(\frac{P_m}{Y}\right)}} \tag{4-35}$$

where

P_m = maximum pressure, lb/in.^{2}

Y = yield strength of material, lb/in.^{2}

W' = wall ratio (outer diameter/inner diameter), dimensionless

When a device is designed to withstand only biaxial stresses Eq. 4-36 may be used.

$$\frac{P_m}{Y} = \frac{W'^2 - 1}{\sqrt{3W'^4 + 1}}\text{, dimensionless} \tag{4-36}$$

These relations are derived in Appendix A.

The convenience of these forms of the distortion-energy equation is apparent when it is realized that the internal pressure P_m can be estimated and the strength Y of the material, guaranteed by the supplier, may be found in most engineering handbooks. The wall ratio and a tube size can then be calculated. Appendix B of this handbook also contains a table of wall ratios for values of P_m/Y from 0.010 to 0.200. This table was calculated from the preceding equations, 4-34, 4-35, and 4-36. Fig. 4-5 presents curves of P_m/Y as a function of W' for biaxial and triaxial stresses based on the tables of Appendix B.

The wall ratio W' may be used to determine the tube size. Tubing is supplied in standard sizes, and it may be necessary to use a tube that is stronger than required (higher W') to avoid the expense of using special tubing.

The tables of Appendix B or Fig. 4-5 also may be used to determine the maximum permissible pressure P_m when the tube size is specified. Conversely, the maximum pressure can be estimated and the wall ratio taken from the tables or Fig. 4-5. From the estimated outer diameter or that specified by the envelope requirements, the necessary inner diameter can be calculated. The commerical tubing size most closely approximating the dimensions would be used.

4-3.4.2 LENGTH OF THREAD ENGAGEMENT

Threads may be designed in accordance with Bureau of Standards Specifications (Ref 6). The length of these threads L may be calculated by using Eq. 4-37.

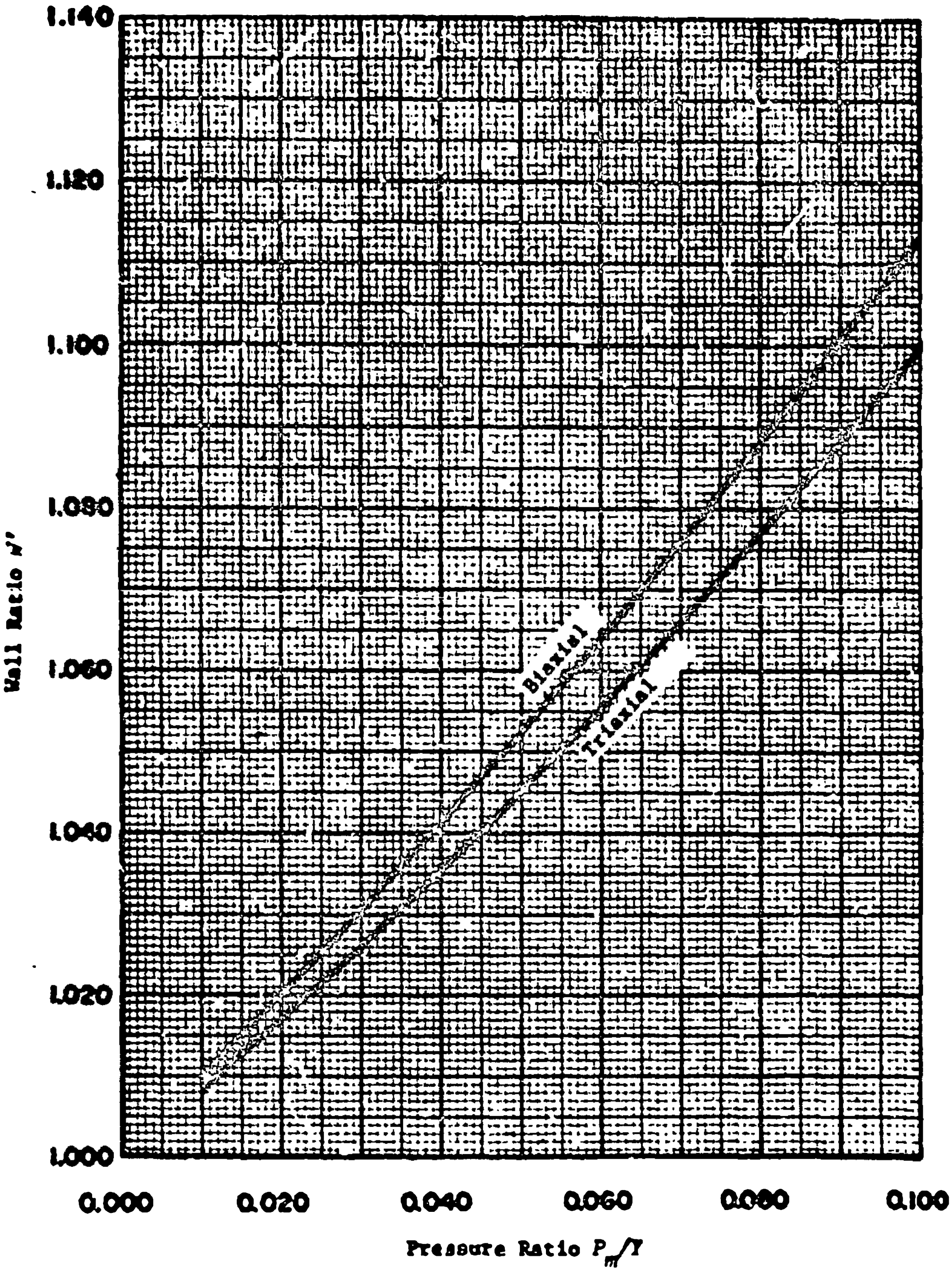


Figure 4-5. Biaxial and Triaxial Strength Curves (Sheet 1 of 2)

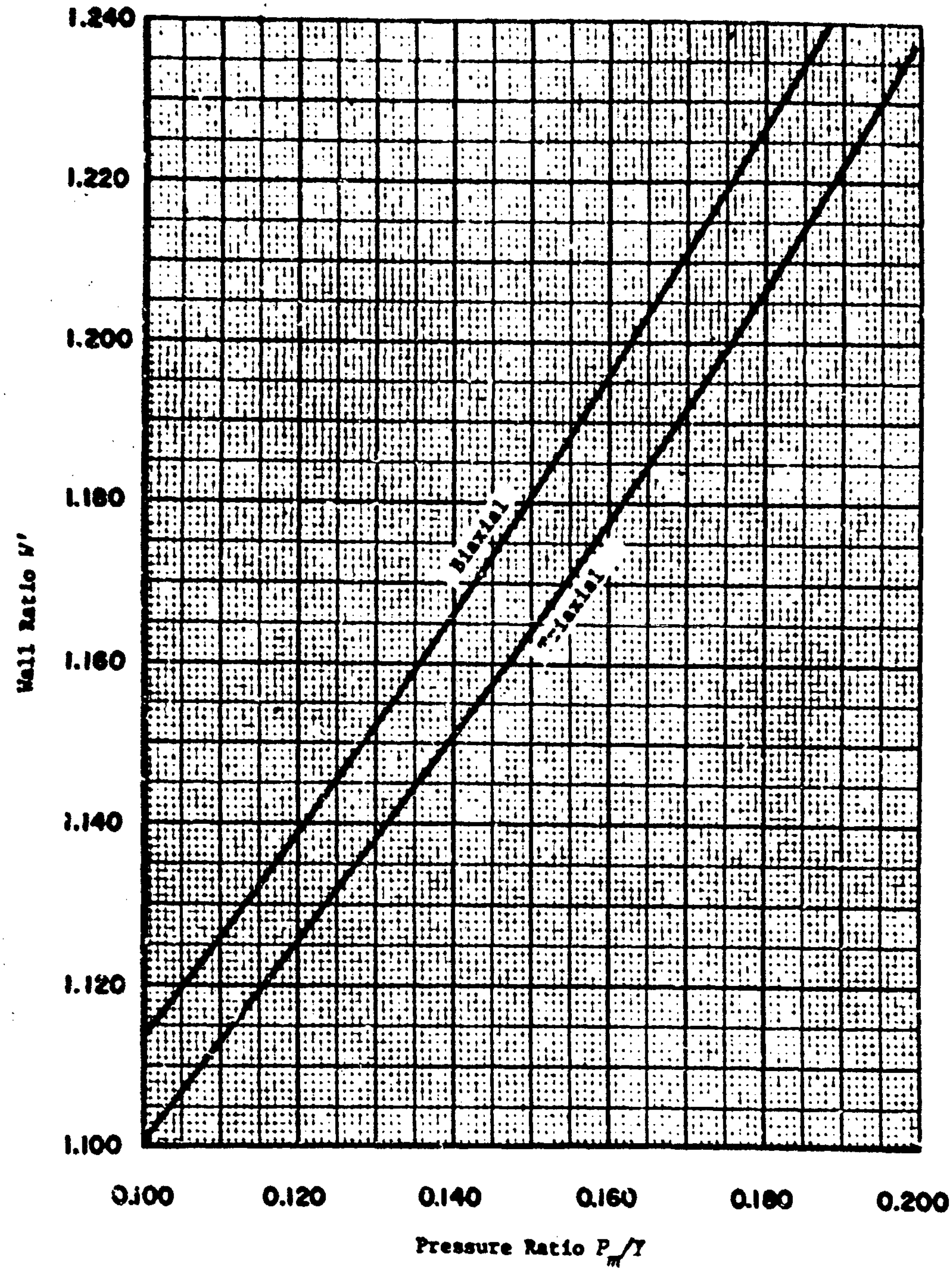


Figure 4-5. Biaxial and Triaxial Strength Curves (Sheet 2 of 2)

$$L = \frac{3P_m R^2}{S_s d}\text{, in.} \qquad (4\text{-}37)$$

where

L = length of thread engagement, in.

P_m = maximum internal pressure, lb/in.^{2}

S_s = shear strength, lb/in.^{2}

R = major radius of female (max), in.

d = minor diameter of male (min), in.

This equation, which is derived in Appendix C, includes a safety factor of 1.5 to allow for tolerances and the distribution of stresses within the engagement.

4-4 DESIGN PROCEDURES

4-4.1 GENERAL

Typical procedures are presented here which, with some variations, are used in the design of propellant actuated devices. The procedures arbitrarily have been divided into three categories: gas-generating devices, stroking devices, and (multidevice) systems. The design of special purpose devices such as cable cutters and gas operated trigger mechanisms is similar to that of stroking and gas generating devices so it was not considered necessary to discuss them separately.

The discussion of systems – unlike those for stroking and gas-generating devices – does not present design procedures, but rather presents material on how systems are established and their reliability maintained.

4-4.2 GAS-GENERATING DEVICES

This paragraph will limit itself to a discussion of initiator design. As an example, an initiator may be required to produce a pressure of 500 psi in an 0.062-in.^{3} chamber at the end of a 15-ft transmission line. Using the envelope specified, the designer estimates the internal volume of the initiator, the volume of the tubing to be used, and the volume of the chamber in which the pressure is to be measured (Fig. 4-6).

The ballistician uses these three values to estimate the propellant charge necessary to produce the required pressure. This estimate is made with the aid of Eq. 4-23. The designer then calculates the maximum pressure that may be developed in the initiator when the device is fired "locked shut", i.e., the initiator is sealed so that it must contain all of the gas generated by the propellant charge. The strength of the walls is calculated from the "locked shut" pressure using the methods described in par. 4-3.4.1.

To estimate the "locked shut" pressure, a modified version of the equation of state, Eq. 4-10, is used as given in Eq. 4-38.

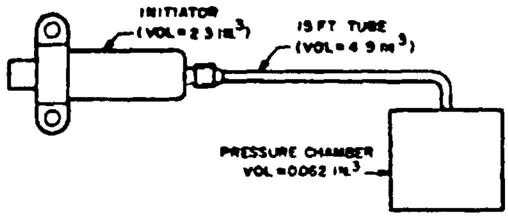


Figure 4-6. Simple PAD System Using an Initiator

$$PV = 0.0264\,FC, \text{ in.-lb} \qquad (4\text{-}38)$$

where T has been set equal to T_o and a factor of 454 has been introduced to allow the charge weight C to be expressed in grams.

To illustrate this technique, assume an initiator is to be designed with an internal volume of 2.3 in.[3] The ballistician determines that 3 grams of propellant with an impetus F of 360,000 ft-lb/lb is required. Apply Eq. 4-38.

$$P = \frac{(0.0264)(360{,}000)(3)}{(2.3)} \approx 12{,}400 \text{ psi}$$

Since the maximum pressure that can be produced is 12,400 psi, this value and the value of Y corresponding to the material may be used in the curve (Fig. 4-5) to determine the wall ratio, and, therefore, the wall thickness.

It is common practice to fabricate the first model of a device out of steel and to make it considerably stronger than necessary so that the operation of the device and the actual pressures that are generated can be studied. This workhorse model also permits repeated firings whereas the final product, in most cases, is designed as a one-shot item. Considerable fabrication cost and time may be saved by the liberal use of removable portions on original test models. These portions can be removed and modified without the necessity of redesigning the complete device.

4-4.3 STROKING DEVICES

The design procedure for stroking devices is more complex than that for initiators. After the design requirements have been examined and the stroke length and stroke time approximated, it must be decided whether to use an open or a closed high-low or direct system, and whether to use a damper to limit the velocity. The decision on the damper is based on the estimated stroke time and required velocity or acceleration. Damper design is discussed in par. 4-6.3, and high-low design is treated in par. 4-6.4.

The next consideration is the envelope of the stroking device. The envelope dimensions may be specified completely or only a few critical dimensions may be given. In the latter case the designer determines all dimensions. The designer now positions the trunnions on the envelope according to the eventual installation of the device. The purpose of trunnions for mounting is to permit self-alignment and thus avoid bending loads in stroking devices. With all of the preceding completed, it then is determined whether the envelope will permit the necessary stroke. Devices may have to be designed with telescoping tubes to reconcile the necessary stroke with the specified envelope.

It is now possible to compute the initial and final volume, and determine the expansion ratio for propellant actuated devices. It is desirable to limit the expansion ratio to 3 to 1.

Ballistics, in conjunction with the design, now determines the charge and cartridge sizes necessary. These determinations are critical for devices using pyrotechnic delay elements, since the delay elements must fit inside the cartridge case with the propellant. The maximum pressure to be developed also is determined. If the device is to bypass pressure at the end of stroke, the designer must insure that sufficient energy remains in the device after completion of stroke to provide (or allow) the proper energy bypass.

The next step is to fit a firing mechanism to the device and design the individual components. Finally, all of the components of the design are reconciled into a functionable unit that may be readily assembled and disassembled. A workhorse model now is fabricated. The procedure then becomes one of test, modification, and retest until all of the design specifications are satisfied.

Some of the trial and error may be eliminated from the design and the test phases may be eliminated by using computer simulation techniques to determine key parameters. Computer simulation of propellant actuated devices is treated in Chapter 5.

4-4.4 SYSTEMS

Multicomponent PAD systems generally are configured by the airframe or missile manufacturer under the direction of the cognizant agency. However, in the design of propellant actuated devices, systems can be improved by reducing the total number of devices or combining several operations into one device to improve reliability and guarantee proper operation of the system.

The sequencing of operations is determined largely by experience with previous systems, but the testing phase is the major determinant in verifying system performance. Systems are tested in breadboard mock-ups, and in static and in high speed sled tests to verify system performance and the limits of the system performance envelope.

The operation of devices in a system may be sequenced mechanically, pneumatically, or electrically. Most systems now in operation are initiated mechanically and sequenced pneumatically. Various fittings and types of transmission lines have been studied, but standardization has not reached the point of determining equivalent lengths of hose for fittings as is done in the hydraulics industry.

4-5 COMPONENT DESIGN

4-5.1 CARTRIDGE

The cartridge, Fig. 4-7, is a metal container which houses the propellant, igniter, and primer. In operation it is designed to burst open from the pressure of the propellant gases. The case is hermetically sealed to keep out moisture. The hardware portion of the cartridge consists of a drawn aluminum case and a head. The head is sealed in position by crimping the cartridge case.

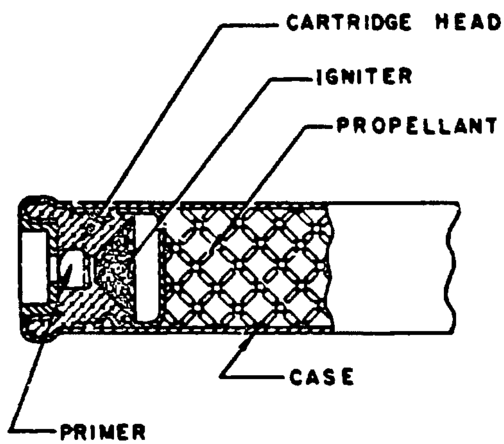


Figure 4-7. Simple Large Cartridge

Most cartridges contain percussion primers, although electric ignition elements are used in place of percussion primers in selected applications. The percussion primer is fired by the impact of a firing pin. The primer, in turn, ignites an igniter charge which then ignites the propellant.

Small cartridges with easily ignited propellants, such as that depicted in Fig. 4-8, ordinarily do not contain separate igniter chambers. Instead, the igniter is mixed with the propellant.

4-6.1.1 CARTRIDGE CASES

Design and development time is reduced by using existing cartridge cases whenever possible. Table 4-1 presents data on several developed cartridge cases. The letters in the column headings refer only to the lettered dimensions in Fig. 4-8 and not necessarily to the type of cartridge. Modifications to several of the cartridges listed in Table 4-1 -- specifically the M31A2, M69, M29A2, M30A2, M28A2, and M36A1 – have been made and have resulted in a simplified head design and increased thermal stability and primer sensitivity. The results of this study are documented in Ref. 7.

If no difficulty is anticipated in staying within the envelope specified, it may be advantageous at the start of mechanical design tentatively to select a cartridge case and build the chamber and body around it. The selection of a case is based on its estimated diameter. The diameter may be set provisionally according to the limitations of final envelope size. Propellant volume may be computed from the propellant grain dimensions. A propellant density of 0.06 lb/in.^{3} may be used with most compositions and large grain configurations.

TABLE 4-1

SIZES OF EXISTING CARTRIDGE CASES

Body Diameter *D*, in.	Head dia. *B*, in.	Length *L*, in.	Shoulder *H*, in.	Propellant chamber* *M*, in.	Approx. volume, in.^{3}	Cartridge**
0.550	0.710	0.915	0.325	1/2	0.1	M67A1
0.550	0.710	1.415	0.325	1	0.2	M73
0.550	0.710	1.665	0.325	1-1/4	0.2	M42A1
0.687	0.875	1.075	0.320	1/2	0.2	M146
0.687	0.875	2.13	0.390	1-1/2	0.5	M48
0.687	0.875	2.40	0.390	1-13/16	0.6	M70
0.710	0.880	1.09	0.330	1/2	0.2	M119
1.085	1.245	3.38	0.390	2-3/16	1.8	M31A2
1.245	1.390	0.755	0.380	1/8	0.1	M122
1.245	1.390	1.56	0.390	3/4	0.8	M69
1.245	1.390	1.81	0.390	1-5/16	0.9	M29A2
1.245	1.390	2.02	0.370	1-1/8	1.3	M150
1.245	1.410	6.25	0.390	5-7/16	6.1	M37
1.495	1.660	5.10	0.390	3-5/8	6.0	M30A2
1.495	1.660	5.40	0.390	4	6.6	M28A2
1.495	1.660	9.50	0.390	8-3/16	13.5	M36A1

*Assuming a standard cartridge head (no delay element).
**One of the cartridges in which the case is used.

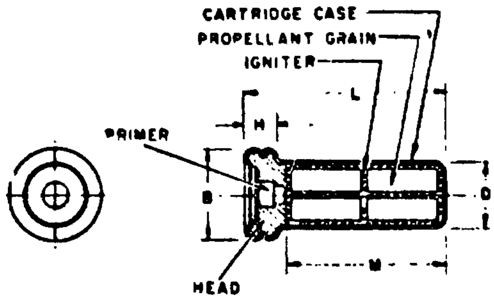


Figure 4-8. Typical Small Cartridge

4-5.1.2 CARTRIDGE HEAD

The head of the cartridge, generally made of aluminum and grooved to accept an O-ring to seal the cartridge, contains a percussion-type primer or a tapped hole to accept an electric ignition element. When a percussion primer is inserted in the center hole of the head, the edges of the head, adjacent to the primer, are crimped to seal the cartridge. In addition, lacquers or silicone sealants can be used as sealants.

The base of the cartridge head, under the primer recess, is machined to a thickness between 0.006 and 0.010 in. to insure that it will "blow through" when the primer fires. Prior to cartridge actuation, this thin web separates the primer from the propellant charge igniter to prevent it from coming in contact with volatile chemicals evolved from these sources which might desensitize it.

4-5.1.3 PRIMERS

Fig. 4-9 shows a typical percussion primer. The dimensions and compositions of four primers in common use in propellant actuated devices are presented in Table 4-2.

The sensitivity of primers, as measured by all fire height, which varies from one type to another, must be determined in accordance with established test methods. The size of the firing pin and the depth of indent necessary to fire these percussion primers are discussed in par. 4-5.4.

4-5.1.4 CARTRIDGE SEALS

The cartridge must be hermetically sealed to permit storage for as long as three years without affecting ballistic performance. As previously described, the primer is separated from the propellant by a thin web at the base

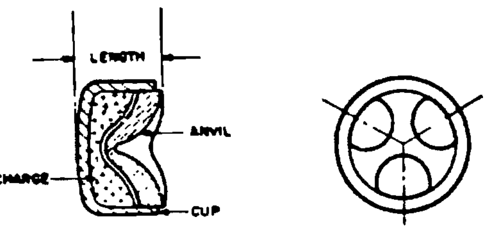


Figure 4-9. Percussion Primer

TABLE 4-2

PERCUSSION PRIMERS USED IN PROPELLANT ACTUATED DEVICES

Designation	OD, in.	Length, in.	Charge Weight, gr	Composition	All fire energy, in.-oz
M29A1	0.206	0.126	0.50	[illegible] Rem	18
M42	0.175	0.119	0.33	5086 Rem	26
72M	0.213	0.133	0.55	5061 Rem	60
50M	0.318	0.228	2.20	5061 Rem	120

of the cartridge. An O-ring between the lead and cartridge case completes the propellant chamber seal, and a crimp around the primer completes its seal. Methods of testing cartridges for leaks are described in Chapter 7.

4-5.2 BODY AND CHAMBER

The body of a propellant actuated device is the enveloping member or housing, and the chamber houses the cartridge. Body and chamber design for gas-generating and stroking propellant actuated devices will be discussed in this paragraph.

4-5.2.1 GAS-GENERATING DEVICES

In simple propellant actuated devices, such as initiators, the body serves as a chamber as well as the housing. One type of initiator is shown in Fig. 4-10. The cylindrical shape is chosen for ease of fabrication. The physical dimensions either are specified or are functions of the necessary internal volume. Wall thickness is a function of internal pressure and is calculated as shown earlier in par. 4-3.4.1. It usually is possible to reduce the bending stresses that occur at the junction of the cylinder and each closed end by using a

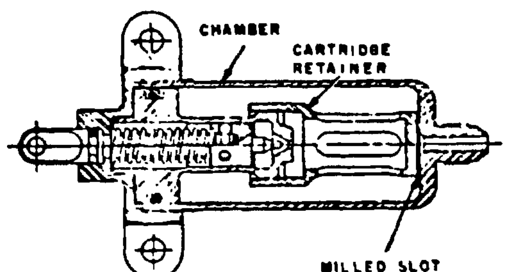


Figure 4-10. Initiator With Cartridge Retainer

thick end section and suitable fillets. The stresses occurring in gas-generating devices are triaxial because a longitudinal stress is introduced by the partially or fully closed ends.

In some initiators, the cartridge must be supported by a cartridge retainer, since the chamber acts as the body and is considerably larger than the cartridge. The retainer is cylindrical in shape and has a series of slots machined in its walls to permit the cartridge to "blow through" when the propellant is ignited. The slots in the retainer serve to contain the burning propellant and prevent the propellant grains from being thrown against the chamber walls and shattered. The base of the cartridge retainer fits over the exit port of the initiator forming a filter. A series of milled slots in the base of the cartridge retainer permits the generated gas to flow through the exit port while preventing small burning particles of propellant from passing into the transmission line. Miniature initiators use the body or chamber as a cartridge retainer and insert a small filter at the exit port to prevent the escape of small particles of propellant. The holes in the filter or slots under the cartridge retainer should have areas that exceed the area of the exit port to prevent their functioning as flow restricting orifices.

4-5.2.2 STROKING DEVICES

The body design of stroking devices is similar to that of gas generators, except that greater strains occur in the absence of longitudinal stress (undamped-type stroking devices are subject to biaxial stresses). In addition, the wall thickness of the body not only must contain the internal pressure, but also act as a structural member.

The increase in diameter with pressure and its effect on sliding fits in the stroking members must be considered. In a thruster, the stresses also are complicated by the piston, discontinuity at the trunnion, and bending effects. Provision must be made for stopping the piston at the end of its stroke. A common means of stopping the piston is to provide an interference fit on the last portion of travel of the piston.

In a catapult or remover, the body or housing is referred to as the outside tube. This member is provided with a complex closure at the one end – which includes trunnions, firing and release mechanisms, and a cartridge. A simple cap closes the other end. The design principles involved are similar to those described for a thruster except that bending forces developed during the stroking may be significant and tubing sizes may be dictated by standard commercial sizes.

The body designs of special purpose devices are not considered since they usually are similar to that of a thruster (closed system) or remover (open system) already described.

4-5.2.3 PISTON

The function of a piston in a propellant actuated device is to transmit the gas pressure developed in the chamber to the load to be moved. In some devices the piston is simply a rod (most thrusters), while in others, one or more tubes may form the stroking member (catapults and removers).

Stresses developed in pistons or moving tubes are caused by gas pressure and reactive forces resulting from moving the load. If the load is guided along a track or runway, the stresses in the piston are pure tension or compression, depending on whether the piston pushes or pulls the load. More involved stresses in pistons or tubes result when the load is guided only partially, which is the case for most removers and catapults. With partially guided loads, any eccentricity of the load produces bending stresses in the stroking member. Whenever possible, the slenderness ratio (length-to-diameter ratio) of compression loaded designs should not exceed 20 to minimize bending effects.

For pistons loaded in compression, Euler's column formulas may be used. The formulas are not presented in this text since they are dependent on end conditions that must be established for each application. For example, a thruster piston may be pinned to a load or connected by a trunnion, in which cases the column (piston) is considered to have a pinned connection. Pistons occasionally are threaded directly into the load; the column here would be considered to have a "built-in" or "fixed" connection.

4-5.4 FIRING MECHANISMS

4-5.4.1 GENERAL

The firing mechanism initiates the primer that ignites the propellant in a device. Firing mechanisms are classified into three general types: (1) gas-operated, in which the driving force for the firing pin is derived from gas pressure from an initiator or by-pass port; (2) mechanically operated, in which the firing pin is driven by a compressed spring; and (3) electrically-operated, in which electric current fires a special primer directly.

4-5.4.1.1 FIRING PINS

Firing pins (Fig. 4-11) are contained on both gas- and mechanically operated firing mechanisms, and their design is critical.

Figure 4-11. Firing Pins

Binding of the firing pin in its guide must be avoided, and one method of achieving this is by maintaining a length-to-diameter ratio of 2 to 1 or more although ratios as low as 0.9 to 1 have been used successfully. The surfaces of the firing pin and guide must be finished for protection against corrosion and to minimize friction. In addition, the tolerances for the clearance between firing pin and guide must be as small as possible. Table 4-3 shows the length-to-diameter ratios and the clearances used in some existing devices.

The firing pin tip is another important consideration in firing pin design. A hemispherical nose tip is used to transfer the kinetic energy of the firing pin in a concentrated pattern and thus secure good primer indent. Such a tip, however, requires accurate alignment of the firing pin, guide, cartridge, etc., or excessive off-center strikes will occur. Reliable operation demands that the firing pin not strike more than 0.020 in. off center of the primer cup.

4-5.4.1.2 FIRING PLUGS

Artillery-type primers may be used in

TABLE 4-3

FIRING PIN RATIOS AND CLEARANCES

Device	Length/diameter ratio	Firing pin and guide clearances, in.
Catapults M3, M4, M5	2.5	0.003 to 0.007
Removers M1, M3	2.5	0.003 to 0.007
Initiators M3, M4	0.9	0.003 to 0.007
Initiators M5, M6, M10	1.5	0.002 to 0.006
Thrusters M1, M2, M5	1.0	0.001 to 0.005
Thruster M3	1.5	0.002 to 0.006

cartridges using firing plugs seated in the cartridge head over the primer cup. This plug (Fig. 4-12) allows a greater amount of off-center striking by the firing pin. When the firing pin strikes any portion of the plug, the plug strikes the primer with a minimum of eccentricity since it is guided. The system suffers, however, from reduced sensitivity since the firing plug does not transfer all of the energy from the firing pin to the primer.

At present, firing plugs are not used as much to compensate for off-center strikes as to prevent "primer blowback", i.e., by backing up the primer with a firing plug and its guide. This makes the firing mechanism more critical, since it is often difficult to provide a sufficient amount of energy. The "firing plug" arrangement is used to prevent the escape of the high-pressure gases, developed in the chamber during locked-shut firings, around the primer cup ("primer blowback").

4-5.4.1.3 FIRING PIN GUIDES

The firing mechanisms of propellant actuated devices are designed so that the end of the firing pin guide contacts the cartridge head, a condition referred to as "zero head space". This contact not only supports the head of the cartridge against "primer blowback", but also determines the firing pin protrusion. The tip of the firing pin must indent the primer sufficiently to fire the primer, but it is equally important that the firing pin does not pierce the primer or gas may escape through the pierced primer. Firing pin protrusion and the diameter of the firing pin tip (to avoid pierced primers) depend upon the primer used. Table 4-4 presents the desired protrusions and diameters for the four primers currently used in propellant actuated devices.

TABLE 4-4

FIRING PIN PROTRUSIONS AND DIAMETERS

Primer	Firing pin Protrusion, in.	Firing pin tip diameter, in.
M29A1	0.025 + 0.005	0.078
M42	0.025 + 0.005	0.040
72M	0.030 + 0.007	0.078
50M	0.058 + 0.010	0.093

4-5.4.2 GAS-OPERATED FIRING MECHANISMS

The firing mechanism should be designed so that the firing pin develops sufficient kinetic energy to fire the cartridge reliably. This reliability is achieved in gas-operated designs by the proper choice of shear pin, firing pin weight, firing pin cross-sectional area, and firing pin travel.

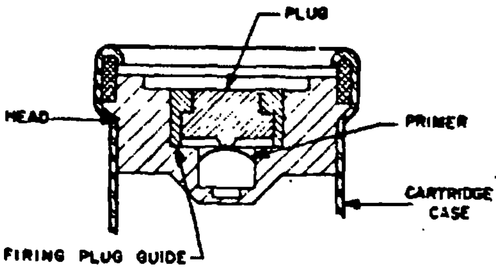


Figure 4-12. Firing Plug

The gas-operated firing mechanism (Fig. 4-13) works in the following manner. Gas enters through the port and pressure rapidly begins to build up behind the firing pin. When the pressure behind the pin is sufficient to shear the firing pin shear pin, the pin shears and the firing pin is propelled toward the cartridge where it strikes the primer. The firing pin velocity is affected more by the force required to shear the shear pin than the maximum force (pressure) attained in the system, since the maximum force against the firing pin usually is attained after the firing pin has completed its travel. For this reason, the selection of the shear pin material and shear pin diameter are vital to the design of gas-operated firing mechanisms. Many propellant actuated devices use the same combination of firing pin and shear pin. It, therefore, was considered advisable to include (in Table 4-5) combinations of firing pins and shear pins that are used widely. The lengths of the firing pins are not common to all, but the length-to-diameter ratios listed in Table 4-3 are used.

The shear pins indicated in Table 4-5 are made of electrical quality copper, while the firing pins are made of stainless steel, or alloy steel. Aluminum firing pins have been used in propellant actuated devices because of their lighter weight and, therefore, greater ability to pass the drop test*. The disadvantage of aluminum firing pins is that the tips deform when they strike the primer. The majority of aluminum pins in present designs are used in conjunction with firing plugs, where the large diameter of the firing pin end does not determine primer indent.

Firing pins are designed with large diameters to increase the force acting against them. However, a means of assembling the firing pin in the device is necessary. For example, 0.5-in. diameter firing pins may have to be assembled from the cartridge end since the gas entry port is sometimes as small as 5/16 in.**. The smaller firing pins may be inserted through the gas entry port.

Firing pins use O-rings to prevent the gas entering the device from passing the firing pin. However, the O-ring must be so positioned that in assembling the firing pin in the firing pin housing or guide and during operation, the O-ring does not pass the shear pin hole, or the O-ring may be torn in assembling the device or in functioning.

4-6.4.3 MECHANICALLY OPERATED FIRING MECHANISMS

The firing mechanism must be designed to deliver sufficient energy to the primer to provide the high reliability of firing necessary in propellant actuated devices. This energy must be delivered without exceeding the stipulated range of lanyard pull. Also, the length of lanyard travel must provide sufficient over-travel to assure release of the firing pin and to permit separation of the lanyard from the mechanism.

The mechanically operated firing mechanism (Fig. 4-14) of a typical initiator operates in the following manner. The firing pin is locked to the sear (pin) by three steel balls. When the sear (pin) is pulled, a spring contained in the housing is compressed and exerts a force on the firing pin. As the firing pin enters the relieved section of the housing, the steel balls move outward and allow the sear (pin) to be disengaged from the firing pin, and the sear (pin) is withdrawn from the device. The firing pin then is propelled by the compressed spring against the cartridge which contains a percussion primer.

The energy required to fire the primer (Table 4-2) must be provided by the spring

*Propellant actuated devices must be dropped 6 ft onto a concrete block, without creating sufficient shock to shear the firing pin shear pin.

**A small diameter ridge is provided between the gas entry port and the firing pin to limit the entry of the hose fitting, preventing its contact with the firing pin.

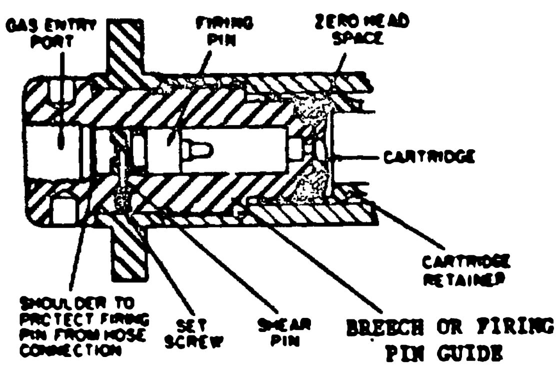


Figure 4-13. Gas-operated Firing Head

force and the firing pin travel. The spring is designed to provide several times the all-fire energy of the primer thus providing a substantial factor of safety.

The selection of spring configurations can best be made by using tables available in spring design handbooks. Such tables present spring forces and deflection per turn for round wire helical springs of various materials.

The spring always is kept in a preload position (partially compressed) to insure continuous engagement between the spring and the firing pin. This continuous engagement prevents vibration of the firing pin when assembled in the device. Propellant actuated devices never are designed with firing pins in the cocked position. However, the cocking and firing of the device are initiated by a single operation.

4-5.5 LOCKING MECHANISMS

Two functional types of locking mechanisms are used in propellant actuated devices: initial and final locks. Initial lock mechanisms prevent motion of the stroking member before firing. This function is of special importance in devices operating against tension loads, since the lock prevents the piston from extending prior to actuation of

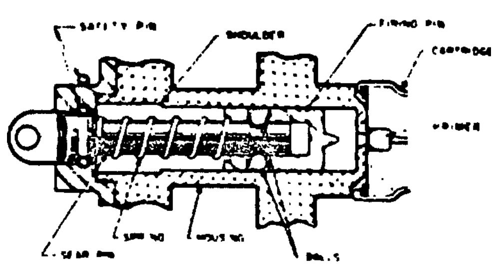


Figure 4-14. Mechanically Operated Firing Mechanism

TABLE 4-5

FIRING PINS AND SHEAR PINS USED IN PROPELLANT ACTUATED DEVICES

Firing Pin Diameter, in.	Shear Pin* diameter, in.	Primer to be struck	Units in which used
0.500	0.048	72M	Thrusters, M1, M2, M6, M7
0.343	0.040	M42	Initiators, M8, M10
0.343	0.040	M29A1	Initiators, M28, M81

*Force required to shear copper pins: 0.048 in. dia. = 48 ± 4 lb, 0.040 in. dia = 41 ± 5 lb.

the device. The two locked sections often act as a structural element, e.g., to hold the pilot seat in its position in the plane. Initial lock mechanisms also prevent unintentional separation of the device due to tampering, vibration, or dropping.

Final locks are required on some devices to maintain the piston in the end-of-stroke position, extended or retracted, as the case may be. The final lock generally is a simple arrangement, consisting of a snap ring or self-locking ball lock that locks into a groove or other depression in the piston.

While an initial lock requirement may be met by a simple shear pin or shear ring which locks a piston and housing together, the problems involved with shear pins (covered in par. 4-6) generally eliminate this type of arrangement from consideration. A method used in several thrusters is shown in Fig. 4-15. This thruster does not unlock until the cartridge fires. When the cartridge fires, gas pressure forces the piston forward (compressing the spring but not moving the end sleeve) until the four locking keys drop into a groove in the piston, removing the connection between the housing and the piston. The spring keeps the piston in the locked position prior to firing. A somewhat similar device is used to lock the tubes of many removers and catapults, except that the locking keys are released by the firing pin prior to firing the catapult. Fig. 4-16 shows a pair of locking keys (latches) in position on a firing pin. When gas pressure is provided behind the firing pin, the pin is propelled toward the cartridge. As the firing pin moves toward the primer, cam action draws the keys inward, thus freeing the stroking members.

Design requirements usually list the initial and final lock requirements from which the size of the components involved may be established. The total shear area and the total area in bearing determine the size of locking keys or locking rings. The emphasis of such designs should be on functioning reliability.

4-5.6 SEALS

Seals in propellant actuated devices perform two important functions: they prevent the entry of moisture and dirt during extended storage periods prior to firing, and they prevent or retard gas leakage during the firing cycle. In units using a fluid-type damping system, the seals prevent the loss of fluid during storage periods, and also prevent or control the leakage of fluid during the firing cycle.

The majority of propellant actuated devices rely on threaded connections and O-rings for sealing. For example, in the initiator shown in

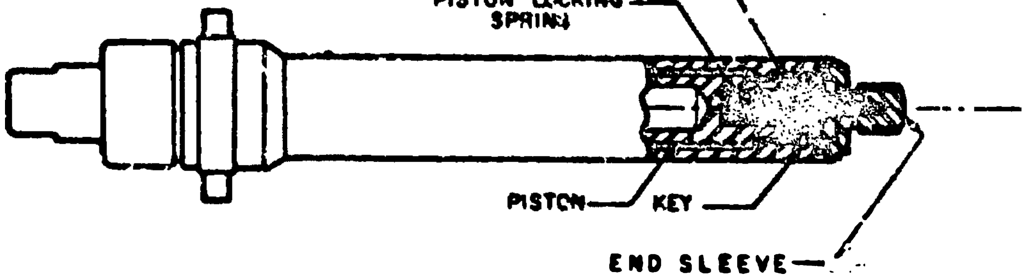


Figure 4-15. Thruster Locking Mechanism

Fig. 4-10, the chamber is joined to the cap by threads, and the firing pin housing is sealed in the chamber with an O-ring. In stroking devices, several O-rings usually serve as static seals against the entry of moisture while others serve as moving seals preventing the loss of high pressure gas. The loss of high pressure gas at the junction of the body and head is prevented by the sealing effect of the threaded connection and the obturation of the cartridge case.

The recommended diametral squeeze dimensions for O-rings, which vary according to size and type of seal, generally decrease the cross-sectional area of the ring by approximately 10 percent. Therefore, it is not necessary to increase diametral squeeze on the seal past the recommended values, except for pressures above 3,000 psi. Whenever O-rings are used in conjunction with buffer liquids, the materials of the rings and the liquids must be compatible.

O-rings are the most effective seals to retain buffer fluids, although rubber bags, metal containers, and sealers have been used satisfactorily in some items.

Where a seal must retain the buffer fluid

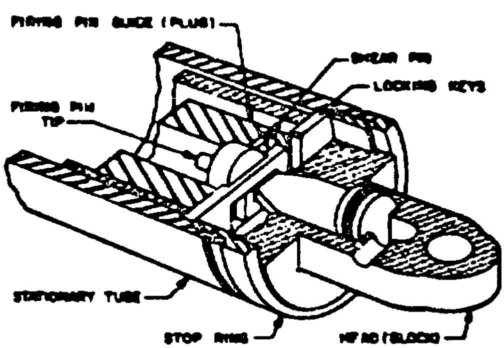


Figure 4-16. Locking Keys and Firing Pin

under static conditions and seal the gas under dynamic conditions; tolerances, clearances, and surface finishes must be selected carefully. Tests, evaluations, and modifications are continued until a satisfactory combination of conditions is obtained. Some catapults employ a tortuous-path-type seal that has proved effective. This type of seal is, essentially, a close-fitting coil of wire that fits in a helical groove. The end of the seal wire is provided with a tang that fits into a hole in the tube, locking the wire in position so it cannot spiral out of the groove and cause the tube to bind.

4-8 SPECIAL PROBLEMS

4-8.1 GENERAL

The design of propellant actuated devices presents many special problems, but this paragraph covers only some of the more important ones. The paragraphs that follow include discussions of shear pins, buffer systems, high-low systems, and the use of protective coatings and dissimilar metals.

4-8.2 SHEAR PINS

Shear pins provide a simple means of locking parts together but have inherent disadvantages. When the unit is assembled or partly assembled there is seldom any way of insuring that the shear pin was not forgotten, and even if one end of the pin were visible, there would be no guarantee that the pin was not bent or already sheared. The shear value or shearing force of shear pins may vary by as much as 20 percent from pin to pin, although all are made of the same material and are the same size.

Spring pins (Fig. 4-17) are special types of shear pins. They may be used in propellant actuated devices; but in accordance with Military Standards, they may not be used in single shear. Military Standards also specify the maximum and minimum hole sizes in which the various size spring pins may be used.

One of the greatest faults of shear pins is the possibility of failing after a series of light blows, each unable to produce failure, but in the aggregate causing it.

4-8.3 DAMPING SYSTEMS

When gas pressure is developed in the chamber of a stroking device operating against

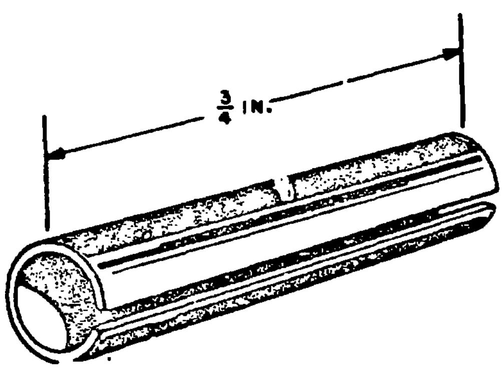


Figure 4-17. Spring Pin

a comparatively light load, the piston is subjected to a relatively high accelerating force. One method of reducing the initial high rate of change of acceleration is through ballistic control. For example, high-low systems (described in par. 4-6.4) are used, the initial volumes of devices are increased, and slower-burning or more progressive-burning propellants are used.

Dampers are used frequently to limit the acceleration of stroking devices. Separate, oil-filled, piston damping devices can be located between the propellant actuated stroking device and the load to limit the acceleration of the piston, and, therefore, the velocity. Most thrusters that use dampers, however, are developed with internal damping for a more compact design. In the simplest type of damper, a liquid with suitable temperature and viscosity characteristics is confined in a cylinder having a piston and orifice. The thruster piston and damper piston are connected (or integral) so that motion of the thruster piston is resisted by the damper. Piston velocity is determined by the rate of flow of the damping liquid through the orifice.

The design of damping systems requires consideration not only with such obvious factors as viscosity of the liquid at various temperatures and its effect on rate of flow, but also expansion of the liquid at higher temperatures. It may be necessary to include a void or a replenisher in the damper liquid chamber. One design compensates for expansion by use of a "floating piston" (Fig. 4-18).

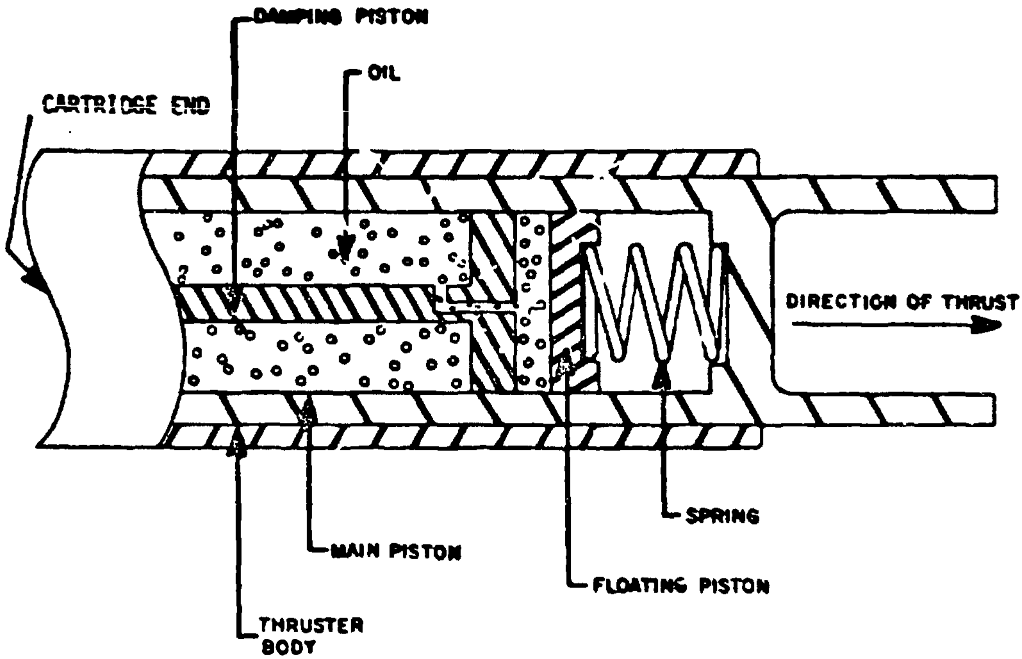


Figure 4-18. Floating Piston and Thermal Expansion Chamber

In this example, the spring between the main piston and the floating piston acts to maintain constant pressure in the buffer liquid. At −65°F, the volume of the oil is at a minimum and the spring compensates by expanding; at 200°F, the oil volume is greatly increased and the spring compensates by compressing.

The design of the spring is similar to that of springs for mechanical firing mechanisms, so it will not be repeated here. In most stroking devices using dampers, the damping liquid is a silicone oil with a relatively constant viscosity throughout the temperature range of propellant actuated devices.

One other damping system that warrants attention is the "hydraulic multiplier" (shown schematically in Fig. 4-19). This device contains a gas piston and a load piston that is connected to the load. An orifice in the load piston permits liquid to pass from the liquid chamber into the space between pistons. When the cartridge fires, the expanding gas exerts a pressure on the gas piston. The liquid on the other side of the gas piston experiences a similar pressure and transmits this pressure to the load piston. The load piston exerts a force on the liquid in the chamber and causes liquid to pass through the orifice into the space between chambers. As the pistons move forward, the load piston moves at a higher speed than the gas piston which is the reason for the name "hydraulic multiplier". The piston speeds are dependent on the size of the orifice in the load piston.

Whether or not damping systems are used is another consideration when calculating wall strengths. For example, the "locked shut" pressure in the gas chamber of the device shown in Fig. 4-19 may be calculated as described earlier in par. 4-3.4, but the greatest pressure that the body of the device must withstand occurs in the damper chamber. The force on the gas piston is equal to the force on the load piston, but on the fluid chamber side of the load piston the force is distributed over a smaller area (because of the area occupied by the piston shaft); therefore, the pressure exerted by the fluid on the body walls is greater than that of the gas. Locked-shut conditions may be simulated by closing the orifice, but not by resisting piston motion.

Other damper arrangements are possible, and one, a system in which the gas acts to rotate a threaded shaft and advance the piston while centrifugal brakes attempt to maintain constant velocity, is being studied at this time. However the majority of dampers in existence and being developed are of the fluid-orifice type described here.

4-6.4 HIGH-LOW SYSTEMS

In propellant actuated devices using high-low systems, propellant gases are generated in a high pressure chamber and then are bled off through a nozzle or orifice into a low pressure chamber where work is performed.

The high-low system is complicated by the two pressure levels of operation and the need for an orifice. The ballistician provides the designer with the approximate pressures and the orifice size, and the designer chooses the

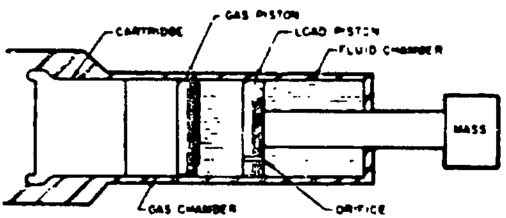


Figure 4-19. Thruster With Fluid Damping

most efficient configuration and the location and mounting arrangement of the orifice.

From an erosion standpoint, high-molybdenum-content steel or pure molybdenum is best for orifice material. If the device is to be fabricated from aluminum, the nozzle may be a threaded insert. If, however, the high-pressure chamber is to be fabricated from a molybdenum-bearing steel it may be possible to dispense with an insert orifice, and fabricate both components as one piece. Ease of fabrication, weight, and cost are the usual factors that apply to decisions in such instances. Nozzle erosion may be a special problem in devices that are produced for repeated applications, and the feasibility of using high-low pressure systems must be weighed carefully.

4-6.5 PROTECTIVE COATINGS

Protective coatings can be used on metallic parts likely to be exposed to corrosion environments to reduce the possibility of service failures. For steel components, cadmium, followed by a chromate dip, is used widely as a protective coating. The chromate finish acts as a sealer and retards or prevents the formation of white corrosion products on surfaces exposed to moisture.

The metallic surfaces of aluminum alloy parts usually are anodized to prevent corrosion. By anodizing a controlled film of aluminum oxide is formed on the surface which serves to protect the underlying base metal from further corrosion. This oxide film is bonded with the aluminum and, for this reason, exhibits excellent adhesive properties with the base metal and cannot be detached readily by bending or any other process used in ordinary fabricating.

Dichromate dipping and anodizing not only retard corrosion, but also retard erosion. In all cases, protective coatings should be relatively nonporous and strongly adherent to the base metal, especially in such localized stress regions as around notches, grooves, and drilled holes. Corrosion around these areas generally is more harmful to the strength of the assembly than corrosion of unbroken surfaces.

4-6.6 DISSIMILAR METALS

In some designs of propellant actuated devices, it is necessary that dissimilar metals contact each other. Aluminum, for example, because of its highly anodic characteristics, corrodes appreciably (galvanic action) when it contacts another metal (steel) with a lesser anodic solution potential for a prolonged period. Common corrosive media as rain water, sea water, atmospheric moisture, or some organic liquids may serve as the electrolytic solution.

Galvanic or electrochemical corrosion is characterized by severe local corrosion of the anodic metal at the point of contact of the two dissimilar metals, if that contact takes place in the electrolyte. The corrosion is in the form of a film, often only to a depth of a few molecular layers. In some instances, this film has the power to protect the metal underneath, thereby preventing further corrosion. In addition, if there are any cracks, the film will promote self-healing. However, in thicker films, which are characteristic of a great number of common metals under the action of a mild, corrosive agent, this self-healing ability of the film is absent. Where the film is broken, corrosion tends to localize. This localizing process eventually causes the metal to pit, thereby lowering the resistance of the metal to further stress, since any hole or notch in the metal tends to intensify the stress at that point.

The condition in which the metal is subjected to repeated stress in a corrosive medium is known as corrosion fatigue and tends to reduce the fatigue strength. Hence, under the combined action of corrosion and stress, a corrodible steel will fail eventually, regardless of the magnitude of the stress. For nonferrous metals, the effects of corrosion fatigue are quite varied; copper is unaffected, while nickel, brass, aluminum, and duralumin are severely affected.

The use of contacting dissimilar metals should be avoided to prevent galvanic corrosion and corrosion fatigue. When it is essential that this combination of metals be employed, an interposing material, acting as a protective layer, should be used.

Although contacting similar metals are not subject to galvanic corrosion, when an aluminum surface passes over another aluminum surface, there is a tendency for the surface to gall. Galling also occurs when a cadmium surface rubs against another cadmium surface, as a cadmium-plated piston sliding (stroking) through a cadmium-plated brushing. Galling is eliminated by the use of microcrystalline waxes on the sliding surfaces and Teflon-coated aluminum pistons and tubes. Teflon coatings and wax finishes also serve to reduce friction between sliding members of propellant actuated devices.

REFERENCES

1. L. A. DeStefano and 1Lt J. E. Holvoet, *An Analysis and Simulation of Breech Launched Rockets, Part I: Analysis*, Frankford Arsenal Technical Report M69-14-1, May 1969.
2. AMCP 706-270, Engineering Design Handbook, *Propellant Actuated Devices*, August 1963.
3. AMCP 706-285, Engineering Design Handbook, *Elements of Aircraft and Missile Propulsion*.
4. Sutton, *Rocket Propulsion Elements*, John Wiley & Sons, Inc., New York, N.Y., 1949.
5. Timoshenko, *Strength of Materials*, D. Van Nostrand Co., Inc., Third Edition, Part II, Page 454, Equation 296.
6. SB 708-800-1, *Screw-Thread Standards for Federal Services*, Handbook M28, Part I, 1957.
7. F. W. Iaconelli, *Improved Design of PAD Cartridges, Impulse, M28A1, M29A2, M30A1, M36, M43, M69 and M94*, Frankford Arsenal Report No. 6007, August 1970.

CHAPTER 5

INTERIOR BALLISTIC ANALYSIS

5-0 LIST OF SYMBOLS

$a(t)$ = acceleration, ft/sec^2

A_p = piston area, in.^{2}

A_s = propellant surface area, in.^{2}

$A_s(w)$ = propellant surface area corresponding to w, in.^{2}

A_t = nozzle throat area, in.^{2}

A_t = orifice area, in.^{2}

b = burning rate coefficient, in./sec-psi^n

C = propellant gas in chamber, lb

C = gas weight actually contained within the volume, lb

C_b = propellant gas weight, lb

C_D = gas discharge coefficient, lb/lb-sec

C_f = thrust coefficient, dimensionless

C_x = weight of gas discharged, lb

d = perforation diameter, in.

D = grain diameter, in.

E_p = maximum propellant energy, ft-lb

$f(x, dx/dt, t)$ = function describing the effect of friction, air resistance, and any other retardation forces, lb

F = propellant impetus, ft-lb/lb

$\mathfrak{F}$ = rocket thrust, lb

g = acceleration due to gravity, ft/sec^2

L = grain length, in.

n = pressure exponent, dimensionless

P = driving pressure, psi

P_a = atmospheric pressure, psi

P_e = pressure at nozzle exit plane, psi

P_H = high-side pressure, psi

P_H = driving pressure, psi

P_L = receiver pressure, psi

PCD = perforation circle diameter

t = time, sec

T_c = initial gas temperature, °R

T_o = adiabatic isochoric flame temperature, °R

v = velocity, ft/sec

V = free volume, in.^{3}

w = burn distance, in.

w_m = maximum burn distance, in.

W = propelled weight, lb

x = displacement of load, ft

α = thermal efficiency, dimensionless

β = fraction of available energy, dimensionless

γ = ratio of specific heats, dimensionless

δ_{max} = maximum spinal compression ft

ϵ = nozzle expansion ratio, dimensionless

ζ = flow factor, dimensionless

η = propellant gas covolume, in.^{3}/lb

θ = angle of elevation with respect to horizontal, deg

ρ = density of solid propellant, lb/in.^{3}

ρ = spinal damping ratio, dimensionless

ω = natural frequency of spinal column, rad/sec

5-1 INTRODUCTION

This chapter presents a more rigorous treatment of the interior ballistics of propellant actuated devices than that contained in Chapter 4. General ballistic equations are presented, and these are adapted to the modeling of stroking (direct and high-low) and gas-generating devices. Computer programs for the simulation of direct and high-low stroking devices are listed in Appendixes D and E, respectively, and sample output are contained in this chapter. A discussion of grain design techniques also is presented. A listing of a high low grain design program is contained in Appendix F. Par. 5-6 contains a short discussion of the dynamic response index, a parameter coming into use as a specification limit for personnel escape systems.

5-2 BASIC EQUATIONS

This paragraph will list the basic equations governing the interior ballistics of propellant actuated devices. They will be structured as first-order differential equations for ease of solution by digital computer techniques. Succeeding paragraphs will apply these equations to the analysis of stroking and gas-generating devices.

5-2.1 PROPELLANT BURNING RATE

The burning rate of a solid propellant usually is approximated as a pressure dependent function according to the relation

$$\frac{dw}{dt} = bP^n \tag{5-1}$$

where

w = burn distance, in.

t = time, sec

b = burning rate coefficient, in./sec-psi^n

n = pressure exponent, dimensionless

Eq. 5-1 is identical to Eq. 4-18.

This expression for the burning rate usually is valid over a given pressure range. For some propellants, however, the pressure exponent or slope n is not constant but may vary for certain pressure intervals. In some instances it may be zero or negative. If the operating pressure of a device spans one or more of the intervals that involve such a change in the slope, then it is necessary to specify the burning rate equation for each region. For instance, consider the burning rate depicted in Fig. 5-1. The relations which characterize this function over the pressure range 100 psi to 10,000 psi are

$$\frac{dw}{dt} = 0.02P^{0.5}, 1600 \text{ psi} > P > 100 \text{ psi}$$

$$\frac{dw}{dt} = 1.672P^{-0.1}, 3000 \text{ psi} > P > 1600 \text{ psi}$$

$$\frac{dw}{dt} = 0.00186P^{0.75}, 10000 \text{ psi} > P > 3000 \text{ psi}$$

If it is intended to determine the interior ballistics by programming the equations for solution by a digital computer, than it may be desirable to input the burning rate as a tabular listing versus pressure and allow the program

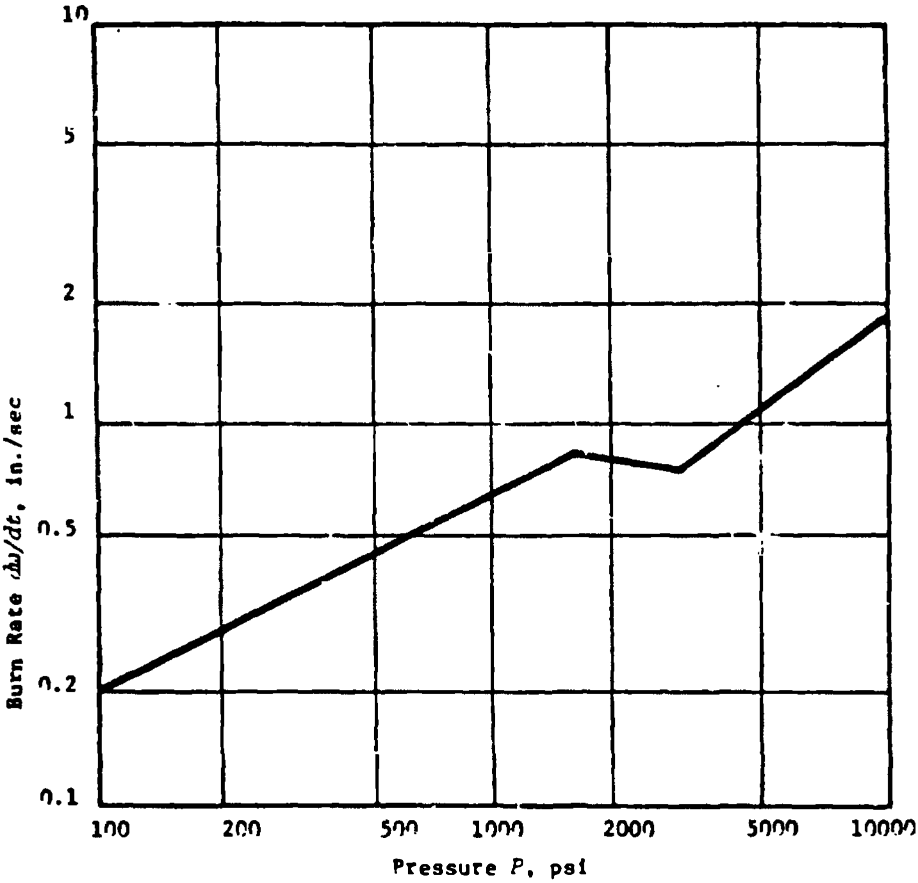


Figure 5-1. Burn Rate Relation

to interpolate to find the burning rate corresponding to a particular pressure. For the preceding example it would be necessary to input the pressures and corresponding burning rates for the end points and at each point where there is a change in the slope (i.e, 100 psi, 1600 psi, 3000 psi, 10,000 psi). For the sake of notation and for use in later paragraphs consider that the burning rate can be expressed by the relation

$$\frac{dw}{dt} = r(P) \tag{5-2}$$

where $r(P)$ will represent the burning rate either determined by Eq. 5-1 or from an interpolation of the tabular values.

5-2.2 PROPELLANT SURFACE DEVELOPMENT

When propellant is combusted, it is assumed to burn in a direction normal to its exposed surface. The burning area thus can be determined geometrically by incrementing the burn distance normal to the exposed surface and calculating the surface area as a function of the burn distance.

The most common propellant geometries used in propellant actuated devices are grains containing one, three, and seven perforations. In addition, each of these types may or may not have its outer surfaces inhibited to restrict burning to the interior of the perforations. These six grains are depicted in Fig. 5-2. For these relatively simple geometries it is possible to specify the surface area as a function of the burn distance. These relations are listed in the paragraphs that follow where it is assumed that the length of the inhibited grains exceeds twice the maximum burn distance w_m or used as defined in par. 4-2.2.4, and that the burn distance does not exceed w_m. The relations for the surface development for three and seven perforation grains, therefore, do not include the contribution due to slivers. The maximum burn distance and perforation circle diameter (PCD) for each grain type are listed in Table 5-1.

Single perforation-uninhibited:

$$A_s = \pi\left(\frac{D+d}{2}\right)\left[\,2L-3D-d) - 8w\,\right] \tag{5-3}$$

Single perforation-inhibited:

$$A_s = \pi L(d + 2w)$$

Three perforation-uninhibited:

TABLE 5-1

BURN DISTANCE AND PERFORATION CIRCLE RELATIONS

	Single Perforation		3 Perforations		7 Perforations	
	Inhibited	Uninhibited	Inhibited	Uninhibited	Inhibited	Uninhibited
w_m	$D-d$	$\frac{D-d}{2}$	$\frac{D}{2}\left[2\sqrt{3}-3\right] - \frac{d}{2}$	$\frac{1}{8}\left[D\left(3-\sqrt{3}\right) - d\left(1+\sqrt{3}\right)\right]$	$\frac{D-3d}{6}$	$\frac{D-3d}{4}$
PCD	–	–	$D\left[4-3\sqrt{3}\right]$	$\frac{1}{2}\left[D\left(\sqrt{3}-1\right) + \sqrt{3}d\right]$	$\frac{2D}{3}$	$\frac{D+d}{2}$

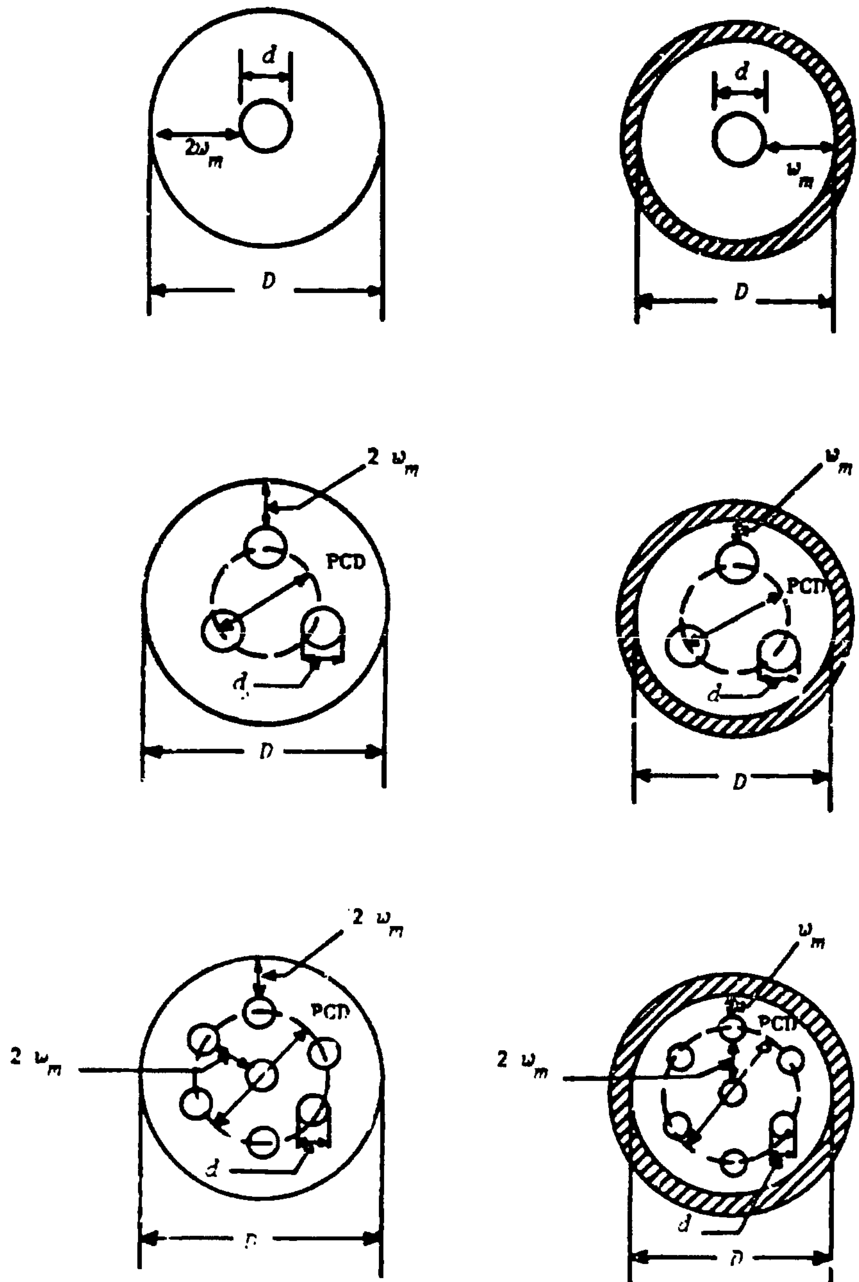


Figure 5-2. Common Propellant Geometries

$$A_s = \pi\left\{\left[L(D+3d)+\frac{(D^2-3d^2)}{2}\right] + 4(L-D-3d)w-12w^2\right\} \quad (5\text{-}4)$$

Three perforation-inhibited:

$$A_s = 3\pi L(d+2w)$$

Seven perforation-uninhibited:

$$A_s = \pi\left\{\left[L(D+7d)+\frac{(D^2-7d^2)}{2}\right] + 4(32-D-7d)w-40w^2\right\} \quad (5\text{-}5)$$

Seven perforation-inhibited:

$$A_s = 7\pi L(d+2w) \quad (5\text{-}6)$$

where

A_s = propellant surface area, in.^{2}

L = length of grain, in.

D = diameter of grain, in.

d = diameter of perforation, in.

w = burn distance, $(0 < w < w_m)$ in.

The inhibited grains always will burn progressively, i.e., the surface area is an increasing function of the burn distance. The uninhibited single perforation grain always will burn regressively. Although, for single perforation uninhibited grains which are long in comparison to their diameters ($L \gg D$) the rate of regression may be negligible and the grain can be assumed to have a neutral or constant surface development. The three- and seven-perforation uninhibited grains may be either progressive or regressive, depending on the dimensions of the particular grain.

The time ratio of change of the propellant surface area can be determined according to

$$\frac{dA_s}{dt} = \frac{dA_s}{dw}\left(\frac{dw}{dt}\right) \quad (5\text{-}7)$$

where

dA_s/dw = rate of change of surface with respect to burn distance, in.^{2}/sec

For the geometries just considered, dA_s/dw can be obtained by differentiating the expressions for the surface development. Again if a digital computer is being used to solve the ballistic equations, the surface development may also be inputted as a tabular function of the burn distance and the derivative or slope computed by the program as the particular value of burn distance.

The use of tabular input is more desirable in that increased flexibility is achieved in the selection of grain geometry. In addition, it will be possible to incorporate the effect of slivers into the surface area development which in multiperforation grains can comprise over 30% of the total grain weight.

5-2.3 GAS PRODUCTION

The time rate of gas production is a function of the exposed propellant surface and burn rate

$$\frac{dC_b}{dt} = \rho A_s(w)\frac{dw}{dt} \quad (5\text{-}8)$$

where

C_b = propellant gas weight, lb

ρ = density of solid propellant, lb/in.^{3}

$A_s(w)$ = propellant surface area, in.^{2}

The value of $A_t(w)$ is the surface area corresponding to the value of w which has been attained.

5-2.4 GAS PRESSURE

The pressure generated by the burning of propellant can be determined from the equation of state as given in Eq. 4-10. Differentiating with respect to time

$$\frac{dP}{dt} = \frac{12F}{T_o}\frac{d}{dt}\left(\frac{TC}{V}\right) \tag{5-9}$$

The gas weight C corresponds to the gas that is actually contained within the volume. Only for a closed single chamber device will the gas weight C equal C_b as defined in Eq. 5-8. For the low side chamber of a high-low system, C would equal the gas weight that has been exhausted into the low site.

5-2.5 FREE VOLUME

The free volume of a chamber equals the initial free volume plus that obtained by the movement of a piston (if any) plus the volume obtained when propellant is consumed (if any) less the volume taken up by the gas in the chamber (covolume). Thus in terms of the time derivative of the free volume

$$\frac{dV}{dt} = 12A_p\frac{dx}{dt} + \frac{1}{\rho}\frac{dC_b}{dt} - \eta\frac{dC}{dt} \tag{5-10}$$

where

V = free volume, in.^{3}

A_p = piston area, in.^{2}

dx/dt = velocity of piston, ft/sec

ρ = density of solid propellant, lb/in.^{3}

η = propellant gas covolume, in.^{3}/lb

C = propellant gas in chamber, lb

For a chamber in which no propellant is consumed the $1/\rho$ term equals zero. If the chamber does not contain a stroking member, then the dx/dt term is zero.

5-2.6 GAS DISCHARGE THROUGH AN ORIFICE

The gas discharge rate through an orifice can be represented by the expression

$$\frac{dC_x}{dt} = \zeta\left(\frac{P_L}{P_H}\right) C_D A_t P_H, \text{ lb/sec} \tag{5-11}$$

where

C_x = weight of gas discharged, lb

$\zeta\left(\frac{P_L}{P_H}\right)$ = flow factor, dimensionless

C_D = gas discharge coefficient, lb/lb-sec

A_t = orifice area, in.^{2}

P_H = driving pressure, lb/in.^{2}

P_L = receiver pressure, lb/in.^{2}

This expression is derived in Appendix C of Ref. 1, Chapter 4. The flow factor ζ which is a function of the driving and receiver pressure, is derived in Appendix B of this reference. For sonic flow, i.e.,

$$\frac{P_L}{P_H} < \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \tag{5-12}$$

the flow factor equals 1.

For values of P_L/P_H greater than this (subsonic flow) the flow factor is given by the expression

$$\zeta = \left[\frac{\left(\frac{P_L}{P_H}\right)^{2/\gamma} - \left(\frac{P_L}{P_H}\right)^{(\gamma+1)/\gamma}}{\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}\right]^{1/2} \quad (5\text{-}13)$$

where

γ = ratio of specific heats.

For $\gamma = 1.25$, P_L/P_H must be less than 0.555 for sonic flow. Eq. 5-13 is plotted in Fig. 5-3 for $\gamma = 1.25$.

5-2.7 EQUATION OF MOTION

The equation of motion of a piston (load) is given by the expression

$$\left(\frac{W}{g}\right)\frac{d^2x}{dt^2} = A_pP - W\sin\theta - f\left(x, \frac{dx}{dt}, t\right) \quad (5\text{-}14)$$

where

x = displacement of the load, ft

θ = angle of elevation with respect to the horizontal, deg

$f(x, \frac{dx}{dt}, t)$ = a function describing the effect of friction, air resistance, and any other retardation forces, lb

P = driving pressure, lb/in.^{2}

W = propelled weight, lb

A_p = piston area, in.^{2}

g = acceleration due to gravity, ft/sec^2

In terms of first-order differential equations, Eq. 5-14 may be rewritten as

$$\frac{dv}{dt} = \frac{gA_pP}{W} - g\sin\theta - \frac{g}{W}f(x, v, t) \quad (5\text{-}15)$$

$$\left.\begin{aligned}\frac{dx}{dt} &= v\\ \frac{d^2x}{dt^2} &= \frac{dv}{dt}\end{aligned}\right\} \quad (5\text{-}16)$$

If the driving pressure is less than the opposing component of the load or if it is less than the shot start pressure, then the acceleration is zero.

5-2.8 ENERGY BALANCE (GAS TEMPERATURE)

The maximum energy available from a solid propellant (see Eq. 4-9) is equal to

$$E_p = \frac{FC}{\gamma - 1}$$

where the gas temperature is equal to the adiabatic isochoric flame temperature T_o. The energy E available at any other temperature T is then equal to

$$E = \frac{T}{T_o}E_p \quad (5\text{-}17)$$

An energy balance can then be set up as follows:

Available Energy = (Internal Energy) + (Work Done by Propellant Gas) + (Energy Loss)

$$\frac{FCT_c}{T_o(\gamma-1)} = \frac{FCT}{T_o(\gamma-1)} + A_p\int P dx + \frac{BFCT}{T_o(\gamma-1)} \quad (5\text{-}18)$$

where C is the gas weight in the chamber under consideration. It is assumed that the propellant gas is initially at temperature T_c

and the energy loss is some fraction β of the available energy. Assuming that T_c equals the adiabatic isobaric flame temperature of the propellant, i.e., $T_c = T_o/\gamma$, and solving for the gas temperature T

$$T = \left(\frac{\alpha}{\gamma}\right)T_o - \frac{(\gamma - 1)T_o A_p}{FC}\int P dx \quad (5\text{-}19)$$

where

$\alpha = 1 - \beta$

and is termed the thermal efficiency.

The term $\int P dx$ can be obtained from the equation of motion, Eq. 5-15, by solving for the driving pressure P and integrating over the displacement x.

$$\int P dx = \frac{W}{gA_p}\int \frac{d^2x}{dt^2}\, dx + \frac{W \sin\theta}{A_p}\int dx + \frac{1}{A_p}\int f(x,v,t)dx = \left(\frac{W}{gA_p}\right)\frac{v^2}{2} + \left(\frac{W}{A_p}\right)x \sin\theta + \frac{1}{A_p}\int f(x,v,t)dx \quad (5\text{-}20)$$

where the first term represents the kinetic energy of the load, the second term represents the potential energy, and the third term represents the energy required to overcome any resistive forces. This last term cannot be evaluated until the expression for the resistive forces are determined.

In terms of a first-order differential equation the gas temperature is then equal to

$$\frac{dT}{dt} = -\left[\frac{(\gamma - 1)T_o}{F}\right]\frac{d}{dt}\left\{\frac{1}{C}\times\left[W\left(\frac{v^2}{2g} + x\sin\theta\right) + \int f(x,v,t)dx\right]\right\} \quad (5\text{-}21)$$

For most propellant actuated devices the thermal efficiency α is found to be between 0.5 and 0.7. This expression for the gas temperature is one of many which could be derived depending on the degree of sophistication and assumptions which are made. However, this form has been found to give a good correlation to the actual ballistics of propellant actuated devices.

5-3 STROKING DEVICES

This paragraph will apply the preceding equations (par. 5-2) to the analysis of direct and high-low propellant actuated stroking devices. Digital computer programs for the solution of the system equations are listed in Appendixes D and E. Sample output from these programs are presented in the paragraphs dealing with the particular type of device.

5-3.1 DIRECT STROKING DEVICE

A direct ballistic stroking device is one in which the mechanical work (motion of a load) is accomplished in the same chamber as the combustion process. In this analysis provision is made for exhausting a portion of the propellant gas to account for leakage or venting if applicable. Fig. 5-4 depicts a schematic of a direct stroking device. The differential equations representing the devices are:

a. Burn Distance:

$$\frac{dw}{dt} = r(P) \quad (5\text{-}2)$$

b. Propellant Surface Area:

$$\frac{dA_t}{dt} = \frac{dA_t}{dw}\left(\frac{dw}{dt}\right) \quad (5\text{-}7)$$

c. Propellant Gas in Chamber:

$$\frac{dC}{dt} = \rho A_t(w)\frac{dw}{dt} - \xi\left(\frac{P_a}{P}\right)C_D A_t P \quad (5\text{-}22)$$

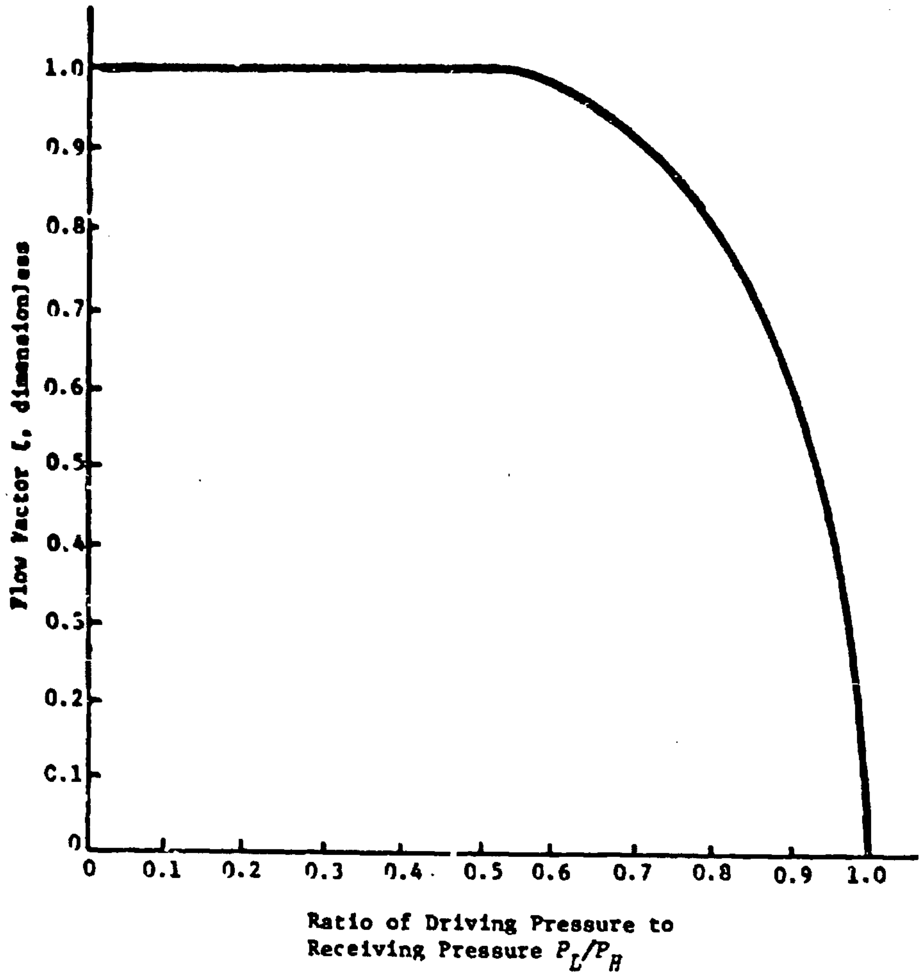


Figure 5-3. Flow Factor vs Pressure Ratio

where

P_a = atmospheric pressure

d. Pressure:

$$\frac{dP}{dt} = \left(\frac{12F}{T_o}\right)\frac{d}{dt}\left(\frac{TC}{V}\right) \quad (5\text{-}9)$$

e. Volume:

$$\frac{dV}{dt} = 12A_p\frac{dx}{dt} + \frac{1}{\rho}\frac{dC_b}{dt} - \eta\left(\frac{dC_b}{dt} - \frac{dC_x}{dt}\right) \quad (5\text{-}10)$$

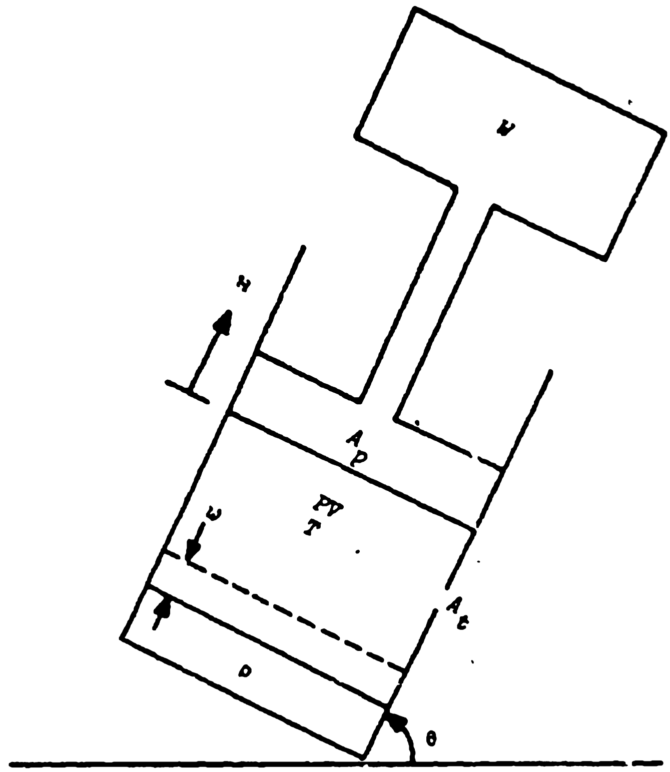


Figure 5-4. Schematic of Direct Ballistic System

since

$$C = C_b - C_x$$

f. Velocity:

$$\frac{dv}{dt} = \begin{cases} \dfrac{gA_pP}{W} - g\sin\theta - \dfrac{g}{W} f(x,v,t) \\ \\ 0 \quad \text{or} \quad \begin{matrix} P < P_{\text{shot start}} \\ P < \dfrac{W}{A_p}\sin\theta \end{matrix} \end{cases} \tag{5-15}$$

g. Displacement:

$$\frac{dx}{dt} = v \tag{5-16}$$

h. Gas Temperature:

$$\frac{dT}{dt} = -\left[\frac{(\gamma-1)T_g}{F}\right]\frac{d}{dt}\left\{\frac{1}{C}\left[W\left(\frac{v^2}{2g} + x\sin\theta\right) + \int f(x,v,t)dx\right]\right\} \tag{5-21}$$

These relations constitute a set of eight first-order differential equations which must be solved simultaneously to give a description of the interior ballistics of direct stroking devices. A digital computer program (written in FORTRAN IV) for their solution is listed in Appendix D. The required input to this program along with the output parameters are listed in Table 5-2 where the burning rate vs pressure and propellant surface area vs burn distance are inputted in a tabular form of five points for each parameter.

TABLE 5-2

DIRECT BALLISTIC STROKING DEVICE INPUT-OUTPUT PARAMETERS

Input

FORTRAN Symbol*	Parameter	Units
P	Pressure	lb/in.^{2}
R	Burning rate	in./sec
W	Burn distance	in.
A	Propellant surface area	in.^{2}
D(1)	Compute interval	sec
D(2)	Print interval	sec
D(3)	Stroke	ft
D(4)	Shot start pressure	lb/in.^{2}
D(5)	Piston area	in.^{2}
D(6)	Vent area	in.^{2}
D(7)	Propelled load	lb
D(8)	Angle of elevation	deg
D(9)	Retardation coefficient	lb/ft
D(10)	Thermal efficiency	–
D(11)	Ratio of specific heats	–
D(12)	Propellant density	lb/in.^{3}
D(13)	Propellant impetus	ft-lb/lb
D(14)	Adiabatic isochoric flame temperature	°R
D(15)	Initial pressure	lb/in.^{2}
D(16)	Initial free volume	in.^{3}
D(17)	No data test**	–

Output

FORTRAN Symbol	Parameter	Units
T	Time	sec
X(1)	Burn distance	in.
GWT	Gas produced	lb
X(4)	Pressure	lb/in.^{2}
C(I, 5)	Load acceleration	ft/sec^2
X(5)	Load velocity	ft/sec
X(6)	Load displacement	ft

*Refer to program listing in Appendix D.

**A value of D(17) < 0 indicates that more data is to be inputted. If D(17) > 0 the program terminates at end of run.

As an example of the use of this program in determining the interior ballistics, consider the following input where the burning rate relation is that used in the example in par. 5-2.1.

PRESSURE	BURNING RATE	BURN DISTANCE	SURFACE AREA
100.	0.20	0.00	10.
1600.	0.80	0.02	15.
3000.	0.75	0.04	20.
10000.	1.86	0.06	25.
20000.	3.34	0.08	30.

Compute Interval: 0.0005 sec

Print Interval: 0.001 sec

Stroke: 2.25 ft

Shot start pressure: 14.7 psi

Piston Area: 1.0 in.^{2}

Vent Area: 0.005 in.^{2}

Propelled Weight: 250 lb

Angle of elevation: 90 deg

Retardation coefficient: 0.0 lb/ft

Thermal efficiency: 0.6

Ratio of specific heats: 1.23

Propellant density: 0.06 lb/in.^{3}

Propellant impetus: 360,000 ft-lb/lb

Adiabatic isochoric flame temperature: 5500°R

Initial pressure: 150 psi

Initial volume: 25 in.^{3}

This input is not representative of a particular device but is used merely to illustrate the use of the program. The computer generated pressure and load velocity are plotted vs time in Fig. 5-5. The propellant grain used in this example corresponds to 43.5 grams of propellant in an inhibited single perforation configuration consisting of forty individual grains each 1 in. in length L and 0.24 in. in diameter D with a perforation diameter d of 0.08 in.

5-3.2 HIGH-LOW STROKING DEVICE

A high-low ballistic stroking device is one in which the propellant is combusted in one chamber (high) and the combustion products vented through an orifice into a second chamber (low) in which the mechanical work is accomplished. Fig. 5-6 depicts a schematic of a high-low stroking device.

The following differential equations representing this device are listed, and where variables subscripted H correspond to the high side chamber and those subscripted L refer to the low side chamber.

a. Burn Distance:

$$\frac{dw}{dt} = r(P_H) \tag{5-2}$$

b. Propellant Surface Area:

$$\frac{dA_s}{dt} = \frac{dA_s}{dw}\left(\frac{dw}{dt}\right) \tag{5-7}$$

c. Propellant Gas Evolved:

$$\frac{dC_b}{dt} = \rho A_s(w)\,\frac{dw}{dt} \tag{5-8}$$

d. Low-side Gas Weight:

$$\frac{dC_L}{dt} = \zeta\left(\frac{P_L}{P_H}\right) C_D A_t P_H \tag{5-11}$$

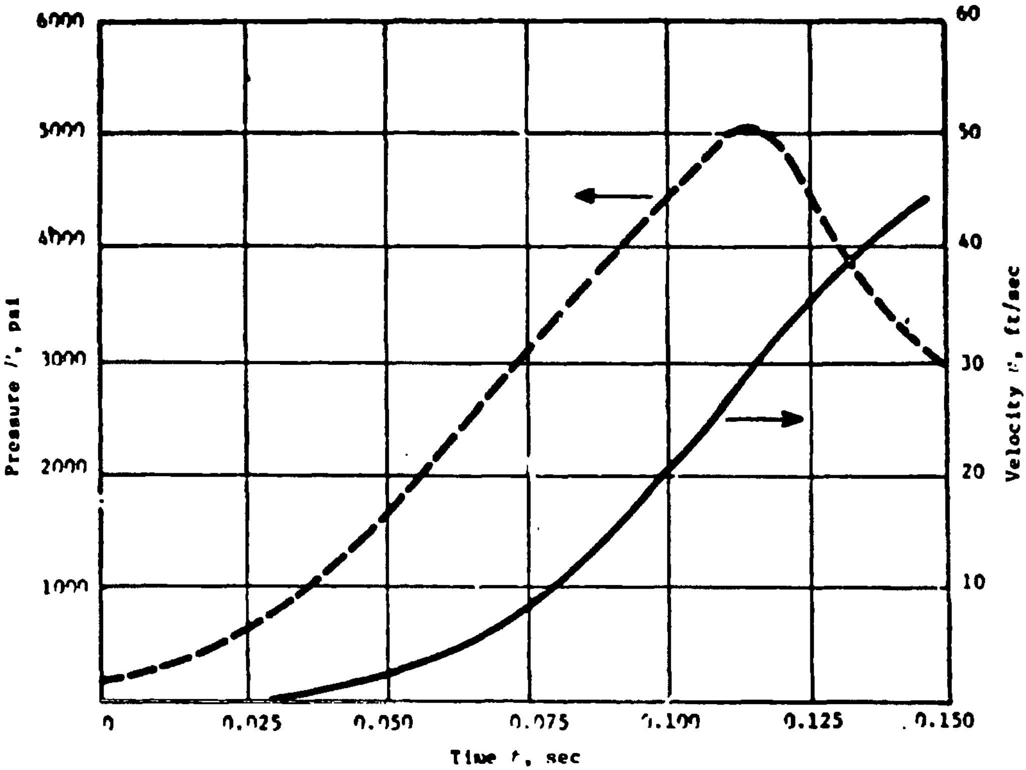


Figure 5-5. Computer Generated Pressure and Velocity

e. High-side Gas Weight:

$$\frac{dC_H}{dt} = \frac{dC_b}{dt} - \frac{dC_L}{dt} \tag{5-23}$$

f. High-side Pressure:

$$\frac{dP_H}{dt} = \left(\frac{12F}{\gamma}\right) \frac{d}{dt} \left(\frac{C_H}{V_H}\right) \tag{5-24}$$

(The high-side gas temperature T_H is assumed constant and equal to the adiabatic isobaric flame temperature of the propellant, $T_H = T_o/\gamma$.)

g. Low-side Pressure

$$\frac{dP_L}{dt} = \left(\frac{12F}{T_o}\right) \frac{d}{dt} \left(\frac{T_L C_L}{V_L}\right) \tag{5-25}$$

h. Low-side Volume:

$$\frac{dV_L}{dt} = 12A_p \frac{dx}{dt} - \eta \frac{dC_H}{dt} \tag{5-26}$$

i. High-side Volume:

$$\frac{dV_H}{dt} = \frac{1}{\rho} \frac{dC_b}{dt} - \eta \frac{dC_H}{dt} \tag{5-27}$$

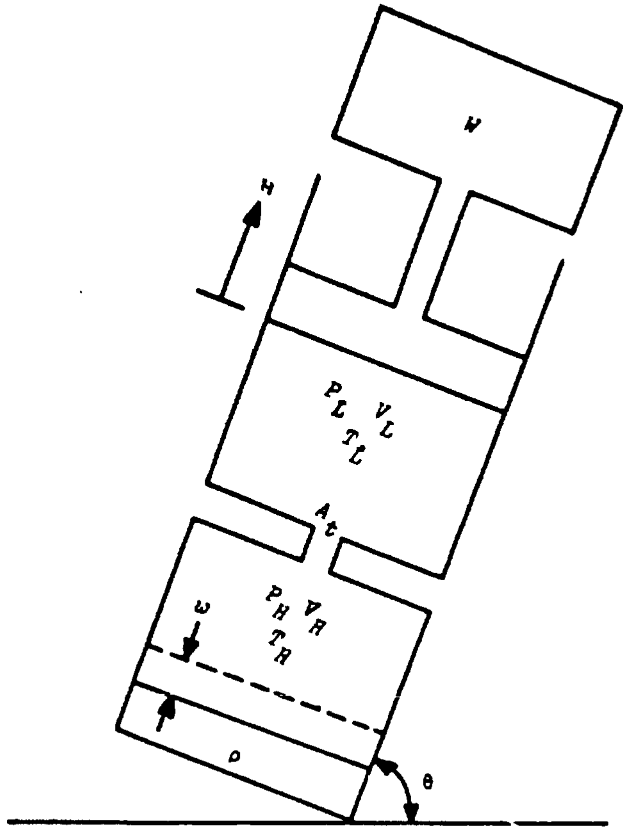


Figure 5-6. Schematic of High-Low System

j. Velocity:

$$\frac{dv}{dt} = \begin{cases} \dfrac{gA_pP_L}{W} - g\sin\theta - \dfrac{g}{W}f(x,v,t) \\ 0 \text{ or } \quad P_L < P_{\text{shot start}} \\ \qquad\quad P_L < \dfrac{W}{A_p}\sin\theta \end{cases}$$

k. Displacement:

$$\frac{dx}{dt} = v \qquad (5\text{-}16)$$

l. Low-side Temperature:

$$\frac{dT_L}{dt} = -\left[\frac{(\gamma - 1)T_o}{F}\right]\frac{d}{dt}\left\{\frac{1}{C_L}\right. \qquad (5\text{-}21)$$

$$\left.\times\left[W\left(\frac{v^2}{2g} + x\sin\theta\right) + f(x,v,t)\,dx\right]\right\}$$

These relations constitute a set of twelve first-order differential equations which must be solved simultaneously to give a description of the interior ballistics of high-low stroking devices. A digital computer program (written in FORTRAN IV) for their solution is listed in Appendix E. The required input to this program along with the generated output is listed in Table 5-3. Again as for the direct ballistic stroking device, the burning rate and surface development are five point tabular inputs.

To illustrate the use of this program the input data corresponding to the example for the direct ballistic program will be employed with the following additions and changes:

Orifice Area: 0.04 in.^{2}

Initial low side pressure: 14.7 psi

Initial low side volume: 25 in.^{3}

Initial high side pressure: 150 psi

Initial high side volume: 2 in.^{3}

The high and low side pressures vs time are plotted in Fig. 5-7, and the velocity and displacement vs time is presented in Fig. 5-8.

5-4 GAS-GENERATING DEVICES

The equations for gas-generating devices are essentially those for a high-low ballistic device where the high side represents the gas generator and the low side represents the volume into which the propellant gas is expelled. If the device is exhausting into the atmosphere, the low side volume is made essentially infinite; large enough so that the gas entering the low side will not raise the pressure appreciably. If the generator is exhausting into a constant volume, then the piston area can be set equal to zero to preclude motion.

If the ballistics of a rocket is to be simulated, then the high-low program (exhausting into the atmosphere) can be used with the addition of a thrust equation and an input corresponding to the nozzle expansion ratio ϵ.

$$\mathfrak{F} = C_f A_t P_H \qquad (5\text{-}27)$$

where

$\mathfrak{F}$ = rocket thrust, lb

C_f = thrust coefficient, dimensionless

A_t = nozzle throat area, in.^{2}

P_H = high side pressure, lb/in.^{2}

The thrust coefficient C_f is given by the equation

$$C_f = \left\{ \left(\frac{2\gamma^2}{\gamma - 1}\right) \left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/(\gamma-1)} \times \left[1 - \left(\frac{P_e}{P_H}\right)^{(\gamma-1)/\gamma}\right] \right\}^{1/2} + \epsilon \left(\frac{P_e}{P_H} - \frac{P_a}{P_H}\right) \qquad (5\text{-}28)$$

where

γ = ratio of specific heats, dimensionless

P_e = pressure at nozzle exit plane, lb/in.^{2}

ϵ = nozzle expansion ratio, dimensionless

P_a = atmospheric pressure lb/in.^{2}

and the ratio P_e/P_H is given as the smaller root

$$\frac{P_e}{P_H} < \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)}$$

of the equation

TABLE 5-3

HIGH-LOW BALLISTIC STROKING DEVICE INPUT-OUTPUT PARAMETERS

Input

FORTRAN Symbol*	Parameters	Units
P	Pressure	lb/in.^{2}
R	Burning rate	in./sec
W	Burn distance	in.
A	Propellant surface area	in.^{2}
D(1)	Compute interval	sec
D(2)	Print interval	sec
D(3)	Stroke	ft
D(4)	Shot start pressure	lb/in.^{2}
D(5)	Piston area	in.^{2}
D(6)	Orifice area	in.^{2}
D(7)	Propelled load	lb
D(8)	Angle of elevation	deg
D(9)	Retardation coefficient	lb/ft
D(10)	Thermal efficiency	–
D(11)	Ratio of specific heats	–
D(12)	Propellant density	lb/in.^{3}
D(13)	Propellant impetus	ft-lb/lb
D(14)	Adiabatic isochoric flame temperature	°R
D(15)	Initial low side pressure	lb/in.^{2}
D(16)	Initial low side free volume	in.^{3}
D(17)	Initial high side pressure	lb/in.^{2}
D(18)	Initial high side free volume	in.^{3}
D(19)	No data test**	–

Output

FORTRAN Symbol	Parameters	Units
T	Time	sec
X(1)	Burn distance	in.
X(3)	Gas produced	lb
X(7)	High side pressure	lb/in.^{2}
X(10)	Low side pressure	lb/in.^{2}
X(11)	Load velocity	ft/sec
X(12)	Load displacement	ft

*Refer to program listing in Appendix E.
**A value of D(17) < 0 indicates that more data are to follow. If D(17) > 0 the program terminates at end of run.

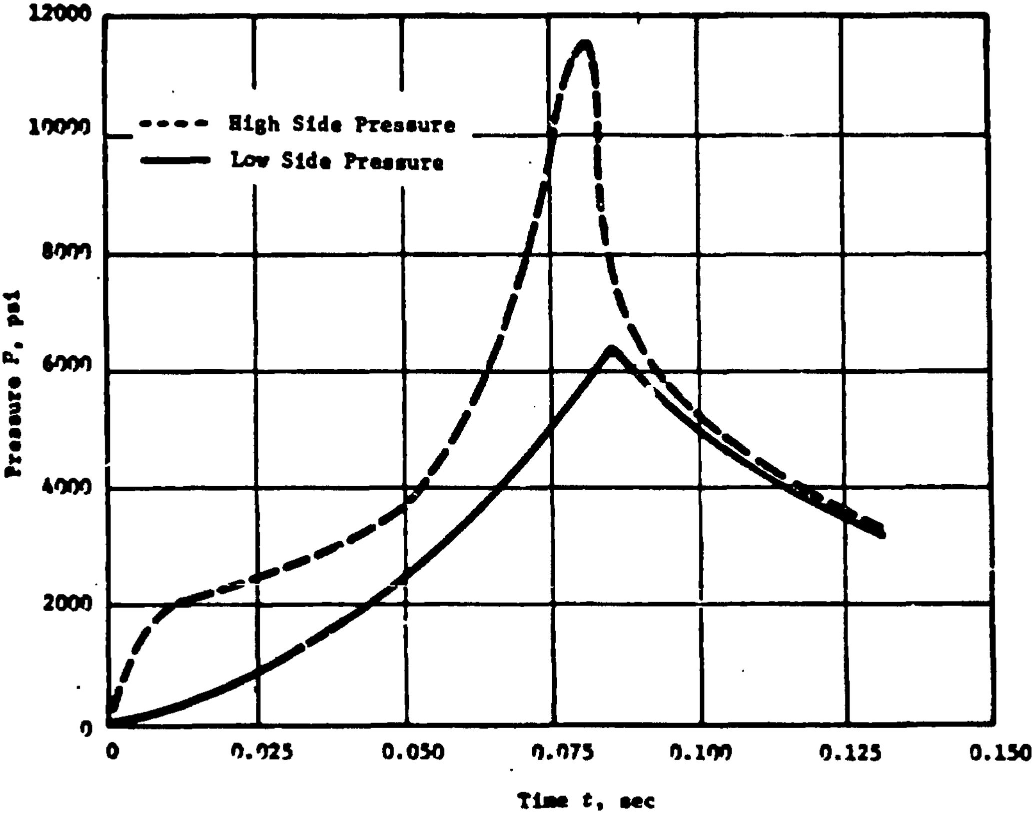


Figure 5-7. Pressure vs Time for High-Low Ballistic System

$$\left(\frac{P_e}{P_H}\right)^{2/\gamma} - \left(\frac{P_e}{P_H}\right)^{(\gamma+1)/\gamma} = \frac{\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{(\gamma+1)}\right)^{(\gamma+1)/(\gamma-1)}}{\epsilon} \qquad (5\text{-}29)$$

Numerical values for the thrust coefficient are tabulated in Refs. 3 and 4, Chapter 4. Eqs. 5-28 and 5-29 are derived in Ref. 1, Chapter 4.

5-6 GRAIN DESIGN

In the analysis of the interior ballistics of propellant actuated devices frequently it is required to design a grain that will produce a preselected performance. The approximate grain weight and geometry can be determined from the relations derived in Chapter 4. With the use of a digital computer program, however, the equations in the preceding paragraphs can be restructured to make the burn distance w the independent variable

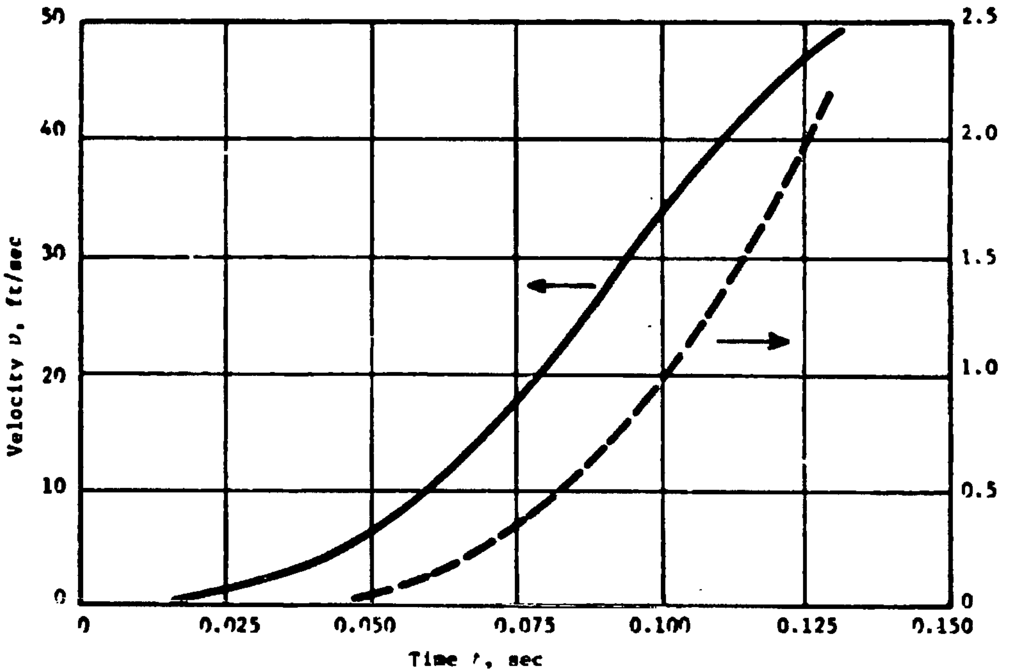


Figure 5-8. Displacement and Velocity vs Time for High-Low System

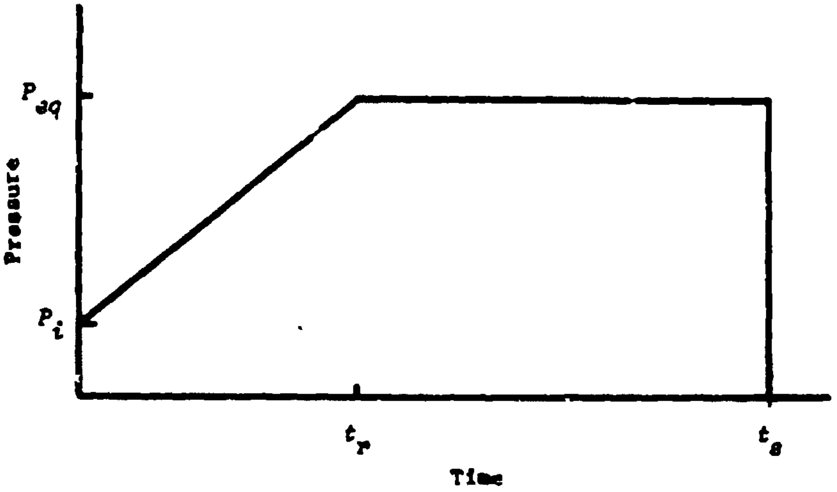
instead of the time t. A specific pressure-time or acceleration-time curve can be inputted, and the propellant surface area development then can be calculated based on this inputted curve.

Ref. 1 is a report which documents this technique as applied to a high-low ballistic system. The computer program to perform this analysis is listed in Appendix F. The form of the inputted pressure-time curve is depicted in Fig. 5-9. The program output consists of the generated interior ballistics as a function of the propellant burn distance. A least squares analysis is performed on the generated surface development-burn distance output to generate the dimensions of single-, three-, and seven-perforation inhibited grains required to produce the desired pressure-time curve. Fig. 5-10 is a sample computer output that lists the input data, condensed output, and least squares generated grain dimensions. Fig. 5-11 depicts the computer generated surface area vs burn distance relation along with the computer generated least squares approximation. The scheme for computing the grain dimensions based on the least squares data as well as the equations used in the analysis are contained in Ref. 1 and are not repeated here.

The grain design technique illustrated has been applied to direct ballistic systems but no reference is currently available. Suffice it to say, the procedure is directly analogous to that for high-low systems.

5-6 DYNAMIC RESPONSE INDEX

The physiological effect of the accelera-



P_{eq} = equilibrium pressure
P_i = initial pressure
t_r = rise time
t_s = time to stroke

Figure 5-9. Pressure-Time Input for High-Low Grain Design Program

tion-time environment on the users of aircraft emergency escape systems must be taken into account in the design of personnel escape catapults. The maximum acceleration and maximum time rate of change of acceleration have been the primary determinants in specifying the acceptable limits. Recently, however, the Dynamic Response Index (DRI) has tended to replace these criteria (Ref. 2). Simply stated, the DRI is a measure of the compression of the ejectee's spinal column and, as such, is a direct measure of the probability of injury. A correlation between the dynamic response index and the operational ejection injury rate is depicted in Fig. 5-12 (Ref. 3).

The DRI is defined according to the relation

$$DRI = \frac{\omega^2 \delta_{max}}{g} \tag{5-30}$$

where

ω = natural frequency of the spinal column, rad/sec

δ_{max} = maximum spinal compression, ft

g = acceleration due to gravity, 32.2 ft/sec^2

The instantaneous spinal compression is given by the relation

$$\frac{d^2\delta}{dt^2} + 2\rho\omega\frac{d\delta}{dt} + \omega^2\delta = a(t) \tag{5-31}$$

```
HIGH LOW GRAIN DESIGN PROGRAM

 1 BURN DISTANCE COMPUTE INTERVAL (IN) ........          .00020
 2 BURN DISTANCE PRINT INTERVAL (IN) ..........          .02000
 3 STROKE (FT) ................................         3.00000
 4 SHOT START PRESSURE (PSIA) .................        14.70000
 5 EQUILIBRIUM PRESSURE (PSIA) ................       750.00000
 6 RISE TIME (SEC) ............................          .07500
 7 ORIFICE AREA (SQ IN) .......................          .02500
 8 PISTON AREA (SQ IN) ........................         5.00000
 9 PROPELLANT LOAD (LB ) ......................       400.00000
10 ANGLE OF ELEVATION (DEGREES) ...............        90.00000
11 BURN RATE COEFFICIENT (IN/SEC*PSIA**N) ....          .11500
12 BURN RATE EXPONENT (DIMENSIONLESS) .........          .30000
13 THERMAL EFFICIENCY (DIMENSIONLESS) .........          .60000
14 RATIO OF SPECIFIC HEATS (DIMENSIONLESS) ...         1.23000
15 ADIABATIC ISOCHORIC FLAME TEMPERATURE (R) .      6000.00000
16 PROPELLANT IMPETUS (FT-LB /LB ) ............    300000.00000
17 PROPELLANT DENSITY (LB /CU IN) .............          .05900
18 INITIAL LOW SIDE PRESSURE (PSIA) ...........        14.70000
19 INITIAL LOW SIDE FREE VOLUME (CU IN) .......        35.00000
20 INITIAL HIGH SIDE FREE VOLUME (CU IN) ......         3.00000
```

BURN DIST (IN)	SURFACE AREA (SQ IN)	TIME (SEC)	LOW PRESSURE (PSIA)	HIGH PRESSURE (PSIA)	VELOCITY (FT/SEC)	STROKE (FT)
0.0000	0.0000	0.0000	14.70	1096.10	0.000	0.000
.0200	1.5421	.0211	223.04	1106.16	.361	.001
.0400	4.4388	.0421	427.29	1349.02	2.271	.029
.0600	5.3640	.0610	610.22	1967.08	5.517	.097
.0800	6.0320	.0744	720.66	2203.24	9.635	.230
.1000	6.9167	.0954	750.00	2455.68	14.066	.432
.1200	8.2224	.1114	750.00	3209.80	18.247	.591
.1400	9.3463	.1258	750.00	3912.79	22.265	.995
.1600	10.4196	.1410	750.00	4585.67	25.989	1.337
.1800	11.4026	.1544	750.00	5219.48	29.573	1.715
.2000	12.3349	.1677	750.00	5863.57	33.028	2.125
.2200	13.2248	.1804	750.00	6474.30	36.179	2.549
.2398	14.0377	.1923	750.00	7039.55	39.419	3.005

```
LEAST SQUARES ANALYSIS

     INITIAL PROPELLANT SURFACE AREA =   2.5128 SQ IN
     FINAL PROPELLANT SURFACE AREA =    14.0902 SQ IN
```

NO. OF PERFS	GRAIN DIA (IN)	PERF DIA (IN)	PERF CIRCLE DIA (IN)	GRAIN LENGTH (IN)	GRAIN WT (LBS)	BALLISTIC EFFICIENCY
1	.5013	.1037	0.0000	7.7136	.1189	.0700
3	1.2525	.1037	.6712	2.5711	.1442	.0667
7	1.7439	.1037	1.1626	1.1013	.1560	.0561

ALL OUTER GRAIN SURFACES INHIBITED

Figure 5-10. Computer Output for High-Low Grain Design Program

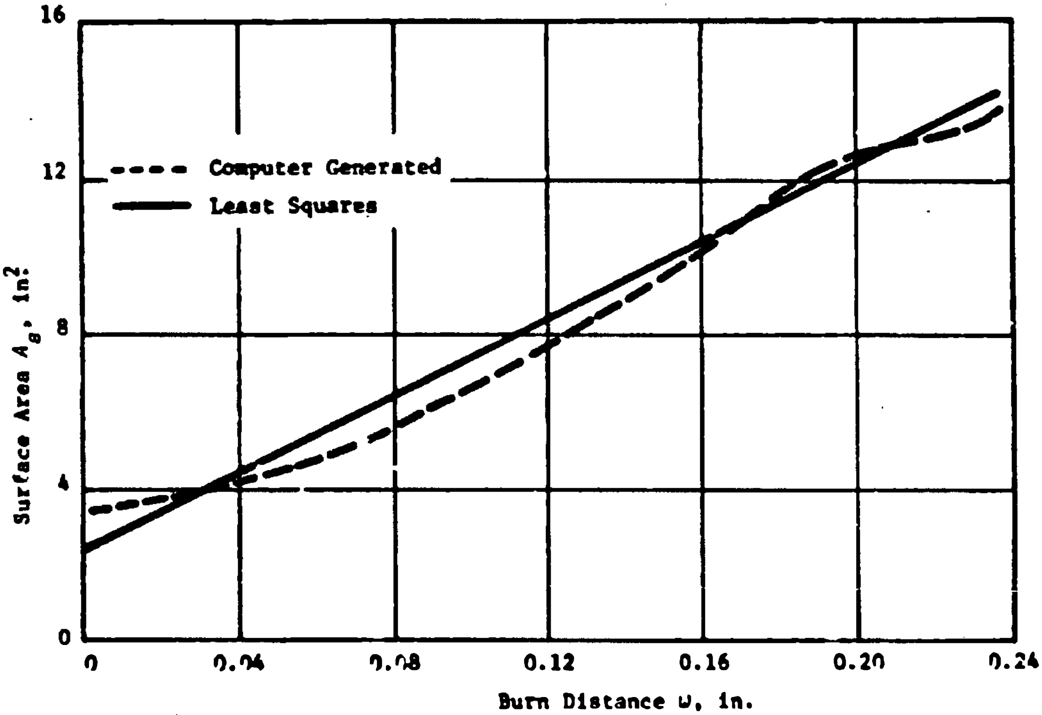


Figure 5-11. Surface Development vs Burn Distance for High-Low System

where

δ = spinal compression, ft

ρ = spinal damping ratio, dimensionless

$a(t)$ = acceleration, ft/sec^2

Essentially, the spinal column is treated as a damped harmonic oscillator where the values of ρ (0.224) and ω (52.9 rad/sec) have been determined as representative of the mean US Air Force flying population.

A DRI of 18 corresponding to about a 5% injury probability has been set as the specification limit for escape systems temperature conditioned at 70°F.

Eq. 5-31 can be solved by making a point-wise approximation to the acceleration-time output and solving it by digital computer techniques.

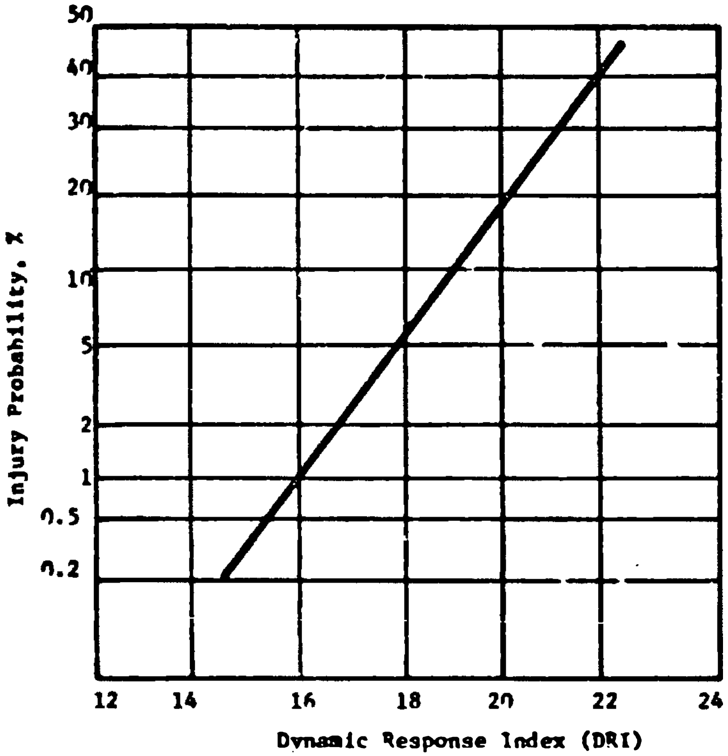


Figure 5-12. Dynamic Response Index vs Spinal Injury Rate

REFERENCES

1. L. A. DeStefano, *Automated Grain Design for Solid Propellant High-Low Ballistic Systems*, Frankford Arsenal Report M69-24-1, October 1969.

2. MIL-S-9479A(USAF), *Seat Systems, Upward Ejection, Aircraft, General Specification for*, 30 December 1969.

3. LTC C. J. Weinberg, "U.S. Air Force Exploratory Development in Impact Injury Prediction and Protection", *Proceedings of the 8th Annual Survival and Flight Equipment Association Symposium*, 28 Sept-1 Oct 1970.

CHAPTER 6

DESIGN EXAMPLES

6-0 LIST OF SYMBOLS

a_m = maximum acceleration, ft/sec^2

$\dot{a}$ = rate of change of acceleration, ft/sec^3

A = area, in.^{2}

A_p = effective area of booster tube, in.^{2}

b = burning rate coefficient, in./sec-psi^n

C = charge weight, lb

d = minor diameter of male thread (min), in.

D = circumferential distance between slots, in.

F = force, load; lb

F = propellant impetus, ft-lb/lb

$\bar{F}_r$ = average resistive force, lb

g = acceleration due to gravity, ft/sec^2

h_t = heat loss per unit hose area, ft-lb/in.

I = impulse, lb-sec

I_{sp} = specific impulse, lb-sec/lb

k = radius of gyration, in.

L = length of thread engagement, in.

L = length of piston, in.

n = pressure exponent, dimensionless

P = maximum internal pressure, psi

P_m = peak pressure, psi

P_t = pressure at end of hose, psi

R = major radius of female thread (max), in.

s = stroke, ft

S_t = tensile strength, psi

S_s = shear strength, psi

S_t = hose surface area, in.^{2}

t = sleeve wall thickness, in.

t_s = stroke time, sec

v = terminal velocity, ft/sec

V = locked shut volume, in.^{3}

V_c = initiator volume, in.^{3}

V_o = hose volume, in.^{3}

w = burn distance, in.

W = propelled weight, lb

W^* = wall ratio, dimensionless

β = heat loss factor, dimensionless

γ = propellant ratio of specific heats, dimensionless

6-1 GENERAL

6-1.1 PURPOSE

This chapter provides examples of the design of stroking devices and a gas-generating device which use the principles discussed in preceding chapters.

6-1.2 SCOPE

The devices chosen to illustrate these principles are the M38 Catapult, the M3A3 Thruster, and the M113 Initiator. The M38 Catapult is a rocket-assisted catapult that provides the sustaining thrust to increase ejection height without exceeding personnel acceleration maximums. The M3A3 Thruster is a typical thruster with a bypass port at the end of its stroke. The M113 Initiator is one of a new family of subminiature gas actuated initiators.

6-2 M38 CATAPULT

6-2.1 GENERAL

The M38 Catapult is a rocket-assisted two-tube telescoping device, designed for upward and forward ejection of a 383-lb seat-man combination from an aircraft in the event of an emergency.

6-2.2 DESIGN REQUIREMENTS

The design requirements for the M38 Catapult specified the following performance and physical characteristics:

(1) Performance Characteristics:

Catapult (booster section)	
Stroke	34. in.
Max acceleration (at 70°F)	18. g
Velocity, at separation (at 70°F)	47. fps
Max rate of change of acceleration (at 70°F)	300. g/sec
Stroke time (at 70°F)	0.170 sec
Firing method	Gas actuation
Rocket (sustain section)	
Action time, max (at 70°F)	0.410 sec
Impulse (resultant at 70°F)	1250. lb-sec
Pressure, average	3200. psi
Ignition delay, max (at 70°F)	0.025 sec
Nozzle angle adjustment range	38° 50' to 52°

(2) Physical Characteristics:

Overall length	42.6 in.
Structural loads:	
Tension	4000. lb min
Compression	8000. lb min
Total weight (loaded)	35.0 lb
Propelled weight (approx 50 percentile seat-man combination)	383 lb
Temperature limits	−65° to +165°F
Mounting	
Airframe	Trunnion at lower end
Seat	Male clevis at upper end

6-2.3 FIRST-ORDER APPROXIMATIONS

Stroke length, stroke time, peak pressure, charge weight, and grain geometry are calculated in the manner described in par. 4-2, Chapter 4. The equation numbers appearing in the text refer to the equations presented in Chapter 4.

6-2.3.1 STROKE LENGTH

By using Eq. 4-6 and the values specified in the design requirements, the approximate stroke length necessary to meet the requirements may be found. The maximum stroke often is specified, since the airframe does have a limit to the maximum stroke that may be guided and it is undesirable to attempt to eject an aircraft seat without guiding its path out of the aircraft. If the maximum stroke is not specified, it may be obtained in the following manner. The overall length of the catapult is 42.6 in. (specified), so that the maximum stroke which may be obtained with a single stroking tube is less than 42. in. By substituting the values for velocity (specified), maximum acceleration, and rate of change of acceleration (approximations) in Eq. 4-6, the stroke length s is estimated as follows:

$v = 47$ ft/sec; $a_m = 15g$; $\dot{a} = 150$ g/sec

$$s = \frac{v^2}{2a_m} + \frac{a_m^3}{24\dot{a}^2} \tag{4-6}$$

$$s = \frac{(47)^2}{(2)(15 \times 32.2)} + \frac{(15 \times 32.2)^3}{24(150 \times 32.2)^2}$$

$$= 2.48 \text{ ft} = 30 \text{ in.}$$

With these values established, the design for the booster section continues.

6-2.3.2 STROKE TIME

Using Eq. 4-5 the values of velocity, (specified) maximum acceleration, and rate of change of acceleration (approximations), the time t_s is estimated as follows:

$$t_s = \frac{v}{a_m} + \frac{a_m}{2\dot{a}} = \frac{47}{15 \times 32.2} \tag{4-5}$$

$$+ \frac{15 \times 32.2}{2(150 \times 32.2)} = 0.147 \text{ sec}$$

6-2.3.3 PEAK PRESSURE

To use Eq. 4-7, either the peak pressure or the booster tube diameter of the catapult must be known. No diameter is specified for the booster tube, but P_m = 7000 psi pressure is specified for the booster section of the catapult. By substituting this value and W = 383 lb in Eq. 4-7, the effective area A_p (a function of diameter) of the booster tube is found as follows:

$$P_m = \frac{Wa_m}{gA_p} \tag{4-7}$$

$$A_p = \frac{383 \times (15 \times 32.2)}{7000 \times 32.2} = 0.82 \text{ in.}^2$$

This corresponds closely to a diameter of 1 in.

Peak pressure and acceleration occur upon separation of the booster tube and the launcher tube. (In the M38 Catapult, the booster tube and motor tube travel together.) Therefore, the outside diameter of the booster tube determines the effective area, and from this calculation the diameter is 1.0 in.

6-2.3.4 PROPELLANT CHARGE WEIGHT

The propellant charge weight for the booster section of this catapult may be estimated by use of Eq. 4-14.

$$C = 4.9 \times 10^{-5} Wv^2 \text{ grams} \tag{4-14}$$

Substituting W = 383 lb and v = 47 fps

$$C = (4.9 \times 10^{-5}) \times 383 \times 47^2 = 41.5 \text{ grams}$$

Fig. 4-2 is a plot of the ratio of propellant charge weight to propelled load for propellant actuated stroking devices. By using this figure, the approximate ratio of propellant weight to propelled weight for a catapult with a terminal velocity of 47 fps is 0.11 gram/lb. Since the propelled weight W is 383 lb, the propellant charge is

$$\frac{C}{W} = 0.11$$

$$C = 0.11 \times 383 = 42.13 \text{ grams}$$

To estimate the rocket grain weight required for the rocket section of the example catapult, Eq. 4-31 is used. Also, as per Chapter 4, par. 4-2.3.3, it is stated that in practice the specific impulse has a value on the order of 200 lb-sec/lb, then:

$$I = I_{sp} C \text{ , or}$$

$$C = \frac{I}{I_{sp}} = \frac{1100 \text{ lb-sec}}{200 \text{ lb-sec/lb}} = 5.5 \text{ lb} \quad (4\text{-}31)$$

6-2.3.5 GRAIN GEOMETRY

(1) Based on experience with previous type devices: the grain to be used for the booster section of this catapult should be cylindrical with a single perforation. The thickness of the web is estimated by using Eq. 5-1. Peak pressure P_{max} and stroke time t_s have already been estimated.

$$w = bP^n_{max} \, t_s \quad (5\text{-}1)$$

which for P_{max} = 7000 psi, t_s = 0.147 sec, and for H8 propellant:

$$w = 0.26 \text{ in.}$$

(2) The web estimated can be used in the initial charge, but it may have to be modified during the charge establishment firings, since it is based on an approximation, i.e., stroke time.

6-2.4 COMPONENT ARRANGEMENT

The component arrangement is used to place sufficient stroking members within the required envelope to give the required stroke, and to estimate the cartridge size and internal volumes. Basically, this requires the volumes at the beginning and at the end of stroke in order to complete the calculations.

The arrangement of the catapult includes the following components: head, motor tube (outside tube), booster and launcher tubes, firing mechanism, mount (lower end), swivel nozzle, locking mechanism, a track (whereby changes in the seat position are transmitted to adjust the nozzle angle), propellant grain (for rocket motor), and a cartridge.

The initial arrangement starts with the specified overall length (42.6 in.) and assumes a 1.0 in. outside diameter for the booster tube previously estimated. (In the rocket-assisted catapult, the launcher and booster tubes are analogous to the telescoping and inside tubes of the conventional catapult.) The necessary components such as the cartridge, firing mechanism, locking mechanism, and stroking member are then fitted to the layout. As previously mentioned, the M38 Catapult requires a single stroking tube. For a first approximation, it is assumed that the launcher, booster, and motor (outside) tubes are approximately 36 in. long, thus providing the necessary stroke.

After the tubes are placed in the motor

tube (3-1/8 in. outside diameter, specified) and space is provided for the firing mechanism and the locking mechanism, the initial and final volumes are calculated. It is desired to make the ratio of final volume (expansion ratio) approximately 2. Assume that the launcher and booster tube are of equal lengths, i.e., 36. in. long. Also, the booster tube (in this case the stroking tube) fits inside the launcher tube. As previously determined, (par. 6-2.3.3), the outside diameter for the booster tube is approximately 1 in. Again, assume an inside diameter of 13/16 in. (3/32 in. wall thickness) for this tube, the initial volume is approximately 19 in.^{3} The final volume is approximately 47 in.^{3} The expansion ratio calculated for the assumed device shown in Fig. 6-1 is approximately 2.5.

The catapult (Fig. 6-2) is ignited by an initiator connected by a flexible hose. The functioning of the initiator produces the gas pressure that flows through the hose, exerting a force on the catapult firing pin. Pressure behind the firing pin increases until it is sufficient to shear the shear pin, driving the firing pin forward to impinge on the booster cartridge primer. This action initiates the firing of the booster phase. The primer ignites the booster charge contained in the cartridge. The booster tube gas pressure moves a spring loaded piston, thereby permitting locking keys to be cammed inward, unlocking the unit. Continued production of booster gas propels the rocket motor and seat vertically. At the point of booster tube separation, hot booster gases are introduced into the motor chamber and ignite the rocket propellant grain. The burning propellant grain produces gas at a high rate, pressurizing the motor chamber. The resulting pressure acts on a piston that rotates the nozzle to a preset position, thus providing thrust that propels the seat and occupant upward and forward. The nozzle angle, which is controlled by seat position, is adjustable from 39 deg to 52 deg so as to direct the rocket thrust through the center of gravity of the seat-man combination.

The cartridge is designed to fit into the booster tube, and contains sufficient propellant to meet performance requirements. The designer, in conjunction with the ballistician, decides on the cartridge size to be used. In the example being considered, it is determined that the case will be 7/8 in. diameter and that approximately 40 grams of propellant will be used. The density for the propellant to be used is 0.066 lb/in.^{3} It has been previously (par. 6-2.3.4) determined that approximately 40 grams of propellant would be required. This would require a volume of 1.3 in.^{3} A cartridge case of approximately 7/8 in. diameter and approximately 9 in. long would provide this volume.

Additional volume must be provided for a cartridge head. Incidentally, this cartridge head is of a new and simplified design. The top of the head incorporates a cavity that provides a positive seat for the primer. The base of the head under the primer cavity is machined thin (0.006 to 0.010 in.) to insure that it will blow when the primer fires. The igniter (black powder commonly is used as an igniter in propellant actuated devices) is contained in a cavity in the body of the head. The approximate igniter charge may be found using the method described in Chapter 4. Also, a rule of thumb has evolved whereby to estimate the igniter charge use about 40 grams of black powder per pound of propellant. In par. 6-2.3.4, it was estimated that approximately 41.5 grams or 0.09 lb of propellant is required. Then the igniter charge for this catapult is:

$$0.09 \text{ lb} \times 40 \text{ gram/lb} = 3.6 \text{ grams or } 55 \text{ grains}$$

This estimated igniter charge as well as the estimated propellant charge may have to be adjusted, depending on the results of firings between $-65°$ and $200°$F.

The igniter charge is retained in the cavity by a sealing disc, which in turn is held in place

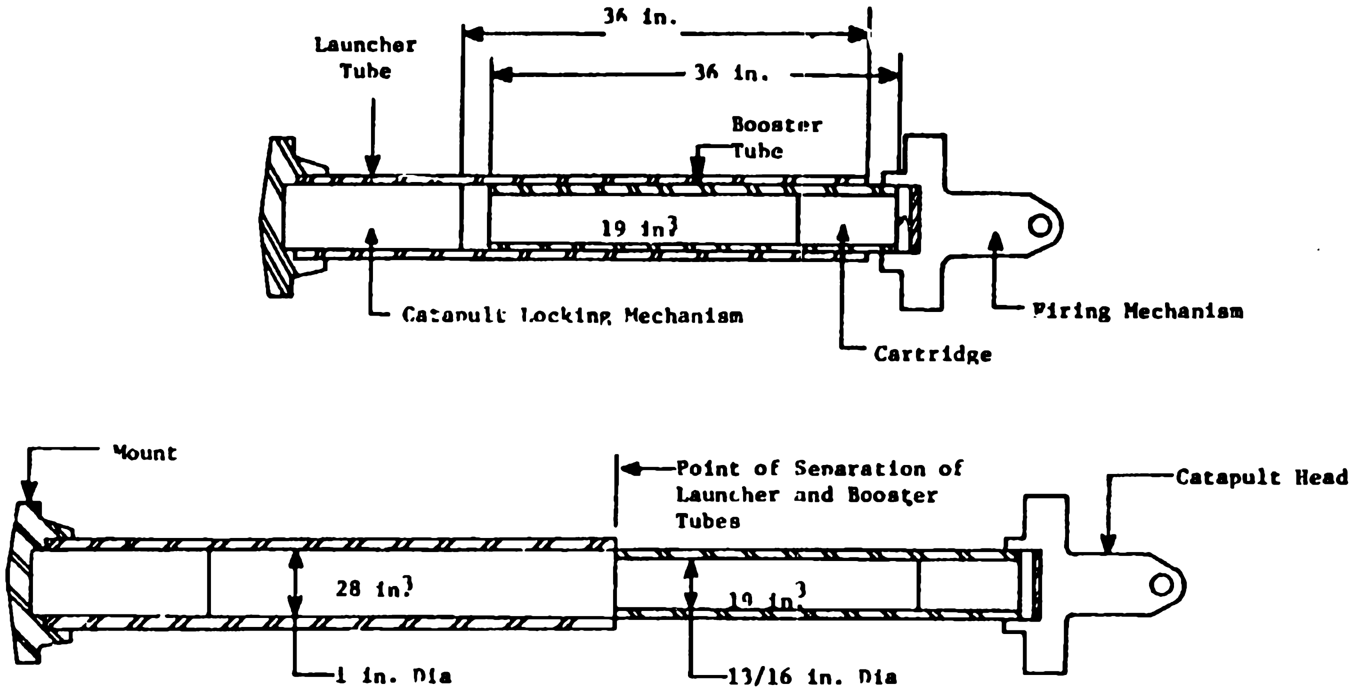


Figure 6-1. Catapult Arrangement

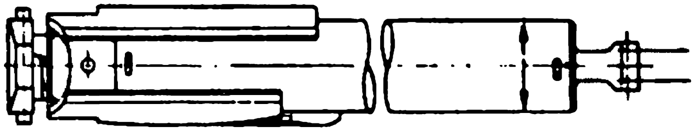


Figure 6-2. Catapult, Aircraft Ejection Seat, M38 Assembly

by a retaining ring. Fig. 6-3 shows the XM270 Cartridge.

6-2.5 COMPONENT DESIGN

6-2.5.1 TUBES

The catapult tubes act as pressure chambers and the stroking members. The booster tube, as previously mentioned, fits inside the launcher tube. The inside diameter, and the tube length, are such as to provide the initial volume to satisfy the expansion ratio determined in par. 6-2.4. One end of the exterior of this tube incorporates a groove to accept an O-ring. This ring provides the seal to prevent prior leakage of propellant gases being generated therein. At the other end, the inside diameter is increased to accommodate the cartridge dimensions estimated in par. 6-2.4. The exterior at this end incorporates a male thread and two blind holes. The thread is the means whereby the booster tube is assembled to the catapult head. Nylon pellets pressed into the blind holes serve as a locking agent for the tube.

The launcher tube acts as a booster gas expansion chamber and a guide for the moving booster tube. Again, here the inside diameter and tube length are such as to satisfy the final volume to give the expansion ratio determined in par. 6-2.4. One end contains the catapult locking mechanism. The exterior of this end incorporates a male thread and two blind holes. The thread is the means for assembling the tube to the catapult mount. Nylon pellets, pressed into the blind holes, serve as a locking agent for the tube. Two slots, 180 deg apart, are machined in the tube body, to accommodate the catapult locking keys.

The motor tube acts as the pressurizing chamber for the rocket motor. At one end, it is fastened to the catapult head, and the other end is fastened to the nozzle retainer. This item is a component of the mechanism which permits the catapult nozzle to rotate to a preset position (see par. 2-4).

The sizes of the tubes are calculated using the equation of Von Mises-Hencky, which are plotted in Fig. 4-5. Catapults generally are not designed to withstand locked-shut pressures; therefore, the peak pressure assumed in the first order approximations (7000 psi) may be used in the calculations.

It was previously assumed that the booster tube had a 1.0 in. outside diameter, and a 13/16 in. inside diameter. But, the outside diameter of the tube must be large enough to permit incorporating a male thread (see par. 6-2.5.1). Then, a tube with an outside diameter of 1-1/8 in. and 5/32 in. wall thickness is selected. Assuming that a high strength seamless steel tube is to be used, the pressure ratio (P/Y) is:

$$\frac{P}{Y} = \frac{7000 \times 1.15^{*}}{135{,}000} = 0.0596$$

*A 1.15 Safety Factor is used since this is a cylindrical part which must withstand internal pressure without rupturing (See par. 4-3.2).

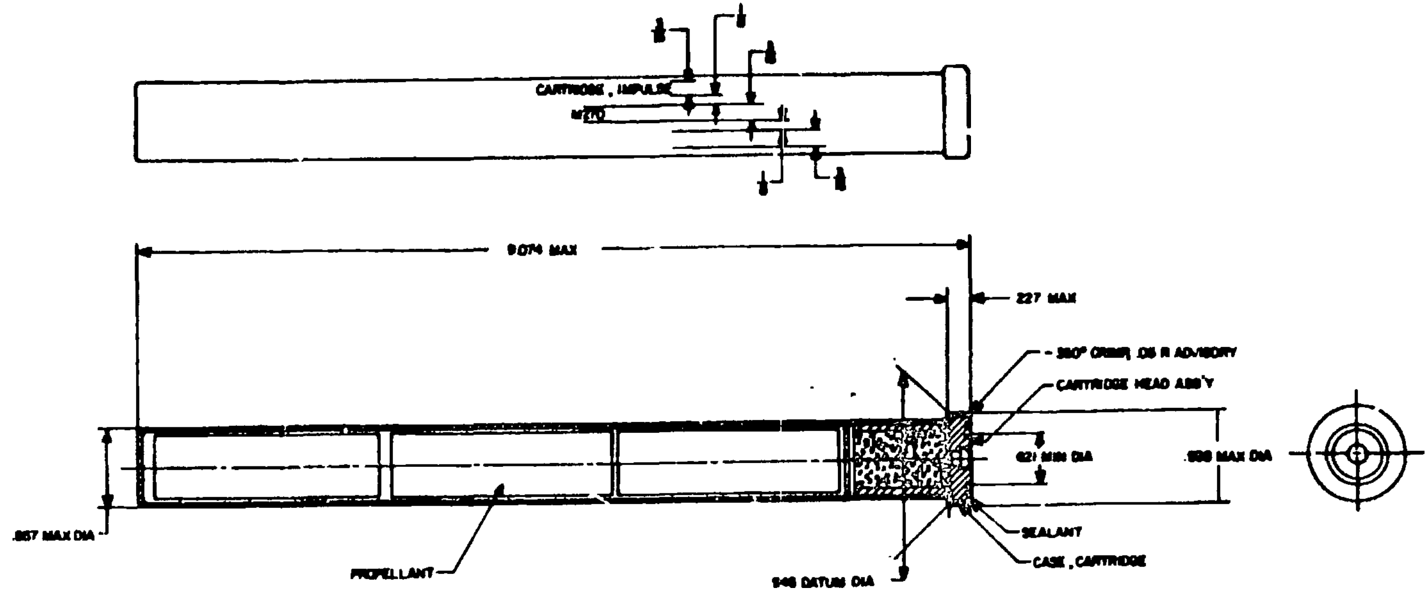


Figure 6-3. Cartridge, Impulse, M270 Assembly

Using Sheet 1, Fig. 4-5 and the ordinate of the intersection of pressure ratio 0.060 and the biaxial stress curve (catapults are subjected to radial and tangential stresses but not to longitudinal stresses), the wall ratio is found to be 1.064. Since wall ratio W' is the ratio of outside diameter to inside diameter, the outside diameter is calculated as follows:

$$W' = \frac{OD}{ID} = 1.064$$

therefore:

$$OD = W' \times ID = 1.064 \times 0.8125$$

$$= 0.8645 \text{ in.}$$

As previously mentioned (par. 6-2.5.1) an O-ring is used at one end as a seal. The dimension for the bottom of this machined groove is 0.890 in. Therefore, the tube selected would be suitable. As designed, the outside diameter of the tube is slightly smaller than the minor diameter of the thread for a short distance from the tube end to the thread. Also, beyond the thread the outside diameter has been reduced to a dimension (approximately 1.0 in.) comparable to the outside diameter previously determined.

The launcher tube is very similar in design to the booster tube. That is, the inside diameter is symmetrical throughout, except for a short distance at one end, which is machined to accept the "release" component of the catapult locking mechanism. Also at this end a thread is incorporated on the exterior of the tube (see par. 6-2.5.1). Again near the thread, two slots, 180 deg apart, are machined through the tube wall, to permit the assembling locking keys (see par. 6-2.4). It was previously determined that the outside diameter for the booster tube is 1.0 in. Since this tube fits inside the launcher tube, then the inside diameter is estimated as 1.0 in. Then, using wall ratio determined previously (1.064)

$$OD = W' \times ID = 1.064 \times 1.0 = 1.064 \text{ in.}$$

The tube selected is approximately 1.25 in. OD with a 1/8 in. wall. The OD would provide the material required to incorporate the thread. As designed the outside diameter of the tube is slightly smaller than the minor diameter of the thread for a short distance from the tube end to the thread. Also, beyond the thread, the outside diameter has been reduced to a dimension (1.13 in) slightly larger than the calculated OD shown.

The motor tube was specified to be 3-1/8 in. outside diameter, with a minimum wall thickness of 0.087 in. With this information, it is determined that the wall ratio W' is 1.059. Refer to sheet 1 of Fig 4-5; it is determined that the pressure ratio P/Y is 0.056. Therefore:

$$Y = \frac{1100 \times 1.15^{*}}{0.056} = 22{,}500 \text{ psi}$$

Since the yield strength for the material selected for this tube is 100,000 psi, it provides a greater factor of safety than the required 1.15.

6-2.5.2 MOUNT (TRUNNION)

The mount shown in Fig. 6-4 is an alloy steel component in which the lower portion is circular in shape. Two pivots, 180 deg apart, are incorporated on the rim. This positions them perpendicular to the longitudinal axis of the catapult. A short flat, parallel to the centerline of the pivots, also is incorporated on the rim. The bottom of the mount is bevelled toward a narrow flat surface, also parallel to the centerline of the pivots. The other side of the mount is machined in the shape of a truncated cone. The base of this cone is a narrow flat surface extending out to the rim. A slot to accept an O-ring, which acts as a gas seal between the mount and the nozzle, is machined into the conical surface

*Safety Factor

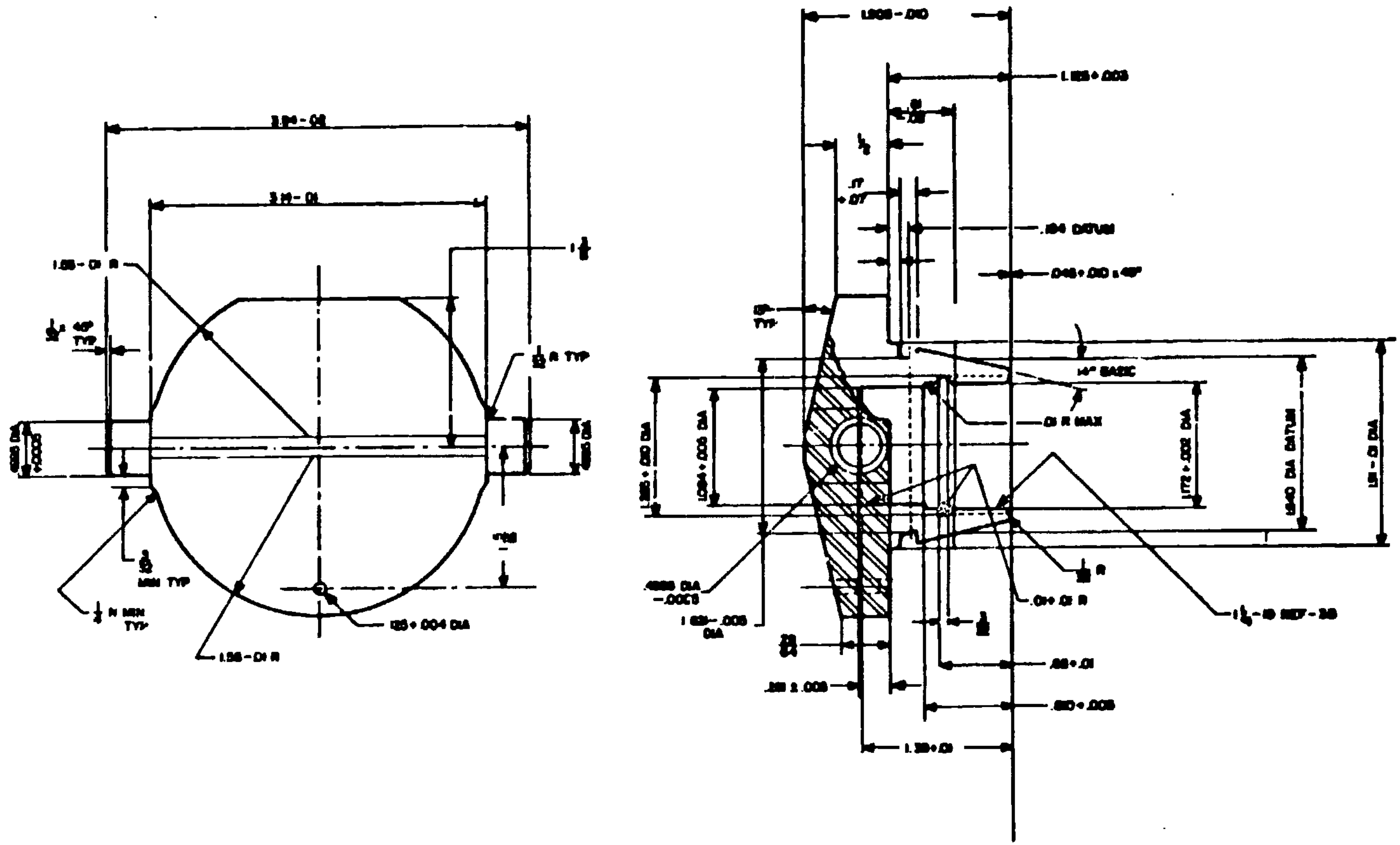


Figure 6-4. Mount

near the cone base. A cavity in the mount accommodates the catapult locking mechanism. A thread to accept the launcher tube is included at the outer end of the cavity.

The mount pivots are integral with the mount. The diameter of these pivots is computed on the basis of shear strength. The maximum static load applied to the pivots, according to the design requirements, is 8000 lb. The maximum kinetic load F applied to the pivots, resulting from operation of the catapult, is computed by using Newton's Law:

$$F = \left(\frac{W}{g}\right) a_m, \text{lb} \tag{6-1}$$

where

W = propelled weight, lb, g = acceleration due to gravity, ft/sec^2

a_m = maximum acceleration, ft/sec^2

Since W = 383 lb and a_m = 15g,

$$F = \frac{383}{32.2}(15 \times 32.2) = 5745 \text{ lb}$$

Since the kinetic load is less than the static load specified, 8000 lb in the design requirements the static load is used in calculating the size of the mount pivots. The mount is made of 4130 steel having a tensile strength of 125,000 psi. Assume that the shearing strength is 60% of the tensile strength or 75,000 psi; the pivot size is calculated as follows:

$$A = \frac{F}{S_s} = \frac{8000 \times 2^*}{75{,}000} = 0.213 \text{ in.}^2$$

where

S_s = shearing stress, psi

F = load, lb

A = area in shear, in.^{2}

The preceding calculation indicates that the shear area required to support the load is 0.213 in.^{2} The pivot diameter design dimension chosen is 0.5 in. with a 0.196 in.^{2} cross-sectional area. Since the design of the mount calls for two pivots, the total shear area of 0.392 in.^{2} is more than adequate to support the load.

Good mount (trunnion) design requires that the section of metal adjoining the pivots be sufficiently thick to prevent the pivot from being pulled out by the "roots". The size of the fillet radius must be a compromise because the mount bearing loads must be taken close into the mount body so as to eliminate excessive bending loads. However, a fillet is required to minimize stress concentrations in the corner.

The internal thread in the mount and the mating exterior thread at the end of the launcher tube may be designed in accordance with the specifications in Handbook H28 (1969) Part I SCREW-THREAD STANDARDS FOR FEDERAL SERVICES. Since the launcher tube has a thin wall, (See par. 6-2.5.1), an extra-fine, 1.25 in. diameter 18 pitch thread has been chosen. To determine the length of the thread required, Eq. 4-37 is used:

$$L = \frac{3P_m R^2}{S_s d} \tag{4-37}$$

$$L = \frac{3 \times 7000 \times (1.262/2)}{0.6 \times 150{,}000 \times 1.1742} = 0.125 \text{ in.}$$

The calculations show that approximately two full threads would hold the design maximum thrust pressure of 7000 psi. As designed, there is sufficient thread in the mount and on the mating male thread on the launcher tube.

*2 is the safety factor used for structural members

6-2.6.3 HEAD

The head (Fig. 6-5) is the component which houses the firing mechanism. It is cylindrical at one end and rectangular at the other. At the cylindrical end, an internal thread accommodates the booster tube, and a slot just beyond the thread accommodates a sealing O-ring. A cavity beyond the slot accommodates the cartridge head and a plate. The booster tube carrying the cartridge is screwed into the head until the cartridge head rests against the plate. The outside diameter of the tube slides through the O-ring, previously placed in the head, thereby providing a gas seal. A hole, behind the plate, extends into the rectangular portion of the head. This hole carries the firing pin. A blind tapped hole, with a smaller hole following, extends into the hole with the firing pin. This is machined through a flat of the rectangular section of the head. A shear pin in this hole and in a matching hole in the firing pin, holds the firing pin in place. A headless set screw in the tapped hole prevents loss of the shear pin. A gas inlet port is provided in the opposite

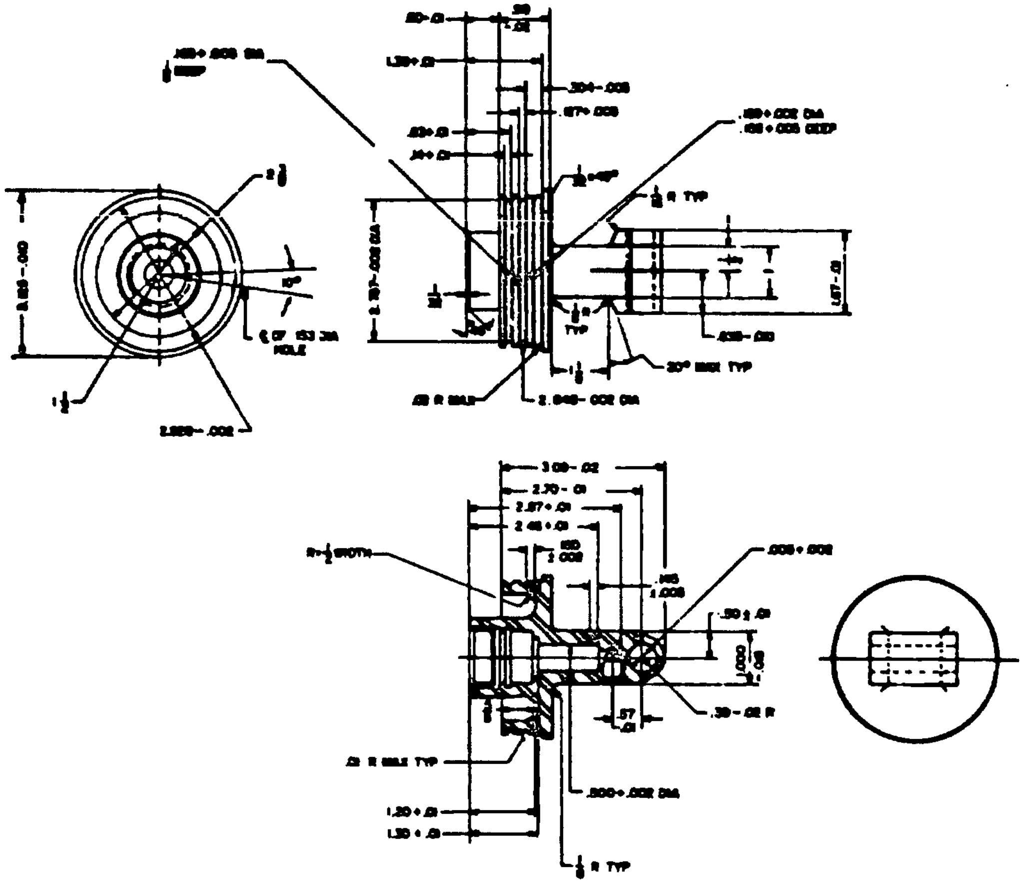


Figure 6-5. Head

flat. A mounting hole located near the end of the rectangular portion of the head permits assembly of the catapult separating tubes to the seat.

The head must be strong enough to contain the gas pressure supplied to the firing mechanism contained in the head. Also the area around the mounting (Fig. 6-6) must be strong enough to withstand the 4000 lb tensile load placed on the mounting.

The minimum thickness of material in the wall of the mounting hole is [(0.39 – 0.02) – (0.500 + 0.002)/2] or 0.119 (see Fig. 6-6). The area A in tension is therefore:

$$A = 1.61 \times 0.119 = 0.192 \text{ in.}^2$$

The head is to be made from a steel casting of class 150-125, therefore, the tension load required to tear the material is calculated as follows:

$$F = S \times A, \text{lb}$$

$$= \frac{125{,}000 \times 0.192}{2^*} \qquad (6\text{-}3)$$

$$F = 12{,}000 \text{ lb}$$

It is obvious from this calculation that the head as designed can easily withstand the 8000 lb specified tensile load.

6-2.6.4 LOCKING MECHANISM

The catapult locking mechanism (Fig. 6-2) consists of two alloy steel keys located in a plane perpendicular to the longitudinal axis of the catapult. When assembled, the keys rest on a boss (Fig. 6-2) on the retainer and extend upward through the slots in the launcher tube, thereby locking the catapult. The keys (Fig. 6-7) are subject to a shearing stress. By use of the stress Eq. 6-2, the area A required for the latches is calculated as follows:

$$A = \frac{F}{S_s}$$

where

F = load, lb

S_s = shear stress, psi

$$A = \frac{7000 \times 2^*}{90{,}000} = 0.155 \text{ in.}^2$$

As mentioned the design provides two locking keys. This provides more than the required cross-sectional area.

*The factor of safety for structural members

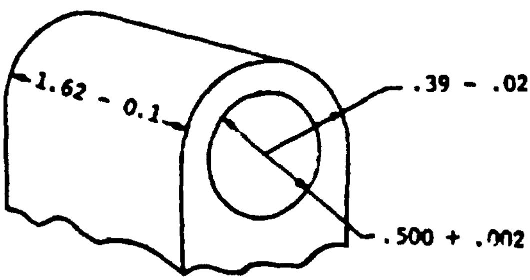


Figure 6-6. Enlarged View of Head Mounting Hole

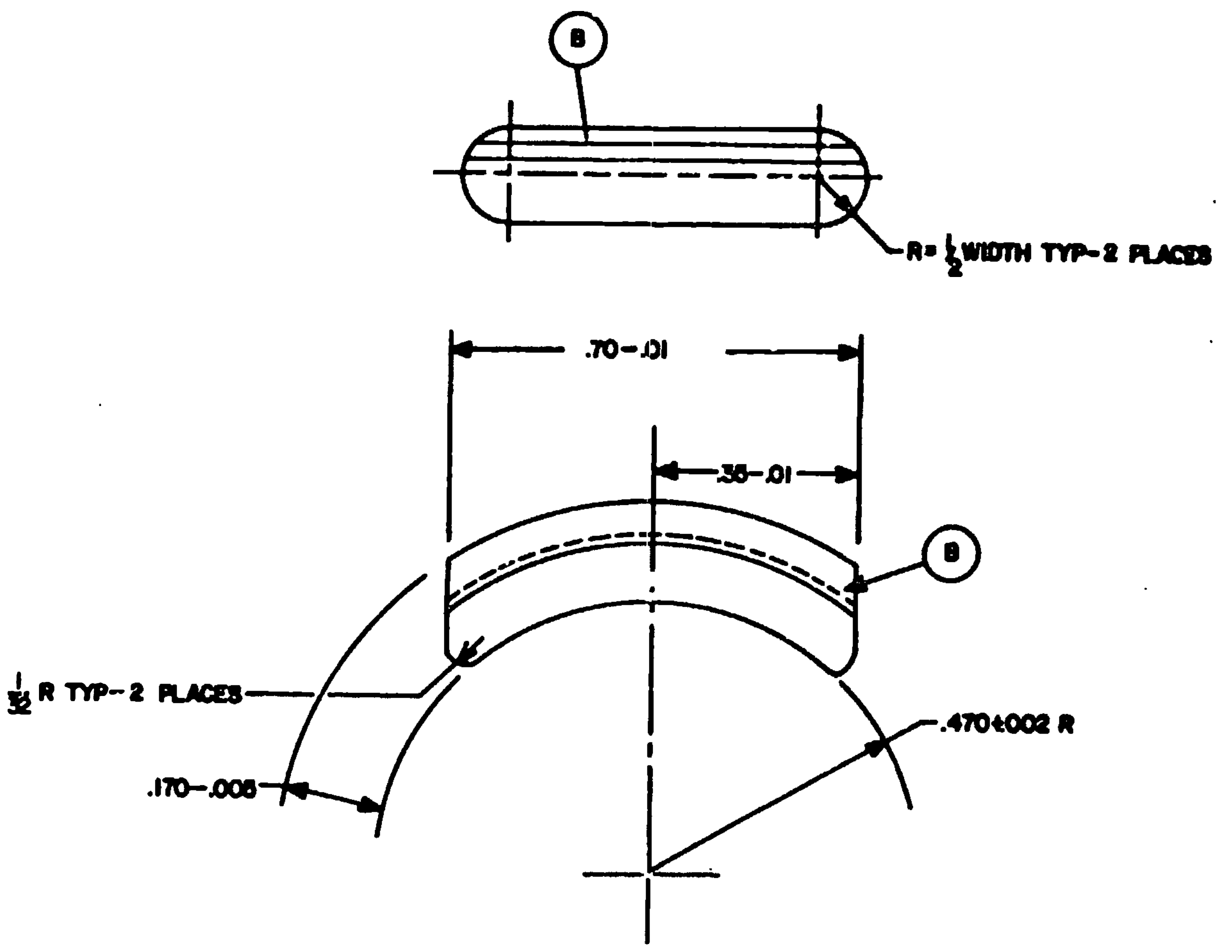


Figure 6-7. Key

6-2.5.5 FIRING MECHANISM

The firing mechanism is contained in the catapult head. It consists of the firing pin firing pin shear pin, and a plate (see Fig. 6-2). The firing pin is a cylinder that has a groove for an O-ring for sealing purposes, and a shear pin hole. The end, from which the pin tip protrudes, incorporates two blind holes. This is the means by which the firing pin is rotated to align the shear pin hole with the hole in the head (Fig. 6-8).

The size of the shear pin for the firing pin should be such that it will shear at the proper pressure build-up (see par. 6-2.4), yet should not fail in drop tests for the item.

The plate acts as a firing pin stop and thereby prevents primer penetration. The small hole in the plate permits the firing pin tip to protrude and strike the cartridge primer. The length of this protrusion is controlled, by limiting the thickness of the plate.

6-3 M3A3 THRUSTER

6-3.1 GENERAL

The M3A3 Thruster is a component part of an aircraft escape system. Its function is to release the control column stowage spring and to supply sufficient energy to operate the seat actuator disconnect.

6-3.2 DESIGN REQUIREMENTS

The design requirements for the M3A3 Thruster are:

Envelope Configuration	Similar to that for the T3 Thruster
Lock Requirements	Initial lock required
Locked-shut	The thruster shall withstand lock-shut firings without mechanical failure
No-load	The piston shall not separate from the body when the thruster is fired without load
Operating Temperature Range	-65° to $+160^\circ$F
Stroke	1.5 in.
Firing method	Gas actuation
Bypass requirements	
Bypass pressure at end of 4 ft length of No. 4 hose	600 psi min
Propelled weight (vertical)	550 lb

6-3.3 COMPONENT ARRANGEMENT

Since the envelope dimensions are specified, the stroke is short, and the load to be propelled is light; it is expedient to fit the necessary components into the envelope and then, with a better knowledge of the volumes involved, estimate the charge.

All components of the thruster may be mounted on a single longitudinal axis. A typical gas firing mechanism, described in par. 4-5.4.2, (Fig. 4-13) is fitted to the envelope near the gas entry port. A cartridge, the exact size of which is still undetermined, is placed in front of the firing mechanism. A piston then is fitted into the remaining space in the envelope. A locking mechanism similar to the one described in par. 4-5.5 (Fig. 4-15) is fitted to the piston. Fig. 6-9 shows the layout of the components.

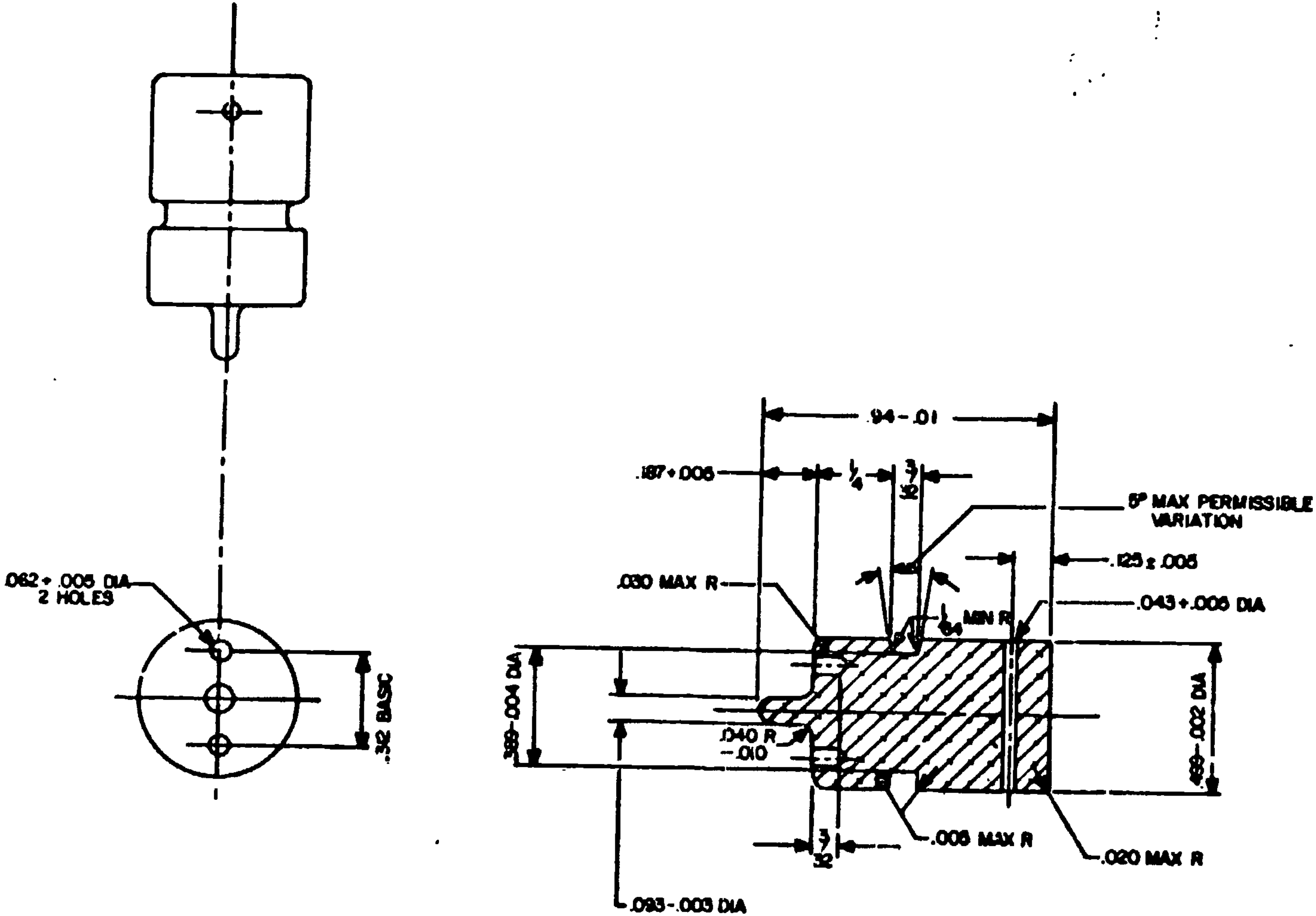


Figure 6-8. Firing Pin

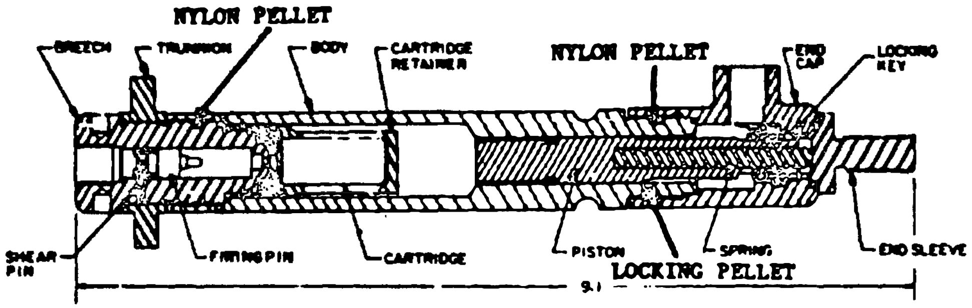


Figure 6-9. Thruster Component Layout

The thruster operates in the following manner. Propellant gas from an initiator enters the gas inlet port and exerts pressure on the firing pin. When sufficient pressure is built up behind the firing pin, the shear pin is sheared and the firing pin is propelled toward the cartridge, where it strikes the primer. The primer fires the igniter charge (black powder) which ignites the propellant in the cartridge. Propellant gas, generated by the burning propellant, causes the cartridge case to rupture. The propellant gas then flows into the volume behind the piston. Gas pressure on the piston forces it forward, compressing the spring and causing the locking keys through camming action to move out of the annular groove in the end cap into the piston unlocking groove. The piston continues to move forward until it contacts the end sleeve. At this point, the piston transmits the force through the end sleeve to the load. As the piston nears the end of its stroke, the O-ring around the piston enters an enlarged section in the end cap, permitting propellant gas to escape around the piston and through the bypass port while the piston completes its stroke.

6-3.4 FIRST-ORDER APPROXIMATIONS

Before workhorse models of the thruster can be fabricated, using the tentative component arrangement already discussed, the propellant charge must be estimated so that a cartridge size can be approximated. The pressure needed to produce the desired thrust with the selected piston is used to establish the wall thicknesses and other component dimensions.

6-3.4.1 THRUSTER

The thruster is designed to supply gas at a pressure of 1,000 psi to a 0.062-in.^{3} chamber at the end of 4 ft of hose after moving a 550 lb weight vertically upward for 1.5 in.

6-3.4.2 PISTON ASSEMBLY

The tentative diameter of the piston is 0.50 in., with a corresponding area of 0.20 in.^{2}. To raise the 550-lb load, the minimum pressure required is 2,750 psi. (The actual pressure should be at least twice this, to allow for such effects as temperature and friction.) The volume swept by the moving piston is 0.20 X 1.5 or 0.30 in.^{3} The initial free volume of the cylinder, taking into account the cartridge retainer, etc., is 0.98 in.^{3} The total final interior volume of the thruster is then 1.28 in.^{3}

6-3.4.3 PROPELLANT CHARGE WEIGHT

Since the thruster must also supply bypass gas, the charge weight is calculated in two parts. The approximate charge for thrust is found by use of Eq. 4-16:

$$C = 3.07 \times 10^{-3} \bar{F}_r s \qquad (4\text{-}16)$$

where

$\bar{F}_r$ = average resistive force, lb

s = stroke, ft

Since F = 550 lb and s = 1.5 in.

$$C = 3.07 \times 10^{-3} \times 550 \times \frac{1.5}{12} = 0.22 \text{ gram}$$

The charge required for bypass can be calculated from Eq. 4-23 with suitable interpretation of P_t. The required pressure at the end of 4 ft of hose is 1.000 psi; however, turbulent, high-velocity flow at the bypass tube entrance will cause loss of pressure to about 70 percent of the theoretical value, i.e., 1,000 psi is 70 percent of P_t. From Eq. 4-23, the required charge is found to be about 1 gram. The total charge, for thrust and bypass, then, is approximately 1.25 grams.

Assume that the ballistician will use H8 propellant for the workhorse studies. H8 is suitably slow-burning, and one grain has adequate size (5/8-in. long, with 5/16-in. OD) to fit the chamber and weight (1.25 grams) to approximate the charge. Eq. 57 in Appendix VIII of Ref. 2, Chapter 4, will give the chamber pressure just before opening of the bypass port. Using the 1.25-gram charge and 1.28-in.^{3} chamber volume, with 3.1 $\times$ 10^5 ft-lb/lb impetus and a β_1 value of 0.35, the chamber pressure P_f is about 5,300 psi. Thus, it satisfies the requirement for a pressure twice the minimum. (The value of β_1 was chosen at the minimum because the thruster is small, and the work done represents only about one-fifth the total charge requirement.)

6-3.4.4 CARTRIDGE

The cartridge consists of a case containing the propellant, igniter, primer, and head (see Fig. 6-10). Table 4-1 shows that the smallest diameter of any of the standard cartridge cases is 0.550 in. This case size is satisfactory because the igniter will be placed in the main propellant chamber along with the grain. (Separate igniter chambers seldom are used with small cartridges.) The cartridge case selected has a chamber length of 1 in.

An M72 Percussion-type Primer is selected for use with the igniter in the cartridge. (See Table 4-2 for data on this primer.)

The cartridge case selected for this application is 0.550 in. in diameter; however, the body of the thruster cannot be made with an inside diameter small enough to house the cartridge properly and still maintain the specified outside diameter without adding appreciably to the weight of the assembly. Equally important, if the inside diameter of the thruster was made small enough for proper housing of the cartridge, the initial volume of the device would be decreased and the expansion ratio would be increased. For these reasons, the inside diameter of the thruster body is made as large as possible. A cartridge retainer, similar to the type used in initiators, is employed to prevent plugging of the bypass port and to prevent shatter of propellant at −65°F. This retainer fits snugly around the cartridge. The breech is threaded into internal threads in the cartridge retainer thereby holding the cartridge and cartridge retainer in place. Four slots are machined in the walls of the cartridge retainer. These slots permit the walls of the cartridge to rupture and allow the propellant gas to escape while retaining the propellant grain in the cartridge.

6-3.5 COMPONENT DESIGN

6-3.5.1 BODY

The body (Fig. 6-11) is a cylinder with an external thread at one end for assembly to the end cap. Two blind holes (180 deg apart) in the thread hold nylon pellets which act as

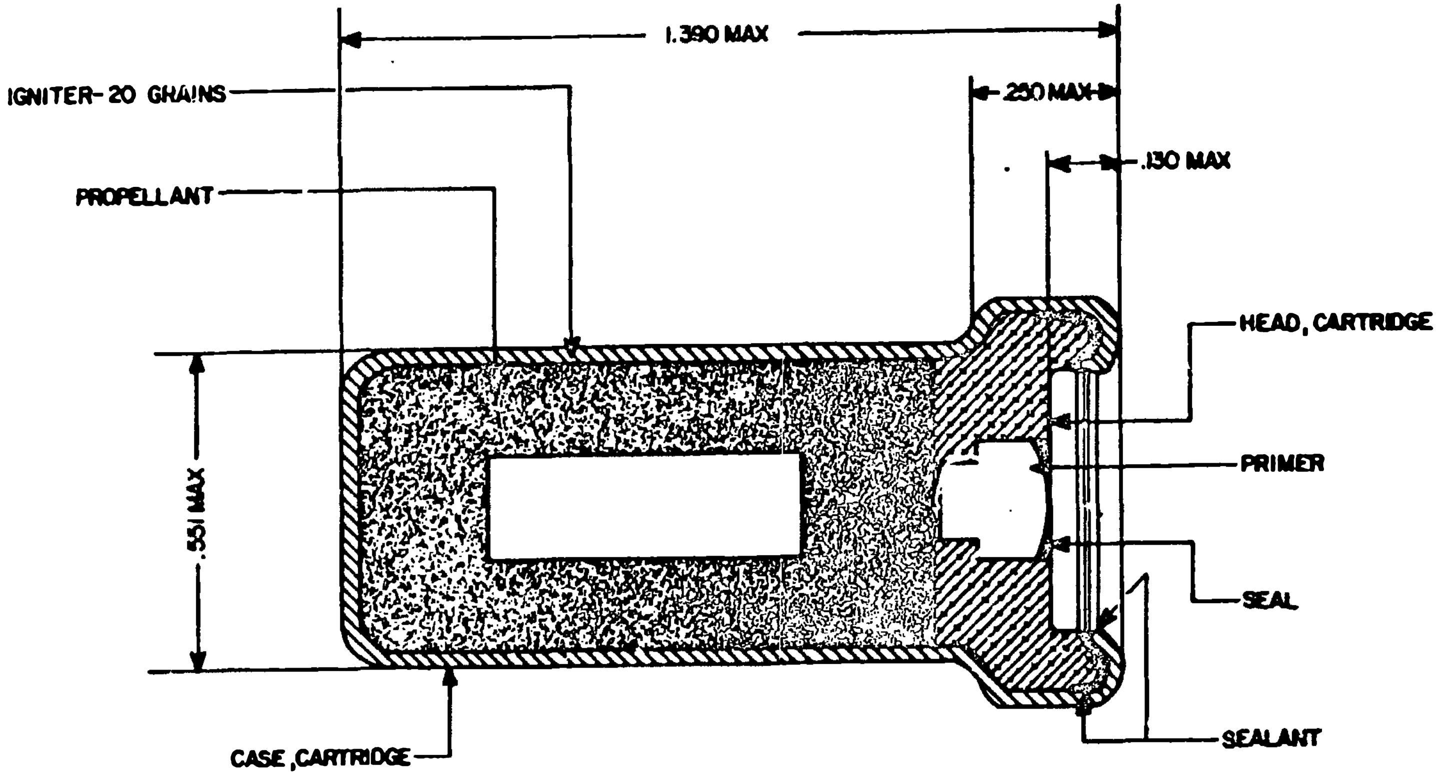


Figure 6-10. Impulse Cartridge, M44A1

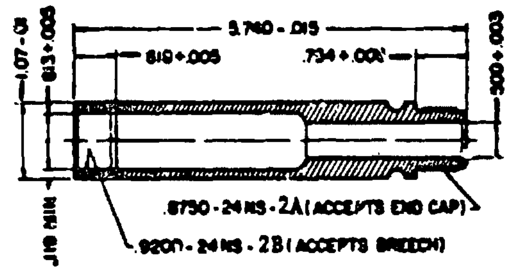


Figure 6-11. Thruster Body

locking agents. The other end incorporates an internal thread for assembly to the breech. The body houses the cartridge at the breech end and houses a part of the piston at the other end. The remainder of the piston extends into the end sleeve.

The maximum pressure that the threaded area (between the end cap and the body) will withstand is calculated by using Eq. 4-37. (It is assumed the body will be made of 7075-T3 aluminum alloy as per FA-PD-MI-2566.)

$$L = \frac{3PR^2}{S_s d}$$

$$P = \frac{LS_s d}{3R^2} = \frac{0.50 \times 36{,}900 \times 0.8227}{3 \times \left(\frac{0.8750}{2}\right)^2}$$

$$\approx 26{,}400 \text{ psi} \qquad (4\text{-}37)$$

In the calculated bypass pressure example (par. 6-3.4.3) for the M3A3 Thruster, the peak pressure is only 5,300 psi; therefore, the threaded connection will withstand over four times the estimated peak pressure.

The wall strength equation, Eq. 4-34, is used to calculate the maximum pressure (locked-shut) that the walls of the body will withstand. When several sections of wall thickness appear thin, the wall ratio of each section is found, and the smallest wall ratio is used in the calculations.

The triaxial load equation can only be used if the piston applies the full load longitudinally to the body. In this case, the peak pressure, which the body will contain, may occur before the end of stroke, before a full longitudinal load could exist; therefore, the biaxial equation, Eq. 4-36 (which provides the highest stress), is used.

$$\frac{P}{Y} = \frac{W'^2 - 1}{\sqrt{3W'^4 + 1}}$$

$$P = \frac{(W'^2 - 1)}{(3W'^4 + 1)^{1/2}} \qquad †(4\text{-}36)$$

where

$$W' = \frac{OD}{ID} = \frac{1.07 - 0.01}{0.920}$$

= 1.16 (at undercut of threads, cartridge end)

or

$$W' = \frac{0.822}{0.500 + 0.003}$$

= 1.63 (at undercut of threads, piston end)

† This equation may not be used where discontinuities are present.

$$P = 56{,}000 \times \frac{(1.16^2 - 1)}{[3(1.16)^4 + 1]^{1/2}}$$

$$\approx \frac{7600}{1.15^*} = 6{,}600 \text{ psi}$$

On the basis of these calculations, it is apparent that the body, as designed, will withstand the maximum pressure developed (5,300 psi).

6-3.6.2 BREECH

The breech (Fig. 6-12) is a steel cylinder with an axial gas inlet port. The breech houses the firing pin and acts as the firing pin guide. The closed end of the breech has a contoured base to fit the cartridge head. The firing pin protrusion beyond the face of the breech is 0.037 + 0.008 in. This is the protrusion permitted by the primer specification. Close tolerances must be established for the forward end of the breech because (1) the face of the breech must seat on the cartridge head to support it, and (2) the closed end of the breech must create the proper spacing for firing pin protrusion. Four equally spaced radial holes are located on the outside diameter to permit the breech to be held with a spanner wrench when assembling the unit. Two threads are incorporated on the exterior of the breech, adjacent to the closed end. Two blind holes, 180 deg apart, are machined into each thread. Nylon pellets pressed into these holes act as locking agents for the

*Safety factor.

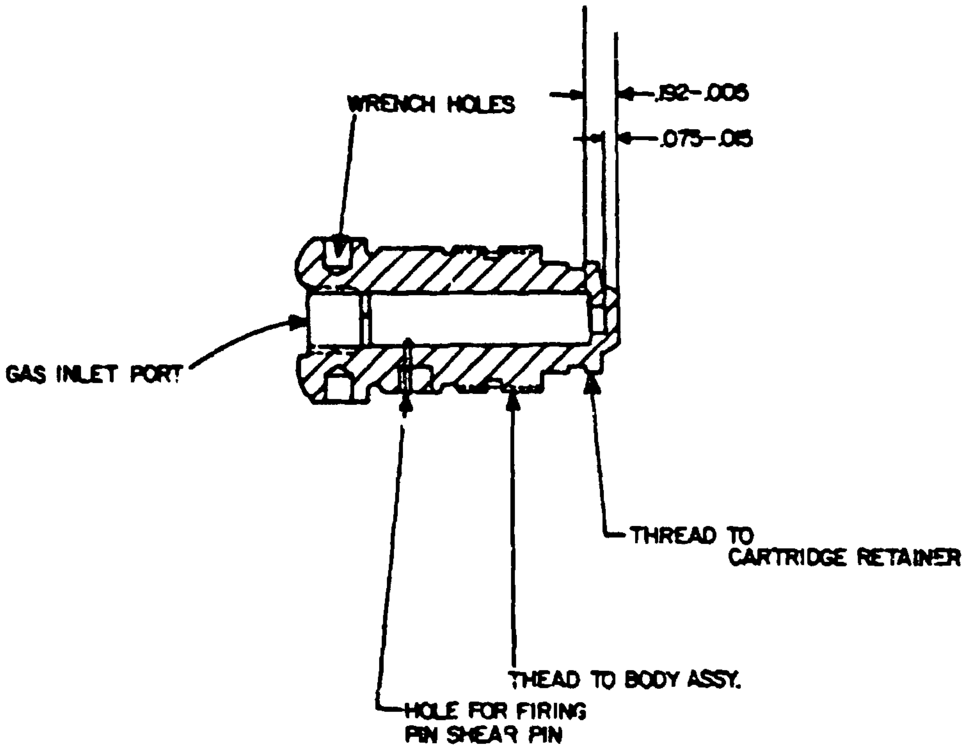


Figure 6-12. Thruster Breech Assembly

thruster body assembly (large thread) and the cartridge retainer (small thread) (see Fig. 6-9).

The firing pin is located ahead of the gas inlet port in a position where it cannot be contacted by the end of the hose fitting. A hole in the breech, normal to the longitudinal axis of the device, is provided for the firing pin shear pin. A setscrew backs up the shear pin to retain the pin and to prevent gas leakage.

6-3.5.3 TRUNNION

The trunnion on the thruster is similar to that used in the example of the catapult. The trunnion (Fig. 6-13), located between the breech shoulder and the end face of the body, is free to rotate a full 360 deg to facilitate mounting the thruster.

In designing any trunnion, the pivots must be located in such a way that there is no free play (side shake) when the thruster is in the mounting; otherwise, the pivots will be exposed to bending stresses as well as shearing stresses. Stress concentrations around the trunnion pivots should be minimized by avoiding sharp corners where the pivots join the trunnion ring.

The trunnion pivots must be strong enough to permit the full tension load to be applied to the thruster without deforming or shearing the pivots. The maximum load that the 0.250-in.-diameter pivots can withstand is

$$F = S_s A, \text{ lb} \tag{6-4}$$

where

F = maximum load, lb

S_s = shearing stress (60 percent of yield strength), psi

A = area of one trunnion pivot, in.^{2}

$$F = \frac{125{,}000 \times 0.6 \times 0.049}{2^*}$$

$$\approx 1{,}840 \text{ lb}$$

From this calculation, it is obvious that one pivot can withstand the maximum load in shear. The trunnion could also fail by tearing through the ring on both sides of a pivot. The area which is subject to tearing is:

A = 2 X (trunnion ring thickness) X (trunnion width)

A = 2 X 0.075 X 0.500

A = 0.075 in.^{2}

*Safety factor of 2 is used for structural member.

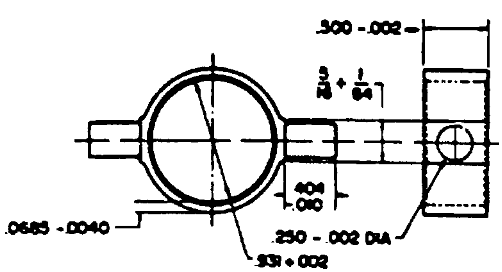


Figure 6-13. Trunnion for Thruster

Use this figure and the stress formula where F = maximum load; S_s = shearing stress; and A = area subject to tearing:

$$F = \frac{125{,}000 \times 0.6 \times 0.075}{2^*}$$

$$\approx 2{,}810 \text{ lb}$$

The preceding calculation indicates that there is sufficient area through the ring on both sides of the pivot to prevent the material from tearing through under the applied load.

6-3.5.4 FIRING MECHANISM

The firing mechanism consists of a firing pin and a shear pin. The firing pin (Fig. 6-14) is a small alloy-steel cylinder with a projection (tip) on one end and a slot on the other end. A shear-pin hole is located radially in the body of the firing pin. This hole accommodates a 0.040-in. diameter shear pin that positions and retains the firing pin in the breech prior to actuation. The slot in the rear face of the firing pin permits the pin to be turned in the breech during assembly to align the shear pin holes in the firing pin body and the breech. An O-ring on the firing pin prevents the gas entering the inlet port from escaping past the firing pin. The O-ring is located so that it does not pass over the shear pin hole as the pin is propelled forward. The length-to-diameter ratio of the firing pin was established at 1.5 (Table 4-3), and the travel was designed to produce the required 60 in.-oz of energy to fire the M72 Primer (Table 4-2).

*Safety factor of 2 is used for structural member.

6-3.5.5 END CAP

The end cap, Fig. 6-15, is a short aluminum cylinder with internal threads for attaching the body. A bypass port extends from the end cap normal to the axis of the thruster. The bypass incorporates a standard type boss. Interference and stopping shoulders, to stop the piston at the end of stroke, are located ahead of the bypass port. The O-ring seals are positioned so that the relative motion of the components will not cause them to pass over any holes or grooves which could tear the seals and render them ineffective.

The thinnest section of wall in the end cap not only has a larger wall ratio than the body, but also is subjected only to the bypass pressure; therefore, it is not necessary to calculate the strength of the walls in this component. A 0.000 to 0.003-in. interference fit (Fig. 6-15) which extends for 0.1 in., absorbs most of the kinetic energy of the

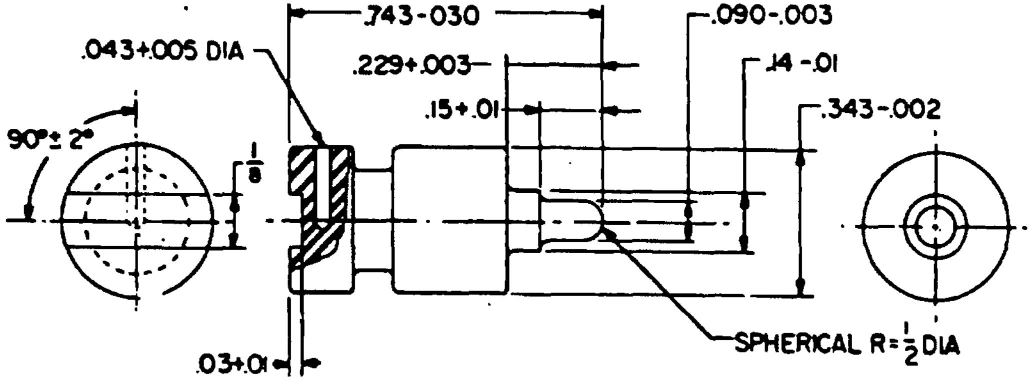


Figure 6-14. Thruster Firing Pin

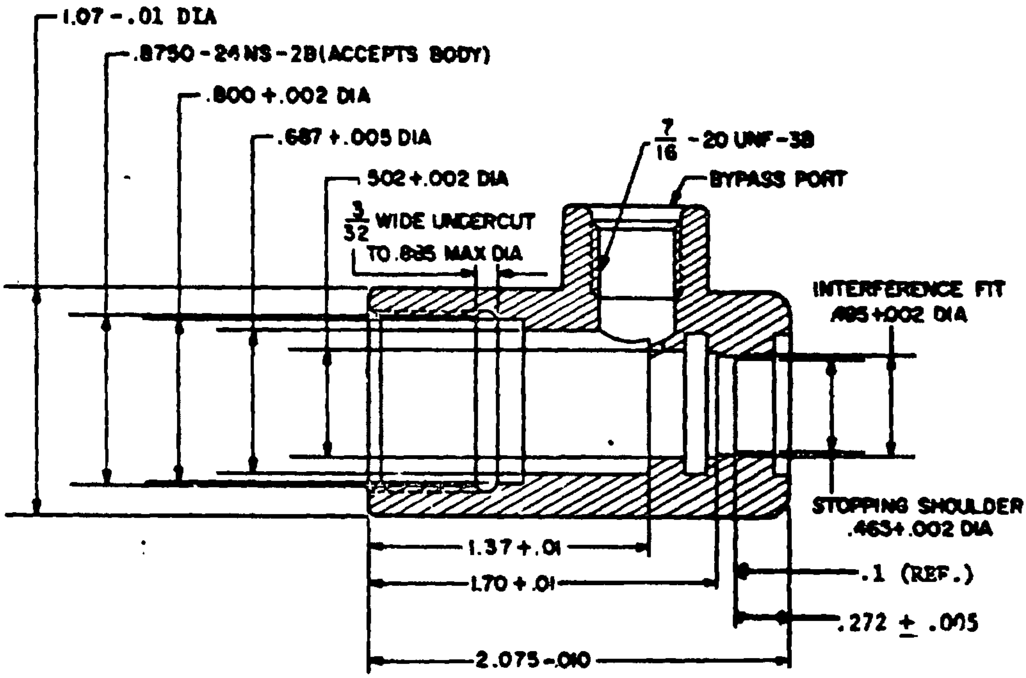


Figure 6-15. Thruster End Cap

piston before it strikes the stopping shoulder in the end cap. Tests must be conducted to determine whether the proposed interface fit and shoulder are capable of stopping the piston without causing permanent deformation to the end cap or the piston.

6-3.5.8 END SLEEVE AND LOCKING MECHANISM

The end sleeve has external threads for connecting the thruster to the mechanism to be actuated. A hexagonal flange is located at the rear of the threaded projection. The locking mechanism for the thruster consists of three kidney-shaped keys (Fig. 6-16) that are located in slots equally spaced around the circumference of the end sleeve.

Due to space limitations of thrusters of this small size, the key lock design becomes most critical. In the design of this thruster, a very shallow groove is provided for the lock keys in the end cap. Although this is not a desirable situation and makes for difficulty in the lock design, space limitations dictated its use. The key lock is far superior to the ball lock design used in earlier designs for the initial locks, although its load capacity is not realized fully when a shallow groove is used. The keys tend to seat when subjected to the loads specified. Therefore, some permanent set occurs in the lock groove due to the loads imposed by the 100 percent inspection of the locks. This load capacity becomes increasingly higher as the bearing area increases because of "Brinelling". Also, this capacity becomes

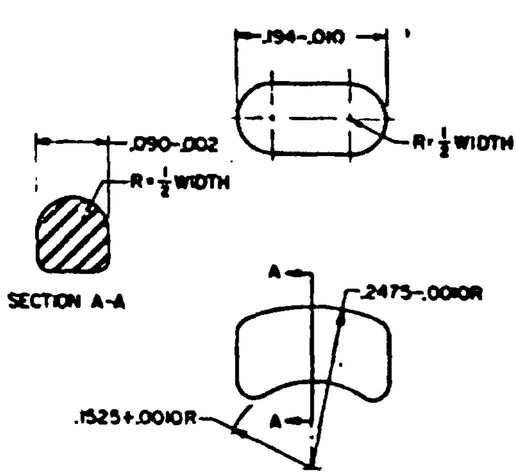


Figure 6-16. Thruster Locking Key

greater because the deformed metal obtains some support from the end sleeve.

The load capacity under certain sudden unsustained loads is greater than the permissible bearing loads within the elastic region. The criterion used for inspection is that the unit shall not unlock under the suddenly applied load, 800 lb in this case. This load should not be used as the operating load in actual installation. Because plastic deformation is encountered and the metal becomes confined by surrounding material, design calculations become impractical. The most reliable solution, therefore, is obtained by experiment. Fig. 6-17 shows a series of load-deflection curves obtained by testing the locking keys in a fixture. It will be noted that the curve is almost linear up to 800 lb, which is the load required in the specifications.

To insure that the material between the slots for the locking keys will not tear because of tension loads while the unit is locked, the minimum thickness of material for walls of the sleeve is calculated:

$$t = \frac{F}{NDS_t}\text{, in.} \tag{6-5}$$

where

t = wall thickness, in.

F = maximum load, lb

N = number of webs

D = circumferential distance between slots, in.

S_t = tensile strength, psi

$$t = \frac{800 \times 1.15^*}{3 \times 0.24 \times 125{,}000}$$

$$= 0.010 \text{ in.}$$

The end sleeve may also fail in compression when the piston is moving the required load.

*Safety factor

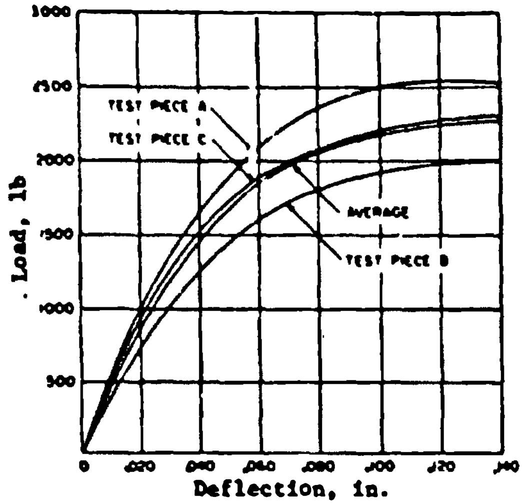


Figure 6-17. Load Deflection Curves for Keylock Mechanisms

The maximum compression force F due to thrust is:

$$F = PA \tag{6-6}$$

where

P = operating pressure (5,300 psi)

A = piston area, in.^{2}

$$= \left(\pi \times \frac{0.486^2}{4} = 0.19 \text{ in.}^2\right)$$

F = $5{,}300 \times 0.19 \approx 1{,}000$ lb

The minimum thickness for the walls of the sleeve to withstand the compressive force is calculated in the same manner (Eq. 6-5) for the tensile force:

$$t = \frac{F}{NDS_t}$$

$$t = \frac{1{,}000 \times 1.15^*}{3 \times 0.24 \times 125{,}000} = 0.013 \text{ in.}$$

The walls of the end sleeve are, therefore, made thicker than 0.013 in.

6-3.5.7 PISTON GROUP ASSEMBLY

The piston group consists of a piston, end sleeve, piston locking spring, and locking keys. An O-ring is located on the large outside diameter of the piston (Fig. 6-18) to prevent the propellant gas from escaping. The stopping shoulder is located on the piston in front of the O-ring groove, and the diameter of the piston behind the O-ring is smaller than the bore of the end cap to permit gas to escape around it after the O-ring clears the bore of the body. The initial locking and unlocking surfaces are located on the outside diameter of the piston at the small end. The forward 2 in. of the piston are hollow, and

*Safety factor.

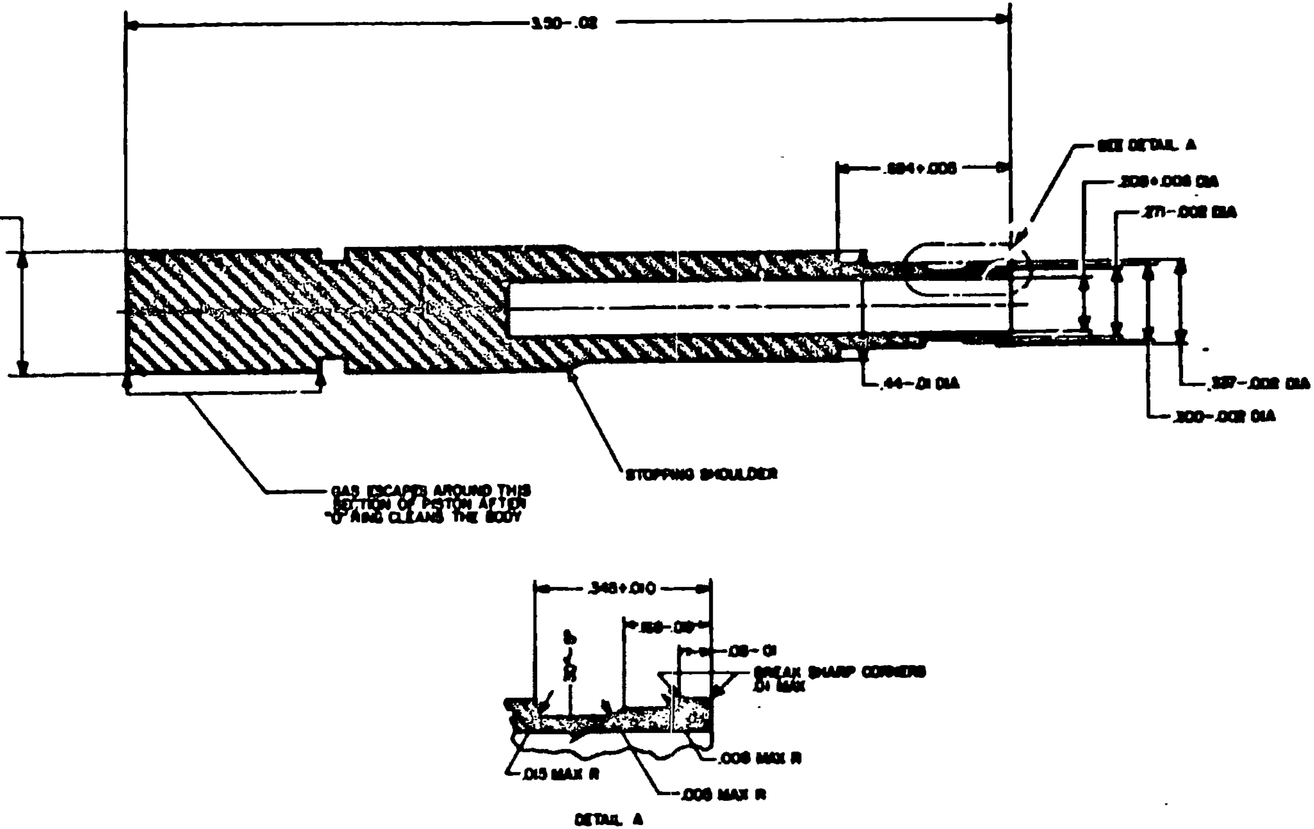


Figure 6-18. Thruster Piston

the piston locking spring is inserted in this section.

The design of the piston locking spring requires a force of 20 lb to be exerted on the piston before the spring will compress sufficiently to permit the locking keys to move inward, and unlock the piston and end sleeve. Although the end sleeve is a part of the piston group, it is described with the locking mechanisms because it contains the locking keys.

In designing the piston, the size of the critical column depends on the area, end conditions, modulus of elasticity, moment of inertia, and the slenderness ratio. The ultimate load or the induced stress can be computed. Much depends on whether the column is a "long" or "short" column. Although the piston is hollow, the moment of inertia is relatively large because of the location of the mass with relation to the center. The hole in the piston (for the spring) is made as small as possible without requiring a spring so small in diameter that it will "snake" or kink. The piston is made of aluminum alloy and has a slenderness ratio of 23. The slenderness ratio (L/k, where L is the length and k is the radius of gyration) is found as follows:

$$\text{slenderness ratio} = \frac{L}{k} \tag{6-7}$$

where

L = the length of the piston taking the maximum load is 2.8 in., i.e., (3.5 − 0.68) = 2.8

$$k = \sqrt{\frac{OD^2_{min} + ID^2_{max}}{4}} \tag{6-8}$$

assuming the hole extended the length of the piston.

$$k = \frac{\sqrt{0.43^2 + 0.214^2}}{4} = 0.12$$

$$\text{slenderness ratio} = \frac{2.8}{0.12} = 23.3$$

Columns having slenderness ratios of less than 40 are not subject to critical bending failure but will fail first in compression. The maximum compressive load which the piston can resist is by Eq. 6-3:

$$F = SA$$

$$F = 66{,}000 \times \frac{\pi}{4}(0.43^2 - 0.214^2) \times \frac{1}{1.15^*}$$

$$\approx 5{,}900 \text{ lb}$$

6-4 M113 INITIATOR

6-4.1 GENERAL

As mentioned at the beginning of this chapter, the M113 Initiator is one of a new family of subminiature initiators. This new group of initiators evolved from the development of an "in-line" subminiature initiator, the M104. This item permitted the integration of a firing mechanism, either mechanical (as the M111) or gas to complete an assembly. Also, these items easily could be converted to delay initiators by assembling a delay component between the firing mechanism and the initiator.

6-4.2 DESIGN REQUIREMENTS

The specifications for the M113 Delay Initiator and M104 Initiator included the following requirements and physical characteristics:

(1) M113 Initiator:

Envelope	To be reduced in size when combined with a delay component (if required) and a M104 Initiator.

*Safety factor.

Standard Size	
Maximum length	6 in.
Maximum width	3 in.
Maximum thickness	2 in.
Operating temperature limits	$-65°$ to $200°F$
Delay time	0.3 sec
Pressure delivered at end of 15 ft No. 4 hose at $70° \pm 5°F$	2300 psi max 1000 psi min
Method of actuation	gas

(2) M104 Initiator:

Operating temperature limits	$-65°$ to $+200°F$
Pressure delivered at end of 15 ft No. 4 hose at $70° \pm 5°F$	600 psi
Method of actuation	gas

6-4.3 FIRST-ORDER APPROXIMATIONS

The propellant charge must be calculated prior to estimating the peak pressure, which the device must be designed to withstand. The propellant charge can be calculated on the basis of the pressure that is to be generated in the pressure gage chamber and the volumes of the pressure chamber, hose, and initiator chamber.

The volume of the pressure gage chamber is specified as 0.062 in.^{3} The volume of the hose can be calculated by multiplying the cross-sectional area (0.0276 in.^{2}) by the length of the hose in inches. The volume of the initiator can be estimated from the envelope dimensions. Since no cartridge is used (the M104 Initiator is used), a substantial reduction of the size of the chamber may be accomplished. The initial volume of the chamber (0.147 in.^{3}) of the M104 Initiator is calculated from its dimensions.

The computed volumes and Eq. 4-23 are used to determine the propellant charge. The charge weight is calculated as follows:

$$P_t = \frac{12FC}{V_c + V_t}\left[1 - \beta - \frac{h_t S_t(\gamma - 1)}{FC}\right] \quad (4\text{-}23)$$

Solve for charge weight C

$$C = \left[P_t + \frac{12h_t S_t(\gamma - 1)}{V_c + V_t}\right]\frac{(V_c + V_t)}{12F(1-\beta)}$$

where

P_t = 600 psi

h_t = 30 ft-lb/in.^{3}

S_t = 0.0276 in.^{2}

V_c = 0.062 in.^{3}

V_t = 4.9 in.^{3}

γ = 1.25

β = 0.25

F = 1×10^5 ft-lb/lb

Substituting these values in Eq. 4-23 gives a charge weight of

$$C = \left[600 + \frac{12 \times 30 \times 0.0276\,(1.25 - 1)}{0.062 + 4.9}\right]$$

(cont'd)

$$\times\left[\frac{0.062 + 4.9}{12 \times (1 \times 10^5)(1 - 0.25)}\right]$$

$$C = 3.3 \times 10^{-3} \text{ lb} = 1.5 \text{ grams}$$

With this calculated charge, the locked-shut pressure may be estimated using Eq. 4-38.

$$PV = 0.0264\,FC \qquad (4\text{-}38)$$

or

$$P = \frac{0.0264\,FC}{V}$$

where

C = charge weight (1.5 grams)

V = locked-shut volume (0.147 in.^{3})

$$P = \frac{0.0264 \times 1.5 \times 10^5}{0.147}$$

$$P \approx 26{,}900 \text{ psi}$$

The device, therefore, should be designed to withstand a maximum locked-shut pressure of 26,900 psi.

6-4.4 COMPONENT ARRANGEMENT

A rough estimate of envelope size has been obtained during the first-order approximations. The firing mechanism, the delay element unit, and the initiator (M104) have been designed to fit into the estimated envelope. The mounting bracket has been designed in conjunction with the estimate envelope and the firing mechanism. This bracket also will permit interchange of the M113 (see Fig. 6-19) subminiature size initiator with the standard size initiator in an aircraft escape system.

6-4.4.1 INITIATOR

The initiator operates in the following manner. Propellant gas from another source enters the gas inlet port and exerts pressure on the firing pin. When sufficient pressure is built up behind the firing pin, the shear pin is sheared and the firing pin is propelled toward the percussion primer in the delay element unit. The primer ignites the delay charge, which – after the elapsed burning period – will ignite the propellant in the initiator. The gas produced by the burning initiator propellant then flows through a hose to another propellant actuated device.

6-4.4.2 FIRING MECHANISM

The firing mechanism consists of a firing pin and a shear pin. The firing pin (Fig. 6-20) is a small aluminum alloy cylinder with a projection (tip) on one end and a slot on the other end. A shear-pin hole is located radially in the body of the firing pin. This hole accommodates a 0.040-in.-diameter shear pin that positions and retains the firing pin in the housing prior to actuation. The slot in the rear face of the firing pin permits the pin to be turned in the breech during assembly to align the shear pin holes in the firing pin body and the breech. An O-ring on the firing pin prevents the gas entering the inlet port from escaping past the firing pin. The O-ring is located so that it does not pass over the shear pin hole as the pin is propelled forward. The length-to-diameter ratio of the firing pin was established at 0.9 (Table 4-3) and the travel was designed to produce the required 26 in.-oz of energy to fire the M42 Primer (Table 4-2).

6-4.4.3 DELAY ELEMENT

A design requirement specified (see par. 6-4.2) that a 0.3-sec delay be included. This is provided by the delay element assembly, Fig. 6-21. The delay element consists of a body, a retainer and primer subassembly, and the delay charge. The delay charge consists of an output material, and a delay composition of barium chromate and boron. The delay time is controlled by variations of the composition and weight. The mixture is pressed into pellet

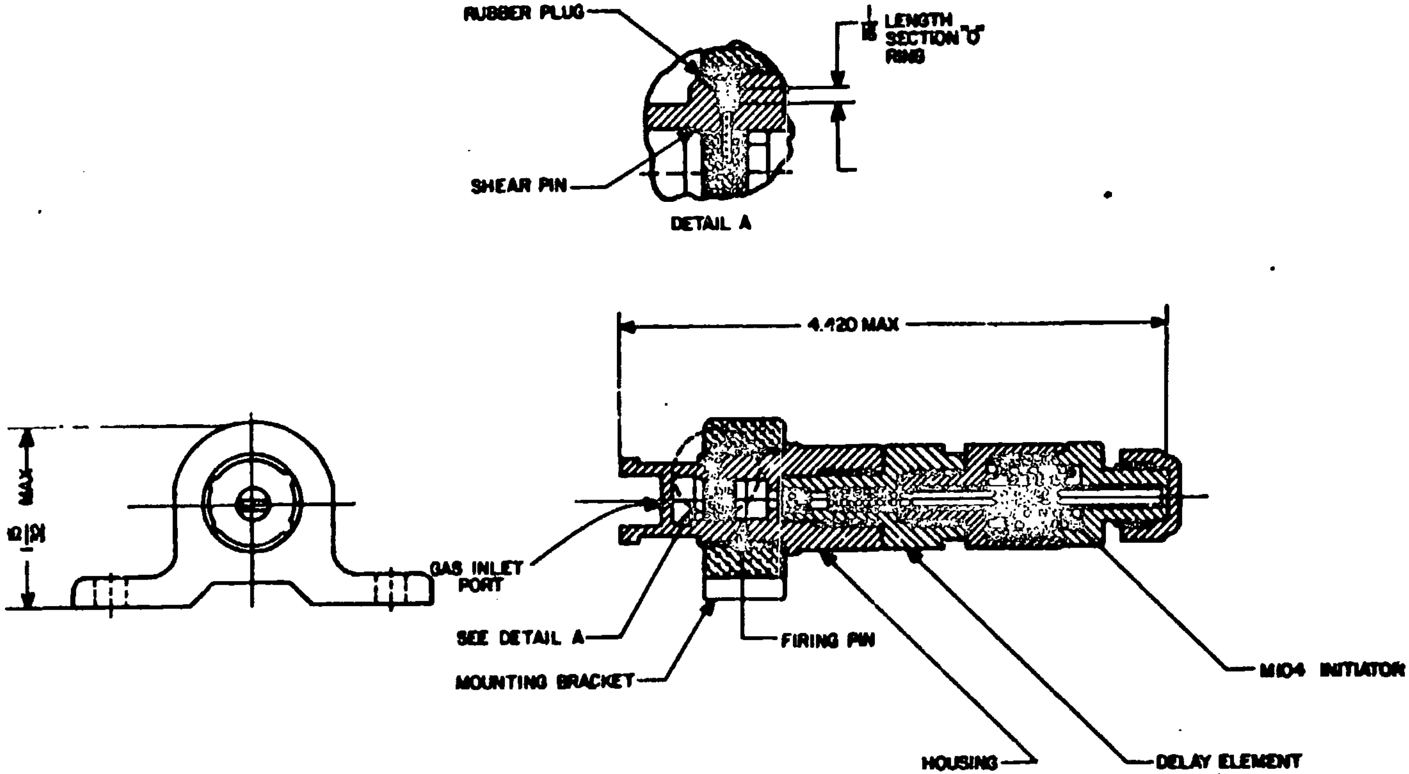


Figure 6-19. Initiator, Propellant Actuated, Delay, M113 Assembly

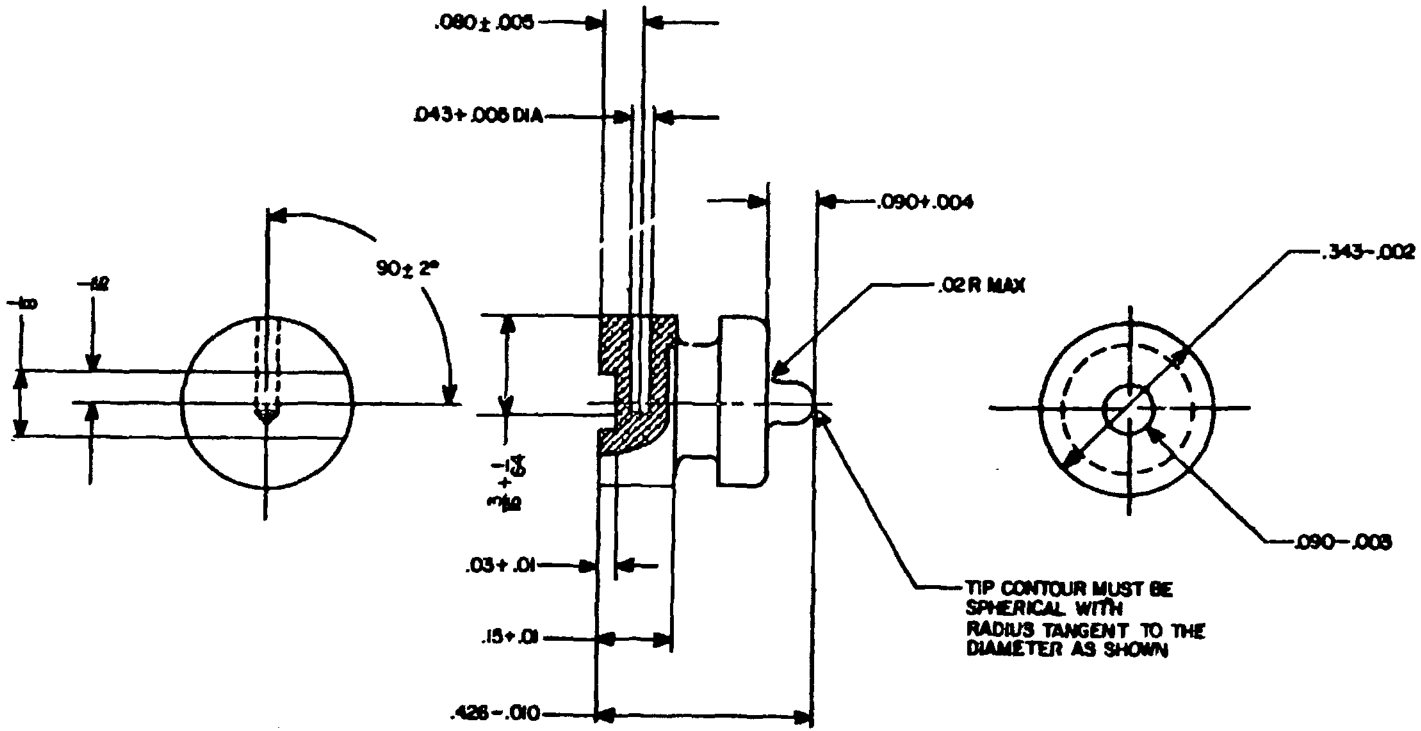


Figure 6-20. Firing Pin, Part No. 11738410

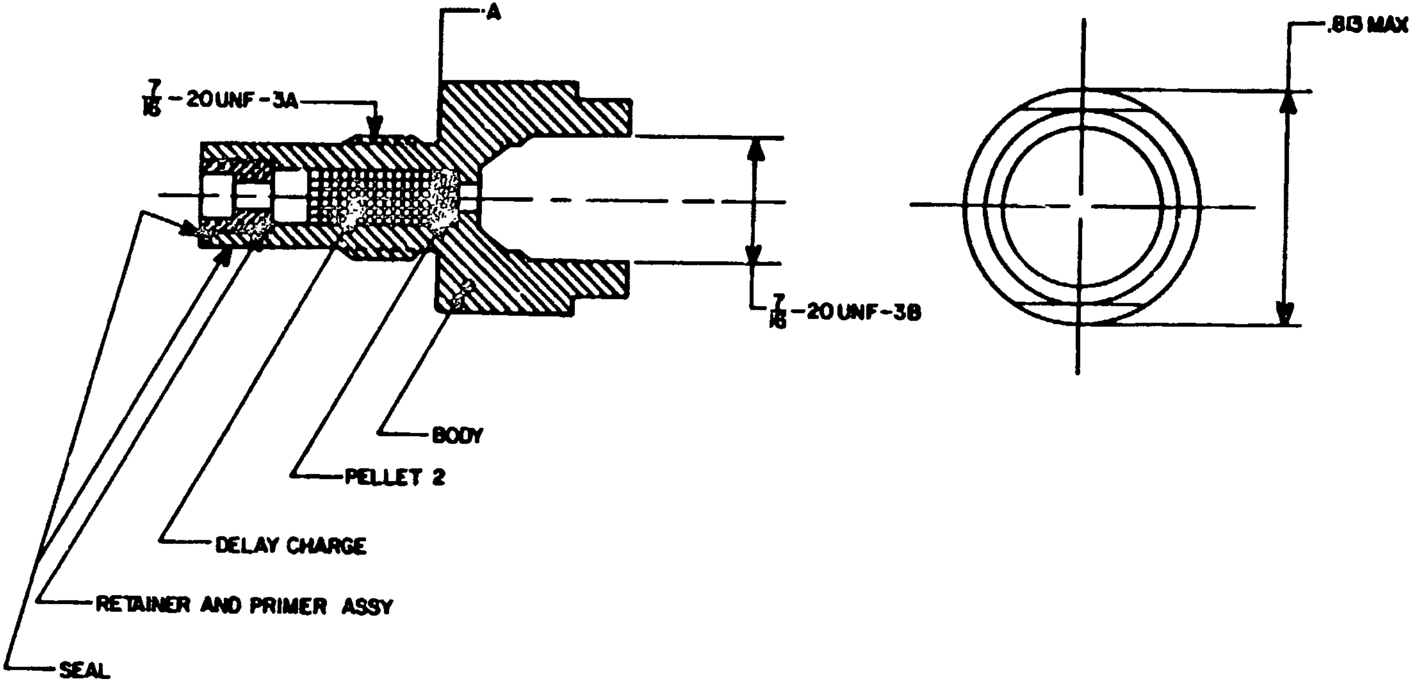


Figure 6-21. Delay Element Assembly

form, and inserted in increments into the delay body. It has been determined that two pellets of output material, and two increments of delay composition are required. The delay composition increments are pressed into the cavity separately.

The delay charge is ignited by a percussion primer. The gas produced during the burning of the delay charge is contained within the volume of the delay element. When the delay element burns through (with a laminar thermal reaction) the output material (pellets – see Fig. 6-21) the gases produced pass through into the initiator.

6-4.4.4 M104 INITIATOR

The M104 Initiator, Fig. 6-22, was first designed as an "in-line" initiator, of reduced size. This item would be inserted at appropriate points in the transmission base of an emergency escape system where a boost in gas pressure is necessary. As mentioned in par. 6-4.1, this initiator made possible the development of the new family of subminiature initiators.

This initiator consists of a female and male bodies, which, when assembled forms the chamber which contains the propellant. The female body has one open end, i.e., a cavity with an internal thread. At the other end, a projection from the body provides a standard male (fitting) thread. A hole runs through the center of the thread into the cavity. The male body is similar to the female body, except that at the open end an external thread is provided. A flash tube is fitted into the holes through the centers of both bodies. This tube has a blind hole drilled in from each end to within 1/8 in. of each other. Also, close to the bottom of each of these holes, eight holes are drilled inward from the outside diameter into these holes. These holes permit the hot gases entering through one end to ignite the propellant in the cavity. The burning propellant generates the gas pressure that will bleed off through the other end of the initiator. The male threads extending from the bodies permit the attaching of the hose whereby the initiator is connected to another remotely installed propellant actuated device. The other thread permits the attachment of a firing mechanism and/or a delay unit when required.

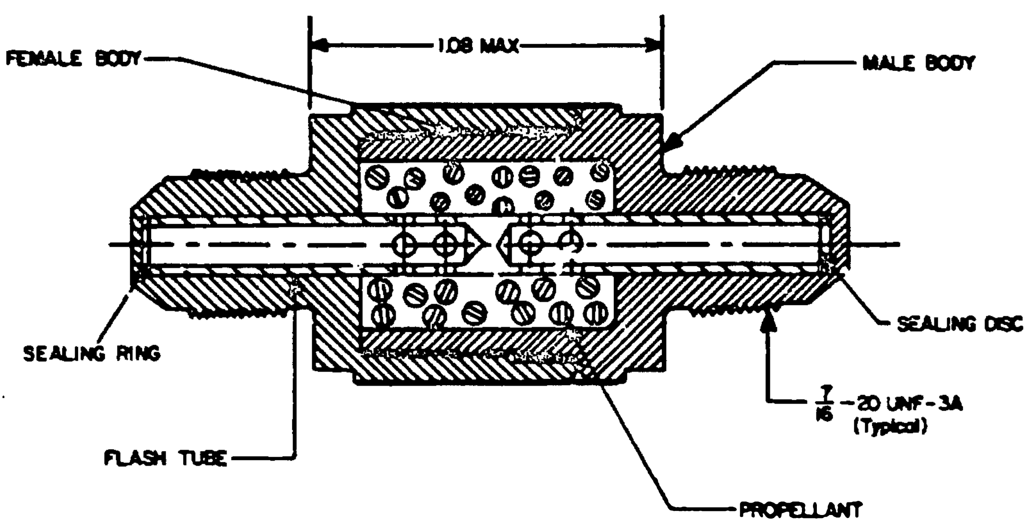


Figure 6-22. Initiator, Propellant Actuated, M104 Assembly

6-4.5 COMPONENT DESIGN

6-4.5.1 FIRING PIN HOUSING

The firing pin housing, Fig. 6-23, is a steel cylinder with an axial gas inlet port at one end. A pair of flat surfaces are included on the outside diameter at this end to permit item to be held when assembling the unit. The firing pin is located ahead of the gas inlet port where it cannot be contacted by the end of the hose fitting. A male thread is located on the exterior next to the flats and above the section housing the firing pin. A shallow counterbored hole is followed by a smaller diameter hole, for the firing pin shear pin is bored through the external thread and into the area carrying the firing pin. A rubber plug is pressed into the counter bored hole. A firing pin stop shoulder is included at the end of the firing pin chamber. A hole in this shoulder permits the firing pin projection to extend into the next chamber. This shoulder thickness is controlled so that the firing protrusion shall be within 0.025 to 0.031 in. (see Table 4-5). A hole on this side of the shoulder is of a diameter equal to the minor diameter of the female thread which continues to the end of the housing. The delay unit is screwed into this end of the housing until it contacts the stop shoulder. The exterior thread permits the assembly of the initiator to a mounting bracket (Fig. 6-24) which in turn permits adoption of the initiator into the aircraft escape system.

The maximum pressure that the threaded area (between the housing and mounting bracket) will withstand is calculated using Eq. 4-37. (It is assumed the mounting bracket will be made of 7075-T6 aluminum alloy per specification QQ-A-225/a.)

$$L = \frac{3PR^2}{S_s d}$$

$$P = \frac{LS_s d}{3R^2} \qquad (4\text{-}37)$$

$$= \frac{0.5631 \times (77000 \times 0.6) \times 0.6717}{3 \times (0.7615/2)^2}$$

$$\approx 40170 \text{ psi}$$

The preceding calculation indicates that the item will be retained in the mounting bracket when subjected to the estimated locked-shut pressure.

6-4.5.2 DELAY ELEMENT BODY

The delay element body is steel cylinder open at both ends. One end incorporates an axial hole which houses the retainer and primer subassembly (see Fig. 6-25). A hole with a smaller diameter follows. The output material and the delay composition are contained in this section. A shoulder is included at the end of this chamber. The shoulder has a central small hole that leads into the next cavity. A standard fitting type female thread in this cavity permits assembly to the M104 Initiator.

The exterior diameter of the body is smaller at the primer end. The diameter at the other end approximates the outside diameters of the adjacent components (see Fig. 6-19). A pair of narrow flat surfaces are provided on this diameter to permit holding the part at assembly.

An exterior thread is included on the smaller diameter adjacent to the large diameter. This provides for assembly of the delay unit to the firing mechanism. The maximum pressure which this thread will withstand is calculated using Eq. 4-37. (It is assumed the part will be made of a carbon steel bar, specification QQ-S-637.)

$$L = \frac{3PR^2}{S_s d}$$

$$P = \frac{LS_s d}{3R^2} \qquad (4\text{-}37)$$

$$= \frac{0.231 \times (80{,}000 \times 0.6) \times 0.369424}{3 \times \left(\frac{0.44879}{2}\right)^2}$$

$$\approx 27{,}000 \text{ psi}$$

This calculation indicates that the delay unit will not separate from the firing mechanism upon development of the locked-shut pressure previously estimated.

6-4.5.3 INITIATOR (M104) BODIES

The chamber that contains the initiator (M113) propellant is formed by the assembly of the female and male bodies described in par. 6-4.4.4 (see Fig. 6-22). The male threads extending from the bodies permit assembly of the item as an in-line initiator. Also, when combined with a firing mechanism (gas or mechanical) and/or a delay unit, it will complete a miniature initiator.

This initiator may fail in either or both of the following conditions: (1) the chamber walls may not contain the estimated locked-shut pressure (25,100 psi) and (2) the threads may fail to hold the initiator to the adjacent components.

The wall thickness required, may be found by using the curves of Fig. 4-5, sheet no. 1. The bodies are made of steel, with a yield strength of 40,000 psi. The mating of the male body with the female body forms the wall of the propellant chamber (see Fig. 6-22). The threaded area is considered as the solid wall of the chamber.

$$\frac{P}{Y} = \frac{25{,}100 \times 1.15^*}{40{,}000} = 0.722$$

The maximum pressure that the male threads at the end of bodies will withstand has been determined as follows. These male threads are identical to the male thread on the delay element body (see par. 6-4.5.2). Also, the length of thread on the initiator bodies is slightly longer than that on the delay element body. Therefore, as determined in par. 6-4.5.2 the initiator will not separate from the adjacent components when subjected to the estimated locked-shut pressure.

---

*Safety factor

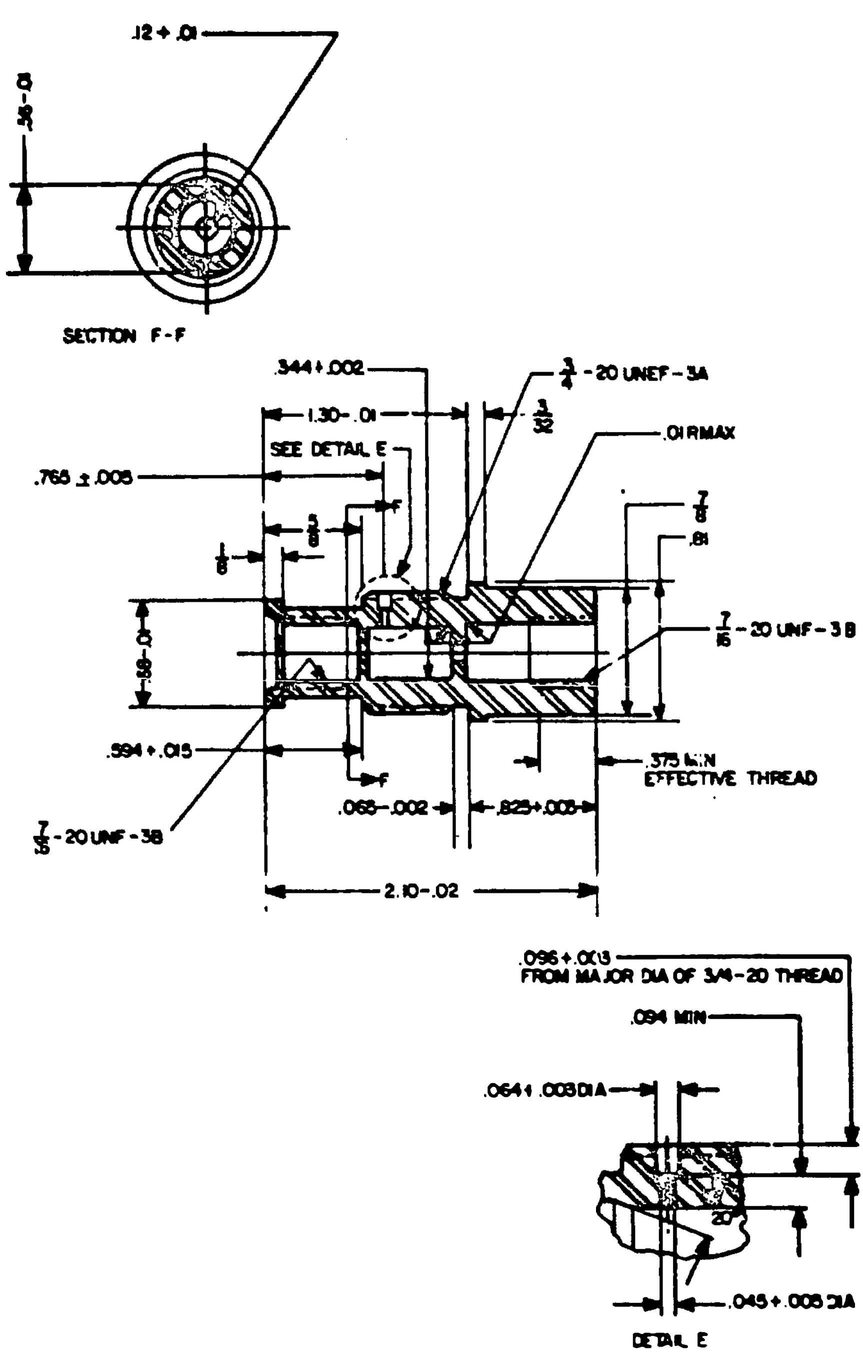


Figure 6-23. Housing

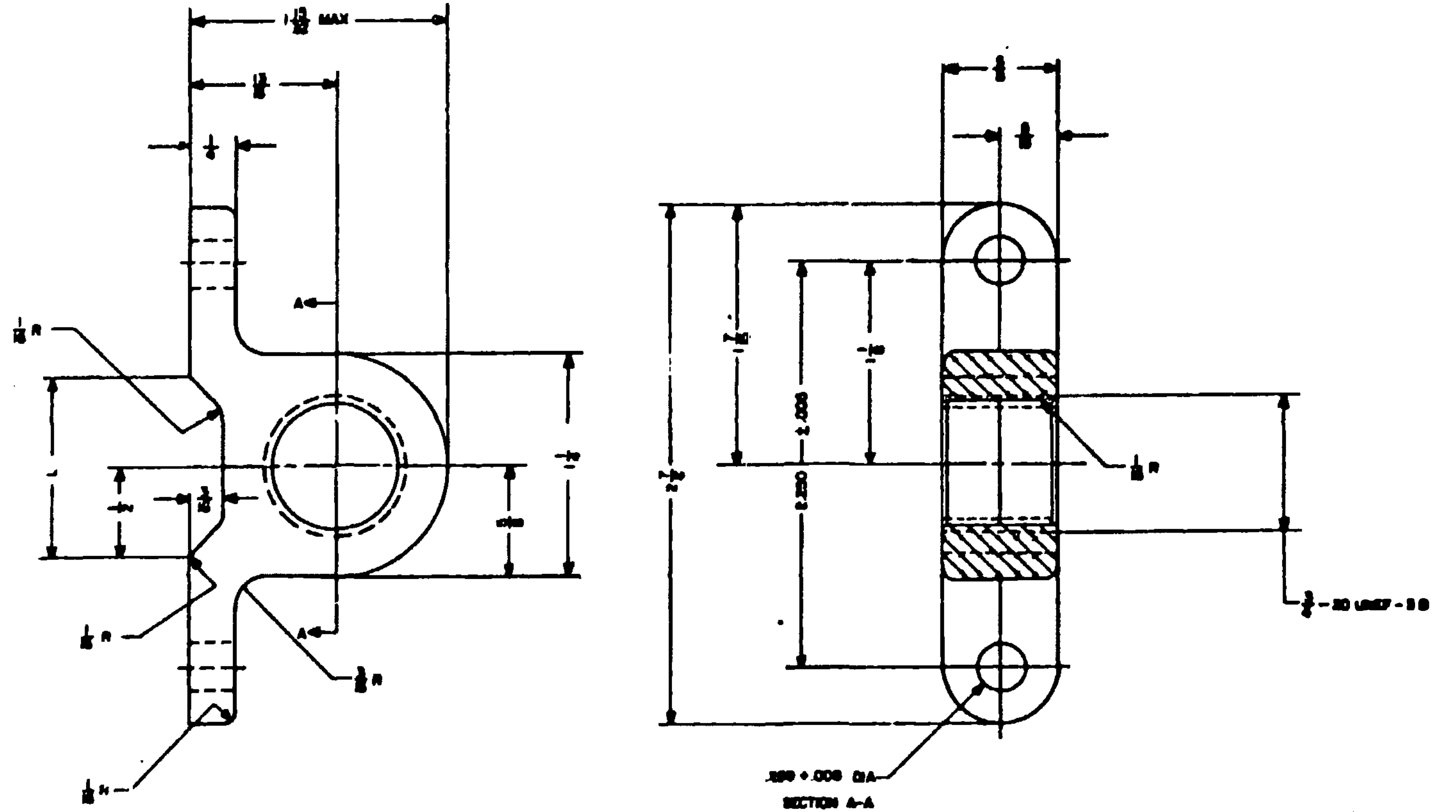


Figure 6-24. Mounting Bracket

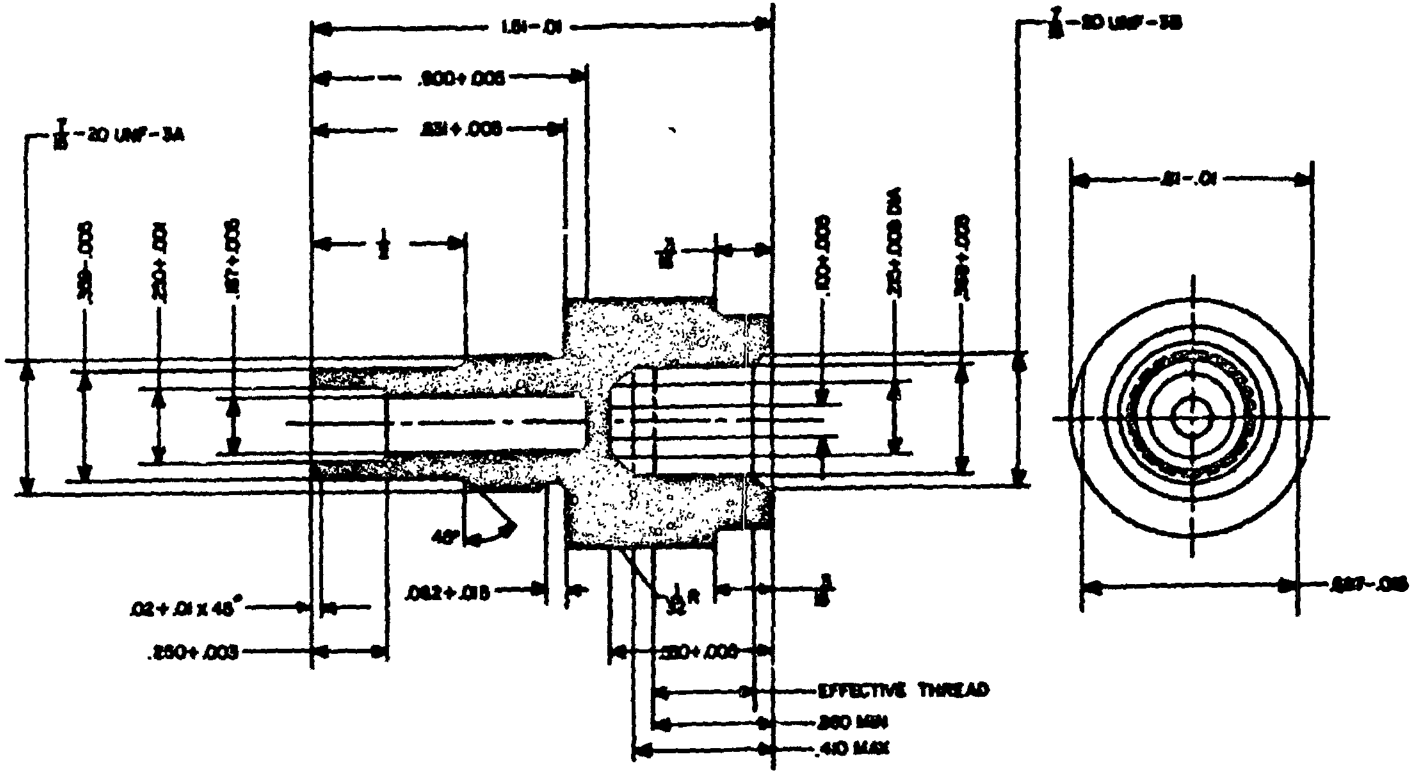


Figure 6-25. Body

CHAPTER 7

PERFORMANCE EVALUATION

7-1 TEST PROCEDURES

7-1.1 GENERAL

Two Military Specifications, MIL-C-83124 and MIL-C-83125, respectively, refer to the test procedures that apply to cartridge actuated devices and to the cartridges for these items. Separate specifications exist for aircraft emergency escape systems and electric ignition elements. Testing that is performed on a propellant actuated device is conducted to determine if the requirements contained in these specifications are met.

7-1.2 DEVELOPMENT EVALUATION PROGRAM

7-1.2.1 GENERAL

During the development program, newly designed propellant actuated devices are evaluated to insure that they meet design requirements. Workhorse models, strong enough to stand repeated firings, are fabricated from design drawings. These workhorse models are fired to develop the proper charge and to assure the feasibility of the design. After charge development and the elimination of weaknesses in design through firings and modification of the workhorse models, several prototype models are fabricated and evaluated.

Prior to development firings, it is important that all devices be given a 100 percent inspection and the dimensions recorded so that, in the event of malfunction or failure, the units may be checked against their original dimensions. All cartridges should be X-rayed to ascertain proper assembly of primer components.

The firings which must be conducted and the characteristics which must be recorded are determined by the design requirements. The ballistic firing program described is typical, except when a device contains a component or subassembly that is identical to one that is a part of an already standardized device; then all or a portion of the ballistic firings may be waived by agreement with user.

7-1.2.2 WORKHORSE MODEL EVALUATION

Workhorse models are used to develop the charge, determine the locked-shut pressure, and check the general operation. The workhorse model may include provisions for measuring characteristics that may not be measured in later models; for example, it may be designed to accept pressure pickups or piezoelectric gages to record internal pressure.

Normally, the test program that follows is implemented. Workhorse models are fired at 70°F to establish the propellant charge. A minimum of three rounds are fired with each experimental charge. When a charge produces satisfactory results, a series of at least 10 rounds is fired; 5 at −65°F, and 5 at 200°F. If the performance at −65°F and 200°F is satisfactory, five cartridges are fired at −90°F to insure that the ignition system functions properly. When the locked-shut requirements are specified, a series of at least three firings is conducted at 200°F to determine that the maximum pressure which the device may experience can be tolerated.

If "no-load" requirements are given, a

minimum of three rounds in the "no-load" condition must be tested, and the parts inspected for rupture or permanent deformation. Component dimensions may be checked against original inspection records to determine if deformation has taken place. No-load requirements generally are given with closed-system stroking devices to insure that the body of the device will retain the piston, tubes, cutter blade, or gas pressure when the device is operated and permitted to stroke without a restraining load.

The satisfactory completion of these firings qualifies the device for prototype evaluation.

7-1.2.3 PROTOTYPE EVALUATION

7-1.2.3.1 GENERAL

Evaluating prototype units is conducted to insure that the performance of the heavy-duty workhorse models can be duplicated in a device that meets weight restrictions. Two programs are conducted: structural and performance.

7-1.2.3.2 STRUCTURAL EVALUATION PROGRAM

7-1.2.3.2.1 General

Structural evaluation includes tension, compression, vibration, drop, wall strength, and leakage tests. The tension and compression tests are conducted at −65°, 70°, and 200°F with the device mounted as it will be mounted in service. The maximum loads are applied, and the trunnions and initial and final locks are checked for permanent deformation or failure.

7-1.2.3.2.2 Vibration

At least three units are vibrated in accordance with Military Specifications.

7-1.2.3.2.3 Drop Tests

Three units that have been vibrated are dropped 6 ft onto a slab of reinforced concrete. Two of the three units are dropped so that the longitudinal axis of the firing mechanism is perpendicular to the concrete at the instant of impact. The units should strike the concrete at opposite ends of the longitudinal axis. The third unit is dropped so that the axis of the firing mechanism is parallel to the concrete at the instant of impact. A similar test is carried out from 40 ft.

7-1.2.3.2.4 Wall Strength

Several special cartridges are fabricated and used to evaluate wall strength. One special cartridge should provide 150 percent of the maximum peak operational pressure. This cartridge is fired in a unit after conditioning at 200°F, and the unit is inspected for deformation. A second special cartridge is fabricated with sufficient charge to produce 115 percent of the maximum locked-shut pressure obtained in the workhorse model tests. This cartridge is installed in a unit that is conditioned at 200°F, and the unit is fired locked shut. If rupture does not occur, the unit is acceptable. When the design does not permit the use of a boosted charge, hydrostatic tests are submitted. In hydrostatic tests, a fluid is pumped into the pressure chamber of the device at pressures comparable to those obtained with the special cartridges. This test often is used to test wall strength in catapult tubes.

7-1.2.3.2.5 No-load Requirements

A final structure test is necessary for thrusters and cutters required to withstand no-load firings. These units are conditioned at 200°F and fired. The devices are inspected for permanent deformation or component failure.

The internal and external joints of the device are tightened to the minimum breakaway torque, as specified, and the assembled units are tested for leaks.

7-1.2.3.2.6 Failures

If a failure occurs during the structural tests, the deficiency must be corrected before the program is resumed.

7-1.2.3.3 PERFORMANCE

7-1.2.3.3.1 General

The satisfactory completion of the structural evaluation program qualifies the design for the second phase of the prototype evaluation program: performance evaluation.

Performance evaluation of the prototype design is the final phase in the development evaluation program. A sufficient number of prototype models must be fabricated to permit the program described.

7-1.2.3.3.2 Performance Requirements

At least 10 firings at each temperature, −65°, 70°, and 200° F, are conducted to insure that the performance of the device meets design requirements. To check ignition and the action of the firing mechanism below the lowest specified temperature, at least 10 firings are conducted at −90°F. These usually are done using only the cartridge and firing mechanism portion of the device.

7-1.2.3.3.3 No Load and Locked Shut

At least two prototype models are fabricated with their chamber walls machined to the minimum thickness specified on the parts drawing. These units are conditioned at 200°F and fired locked shut. If no-load requirements are specified, several units are tested at −65° and 200°F under no load, and the units are inspected for permanent deformation.

7-1.2.3.3.4 Environmental Performance

Four prototype units are subjected to environmental conditioning. These evaluations include vibration, high- and low-temperatures, temperature-shock cycling, and temperature-altitude-humidity tests.

7-1.2.3.3.5 Failures

A new development program must be initiated if a failure occurs during any evaluation and a design modification is necessary.

7-1.3 ENGINEERING DESIGN TESTS

After successful completion of prototype testing, the cartridge actuated device or cartridge is subjected to Engineering Design Tests. Prior to the start of Engineering Design Tests, metal part assembly inspections are conducted to insure that only properly manufactured items will undergo Engineering Design Tests.

If a device already exists and a new cartridge is developed, the requirements of MIL-C-83125 are followed. If a device is developed where the propellant is an integral part (e.g., cast in the unit), the requirements of MIL-C-83124 are used. In the main, however, the development of a device usually includes the development of a cartridge and the requirements of both specifications apply.

7-2 INSTRUMENTATION

7-2.1 GENERAL

Instrumentation is used in PAD ballistic testing to collect, process, and record performance information. Safety considerations mandate that PAD's be tested remotely. MIL-C-83124 (General Design Specification for CAD/PAD) lists three requirements for instrumentation:

(1) Must be state-of-the-art.

(2) Accuracy shall conform to requirements of MIL-STD-810.

(3) Documented calibration records will be maintained and be available for inspection by the cognizant design agency.

7-2.1.1 MEASUREMENT OBJECTIVES

The objectives for measuring PAD parameters during ballistic tests are to:

(1) Determine the feasibility of a design

(2) Measure the correctness and completeness of a design.

(3) Uncover PAD defects at an early stage.

(4) Evaluate the performance of the system.

(5) Determine data for a new or improved design.

(6) Confirm theoretical calculations.

Careful measurements are required to accomplish these aims.

7-2.1.2 SELECTION OF MEASUREMENT EQUIPMENT

There are many state-of-the-art methods available for measuring ballistic data. The MIL-SPEC's for qualified items and the "Test and Evaluation Request" form for unqualified items indicate the parameters that are to be measured, with specified range and accuracy. The particular method used to collect these data should be based on factors of convenience of use, cost, reliability, etc. Generally, the required accuracy is 2% and the equipment should be capable of responding to rise times of 2 msec and higher.

Since the introduction of automatic data processing equipment, data can be analyzed and reduced automatically. Minicomputers can be flexibly programmed and interfaced to display, printing, or plotting devices. Economic considerations dictate that automatic processing equipment should be employed for repetitious functions associated with data reduction.

7-2.1.3 SOURCES OF MEASUREMENT ERROR

7-2.1.3.1 LIMITATIONS OF THE MEASURING EQUIPMENT

Errors in equipment accuracy may be due to linearity, zero drift, hysteresis, frequency response, and sensitivity changes caused by deterioration of equipment. Periodic calibration should be performed to detect any such errors.

7-2.1.3.2 ENVIRONMENTAL INFLUENCES

Use of equipment in temperatures, humidities, or other environments for which the equipment was not intended will introduce errors.

7-2.1.3.3 INTERFERENCE

Conducted interference is caused by fluctuations in AC supply voltage, voltage bias due to unbalanced circuitry, etc. Interference can also be caused by stray radiation, which can easily influence low level transducer signals. For example, a signal line in close proximity to an AC power line may pick up (have induced) some AC signal. As another example, unshielded arcing switches will generate electromagnetic radiation. In instrumentation, therefore, it is necessary to use regulated AC power, to shield all signal lines and isolate them from power lines, and take any other measures necessary to prevent interference.

7-2.1.3.4 INTERACTION

The equipment used to measure a phenomenon should not influence the phenomenon in any way. A voltmeter, for example should have a sufficiently high input impedance so that it doesn't provide a current path that will interfere with the voltage being measured. Likewise, a pressure transducer placed in a system should not alter the volume (and therefore pressure) of that system. Measuring equipment, therefore, must be examined to insure it is measuring phenomena and not interacting with it.

7-2.1.3.5 RESPONSE TIME

Special precautions must be taken when measuring time. The "RC" effect in transmission lines and some instrument circuitry tends to introduce a time lag. Likewise, amplifiers and other components should be chosen with sufficient frequency response to handle PAD dynamic signals.

7-2.1.3.6 SYSTEM ERRORS

Even when each instrumentation component has high accuracy, the whole system may not. This may be due to incorrect impedance matching between components, cumulative component errors, etc. Therefore, it is necessary to calibrate the whole system. This is done by generating standard parameters into the input device and comparing with the finalized data from the system.

7-2.1.3.7 ERRORS OF OBSERVATION AND INTERPRETATION

These errors occur because some output devices are difficult to read (e.g., analog meters) and others produce complex data output that requires careful interpretation (multichannel oscillograph records). Human errors of this sort often can be minimized by use of automatic data analyzing equipment that prints out data summaries.

7-2.1.4 CALIBRATION

To insure the accuracy of the instrumentation, periodic calibration is required on all test and measuring equipment. Calibration not only should be performed on components, but on the entire instrumentation system. Calibration is performed by comparing equipment with precision standards whose accuracy is traceable to the National Bureau of Standards.

7-2.2 INSTRUMENTATION COMPONENTS

PAD instrumentation may be viewed as an open system consisting of input devices, signal conversion, and output devices (see Fig. 7-1).

7-2.2.1 INPUT DEVICES

Input devices convert physical quantities into signal voltages that can in turn be amplified or otherwise made into suitable form for recording or indication. Input devices are either active, meaning they generate their own voltage, or passive, in which case they alter a pre-existing voltage. For PAD use, input devices must be rugged, accurate within 1%, convenient to use, and respond to 2 msec rise times. Some input devices commonly used in PAD instrumentation will now be discussed.

7-2.2.1.1 STRAIN GAGE TRANSDUCERS

Strain gage transducers are passive input devices that convert strain on an elastic element into voltage signals. Strain gages are used to measure force, pressure, and acceleration. They are based on two principles: Hooke's law and Ohm's law (in conjunction with the resistivity equation for wire).

In simplest form, a strain gage consists of a wire about 5 in. long and approximately 0.001 in. in diameter wound into a grid shape and securely bonded with cement to the surface of the test member (elastic element) to be measured (see Fig. 7-2).

In accordance with Hooke's law, the deformation (strain) on the elastic test

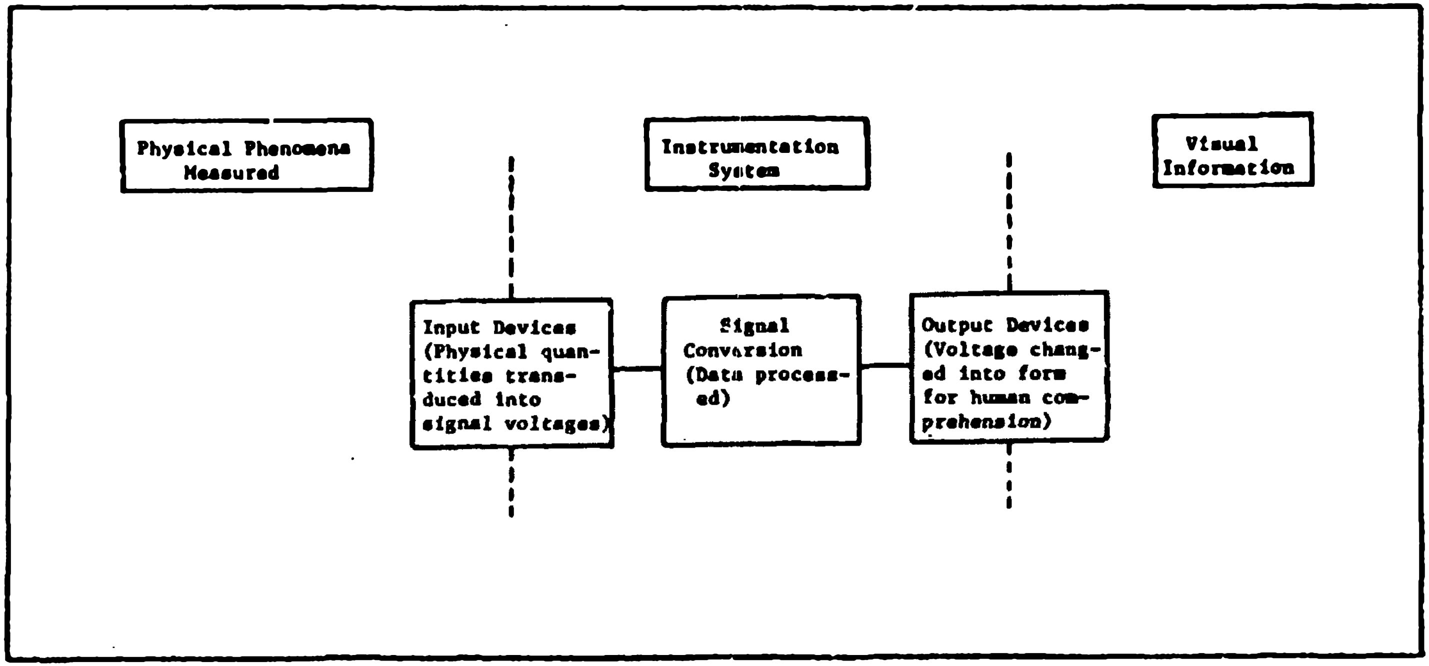


Figure 7-1. The Instrumentation System

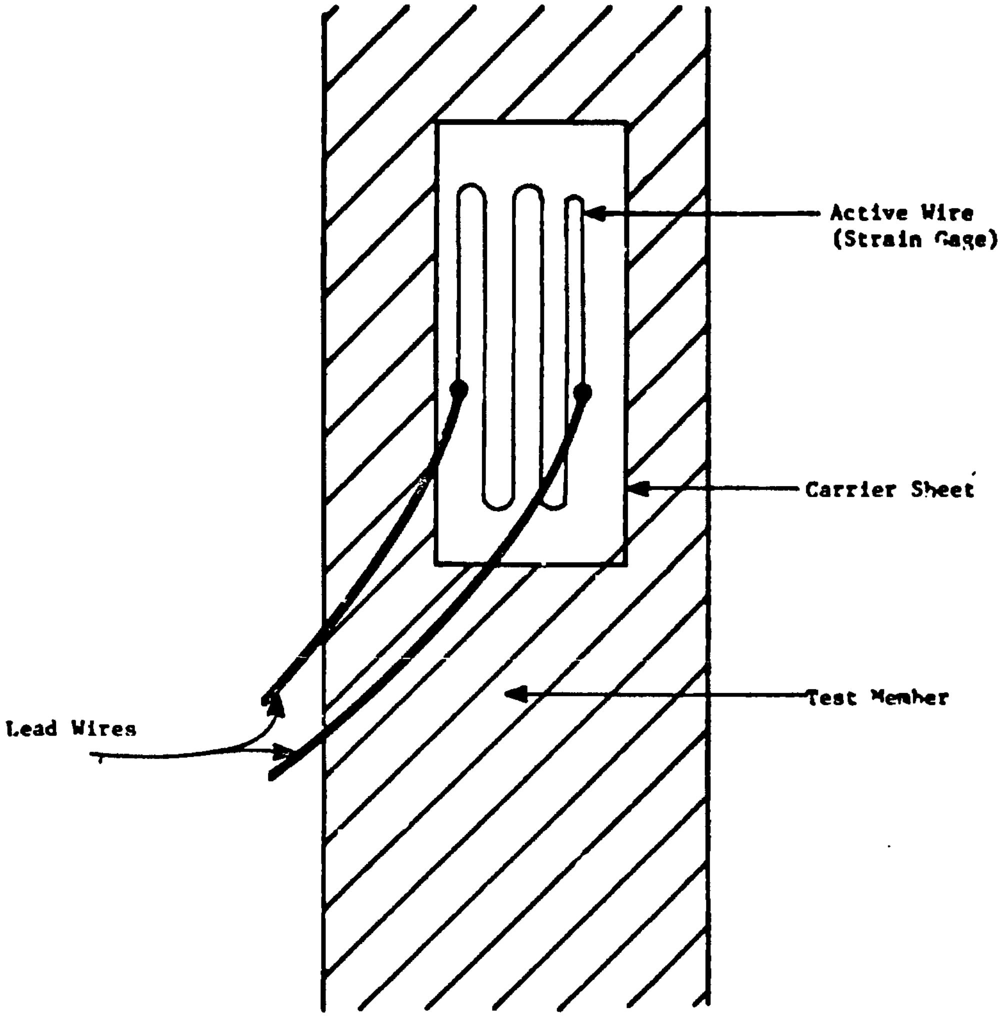


Figure 7-2. Strain Gage

member is proportional to the applied load:

$$W = KY \quad (7\text{-}1)$$

where

Y = elongation

W = deforming force

K = constant of proportionality

The strain gage (on the carrier sheet) is bonded to the test member so it deforms longitudinally an equal amount as the test member. It will be found that its resistance change is proportional to the elongation. The basic equation is that for wire resistivity:

$$R = \rho L/A = K L/D^2 \qquad (7\text{-}2)$$

where

R = resistance

L = length of wire

A = area of wire

D = diameter of wire

ρ, K = resistivity constants

Differentiating, it will be found that:

$$\frac{dR}{R} = G\left(\frac{dL}{L}\right) \qquad (7\text{-}3)$$

where G is the gage factor and is equal to $1 - 2(dD/D/dL/L) + d\rho/\rho/dL/L$. Over the range of gage operation, G will be relatively constant.

Single strain gages are useful but have the following limitations:

(1) Change in output ΔR is small compared to the base R.

(2) They are highly temperature sensitive.

(3) Impedance changes with load.

(4) Side loads tend to introduce significant errors.

All these problems are solved by using four strain gages in Wheatstone bridge formation bonded to a ring shaped elastic member (see Fig. 7-3).

Two of the gages are bonded at compression points on the inner circumference and the other two are bonded at tension points along the outer circumference. Usually the four gages are of equal resistance (350 Ω) and arranged as in Fig. 7-4.

Generally the excitation voltage is 5 V. As mentioned earlier, two increase in resistance (at tension points) and two decrease in resistance (at compression points) as in Fig. 7-5. In actual practice, adjustment resistors are added within the transducer to improve linearity and other characteristics. As can be seen from Fig. 7-5, the resistance of parallel branches AB and CD remain constant as viewed from the input terminals and since E excitation remains constant, I_{AB} and I_{CD} also are constant. As load is applied to the test member and R changes, the voltage potential across each arm will charge and in such a way that the output voltage will be proportional to ΔR.

Strain gage pressure transducers are load cells modified as in Fig. 7-6. Pressure building up in the inlet port pushes against the sealing disk. Because the inlet cylinder area is constant, the incoming pressure can be considered as a force ($F = PA$). The force on the sealing disk is transmitted to a piston and in turn to a ring (similar to the one used in a load cell). Strain gages mounted on the circumference of the ring complete the pressure transducer.

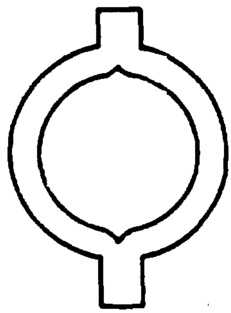


Figure 7-3. Ring Shaped Test Member Used With Strain Gage Wheatstone Bridge

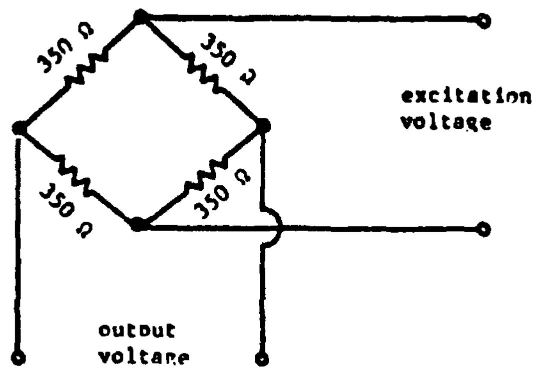


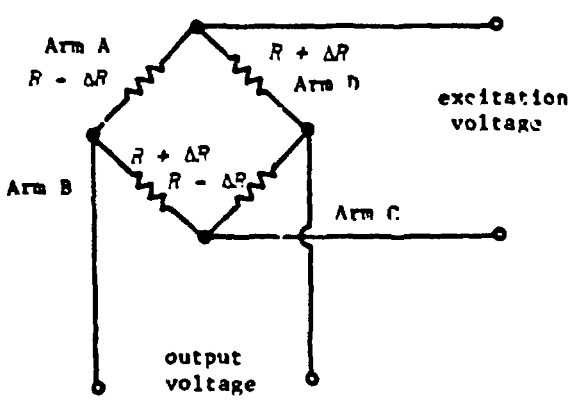
Figure 7-4. Wheatstone Bridge Strain Gage Transducer

Strain gage accelerometers use an elastic (spring) member with four strain gages. A ball of known mass pushes against this member under acceleration in accordance with $F = ma$.

Strain gage transducers are used in PAD work because of their durability, high accuracy (>99.5%), and adequate frequency response.

7-2.2.1.2 THE SWITCH

A switch is a passive device that opens or closes an electric circuit. Switches are used to pass a discrete signal when certain force, pressure, or travel conditions are met. In PAD instrumentation, three types are commonly employed: the snap-action switch, the carbon rod, and the pressure switch.



where R = 350 Ω and excitation voltage = 5 V

Figure 7-5. Detailed Strain Gage Bridge

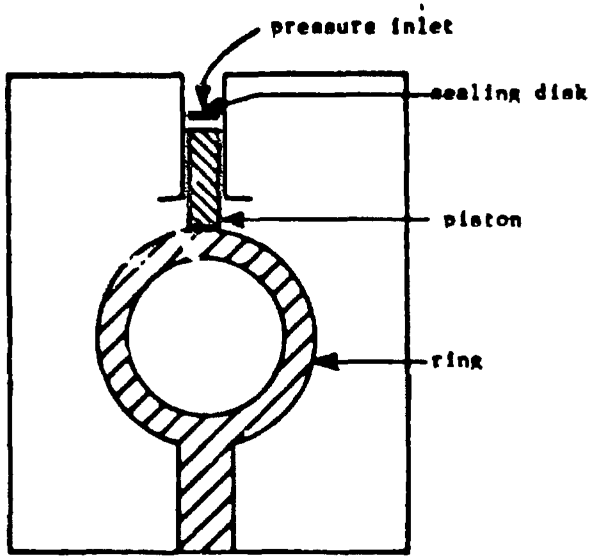


Figure 7-6. Strain Gage Pressure Transducer

When a specified force pushes against the external lever of a snap-action switch (see Fig. 7-7), the internal electrical contacts open or close with a quick movement. In a snap-action switch there is no intermediate position; the contacts are either open or closed. In PAD testing, the blast of delay ignition elements serves as the actuating force. Since all snap-action switches have an inherent time delay, though usually very short, care must be taken to insure that this time error is acceptable.

Carbon rods are of small diameter and brittle, such as the lead used in mechanical pencils. When a projectile or moving PAD component strikes the carbon rod, it breaks it and this functions like the opening of a switch. Carbon rods, then, can indicate amount of travel of a projectile; and if two rods are positioned, one behind the other, velocity can be measured.

Pressure switches are designed so that a given pressure will open or close a circuit. In one type, the pressure pushes against a spring loaded piston. When the pressure is sufficient, the metallic piston travels back and directly closes a circuit. In another type, the pressure builds up against a diaphragm which in turn actuates a snap action switch. The pressure switch normally is used to indicate the start of rise of pressure, and this signal can be transmitted to a counter or graph.

7-2.2.1.3 MAGNETIC SENSOR

The magnetic sensor is an active device for detecting moving ferrous targets. When the ferrous target disrupts the magnetic field, an electrical voltage is generated. There are three factors which determine the amount of voltage generated (given a particular magnetic sensor): (1) the target speed, (2) the geometry (size and shape) of the target, (3) target distance from the sensor.

The magnetic sensor is constructed so that a coil of wire is placed in the field of a permanent bar magnet (see Fig 7-8). The

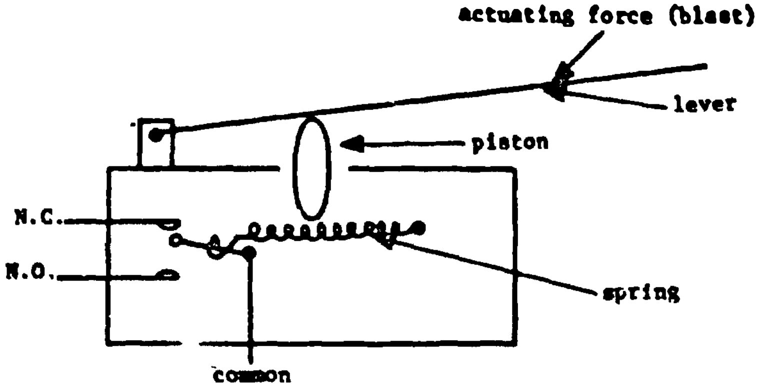


Figure 7-7. Snap action Switch

ferromagnetic target passing through the field is a magnetic "conductor" (high permeability) and so the magnetic "current" (flux) increases. The resultant emf induced in the coil is:

$$E = n\frac{d\phi}{dt} \qquad (7\text{-}4)$$

where

E = induced emf in coil

n = number of turns of the coil that pass through the affected magnetic field

$d\phi$ = change in flux

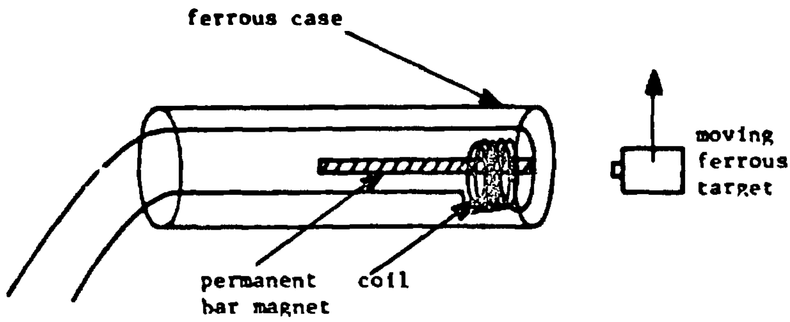


Figure 7-8. Magnetic Sensor and Passing Target

dt = time period during which the change in flux occurs

The coil is situated at the end of the magnet by which the target passes and consists of numerous turns so that maximum emf is generated. The magnet and coil are encased in a ferrous shell that serves the primary function of shunting any stray fields so that the coil will be interference free.

As the target approaches the centerline of the sensor an emf is induced in the sensor. When the target passes the centerline and moves to the other side an emf of opposite polarity is induced. The result is that a sine wave is generated. Pulse forming networks can be used if a sharper signal than a sine wave is desired. Also, digital output sensors are available.

Besides being employed to measure velocity of a passing target, magnetic sensors can indicate PAD ignition. This is done by attaching a magnetic sensor either directly or through mechanical leverage to a PAD. When it is fired it will vibrate and the distance between the PAD and the sensor will vary, inducing a voltage signal.

7-2.2.1.4 OTHER TRANSDUCERS

Other transducers used in PAD testing include:

(1) The variable reluctance transducer, in which pressure, force, or acceleration cause a movable component within the transducer to vary, thus changing the gap space and magnetic circuit reluctance in a core configuration. This produces a proportionate variation in the inductance of the coils and this variation is used to modulate the amplitude or frequency of a carrier voltage, with the net result being an electrical response that is proportional to the applied pressure. These transducers are rugged, produce a high output signal and are low impedance devices.

(2) Piezoelectric transducers work on the principle that crystals produce a voltage when subjected to external forces or pressures. They are small, high-impedance devices with outstanding dynamic response capabilities.

(3) Thermocouple networks are used to measure temperature. They produce an accurate millivoltage output that is a function of the materials used and the temperature differential between a reference junction and the measuring junction.

(4) The photoelectric system is based on the quality of some materials to change their electrical characteristics when subjected to light. Some are photoresistive and change their resistance to a current; others are photogenerative and generate a voltage. Photo-cells are used to measure travel and velocity. They must be used carefully since they often have an associated time delay.

Many other principles are used to translate physical quantities into voltage signals. Input devices are purchased and used in accordance with considerations in par. 7-2.1.2.

7-2.2.2 SIGNAL CONVERSION

Signal conversion is the process of converting the signal from the input device into a form compatible with the output device.

7-2.2.2.1 GAGE ZERO COMPENSATION

This compensates for any initial zero unbalance (bias) in the input device. For example, a load cell may have a slight voltage output when no load is on it. This voltage, unless corrected, will create an error. Generally a zero adjustment procedure increments each point on the transducer linearity curve by the same amount (see Fig. 7-9). This is accomplished for bridge transducers by counterbalancing any initial voltage output by an opposite potential derived from the excitation voltage (see Fig. 7-10).

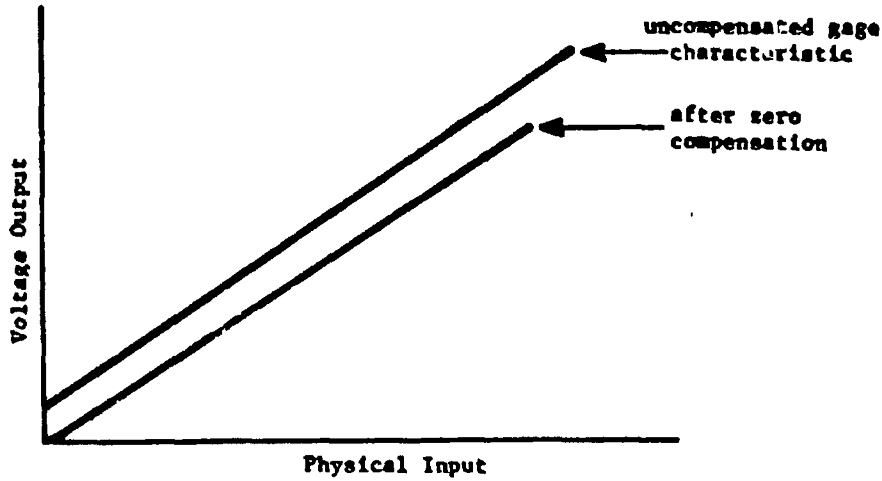


Figure 7-9. Zero Compensation

7-2.2.2.2 GAGE RANGE COMPENSATION

This compensates for incorrect output over the entire range (span). In the case of many transducers, this adjustment is not necessary since the same effect will result by changing the amplifier gain. The effect of gage range (span) compensation is shown in Fig. 7-11.

7-2.2.2.3 PRE-FIRE SYSTEM CALIBRATION

It is desirable immediately before each ballistic test to generate a signal to the

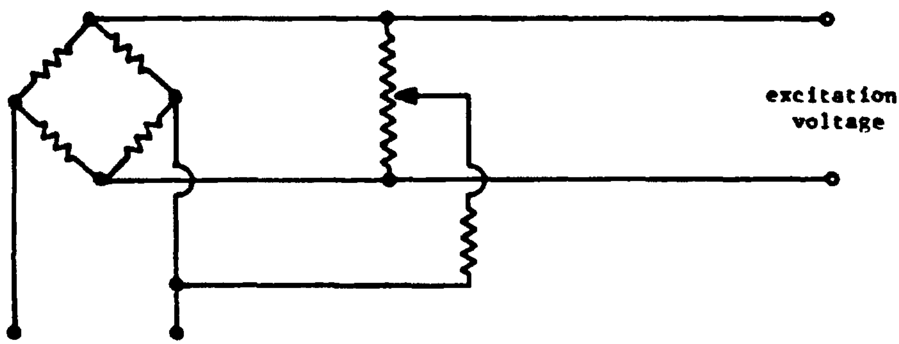


Figure 7-10. Zero Balancing Circuit for Strain Gage Transducer

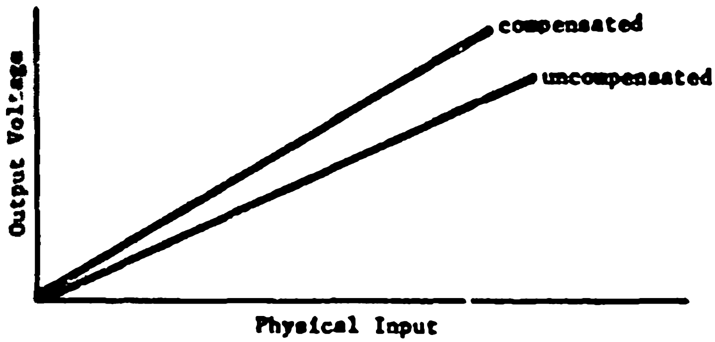


Figure 7-11. Effect of Gage Range Compensation

instrumentation system which provides a standard for measuring the output against. For example, using an oscillograph, it is necessary to produce a reference line (of a particular physical load) before firing in order to measure the ballistic curves produced during the test. Preferably a physical standard should be used to generate this output reference, but, as this is sometimes impractical, another means may be employed, e.g., electronic simulation of a physical load. If a known relationship exists between an impedance connected to a particular transducer and a physical load, this impedance can be used to generate a simulated physical load which, when connected to the instrumentation system, will produce a reference signal for that physical parameter. For example, in the case of a resistance bridge, a resistor thrown in parallel with one arm of the bridge (see Fig. 7-12) produces an output signal since it unbalances the circuit and the relationship of this resistive unbalance to a physical load can be ascertained during transducer calibration (e.g., a 67,000-Ω resistor may produce an output signal equivalent to a 7250-lb load) Furthermore, the shunt resistance and equivalent load are inversely proportional and so their product is a constant, (called the K-factor). K = (resistance) X (simulated load). Hence, different resistances can be used to generate a variety of simulated loads.

7-2.2.2.4 AMPLIFICATION

The purpose of an amplifier in PAD instrumentation is to increase the voltage or power of a signal (see Fig. 7-13).

Amplifiers chosen for PAD use should be linear, responsive from DC to over 2 kHz, have gain capabilities of at least 1000, and be compatible with input and output devices.

7-2.2.2.5 ELECTRONIC SWITCH

Electronic switches are used in conjunction with physical switches (described in par. 7-2.2.1.2) to insure immediate transmittal of a sharp signal. This is necessary because the cable leading from the physical switch introduces an "RC" time delay effect (see Fig. 7-14) before a usable voltage is reached. The electronic switch overcomes this effect by transmitting a short pulse of extremely fast rise time at high voltage. It should be placed as close to the physical switch as possible. Both electron tube and solid-state circuits are available for this function.

The electron tube circuit employs the thyratron tube V_1 (see Fig. 7-15). When the physical switch S is closed, the grid is thrown relatively positive, overcoming the negative bias, and causing immediate conduction in the

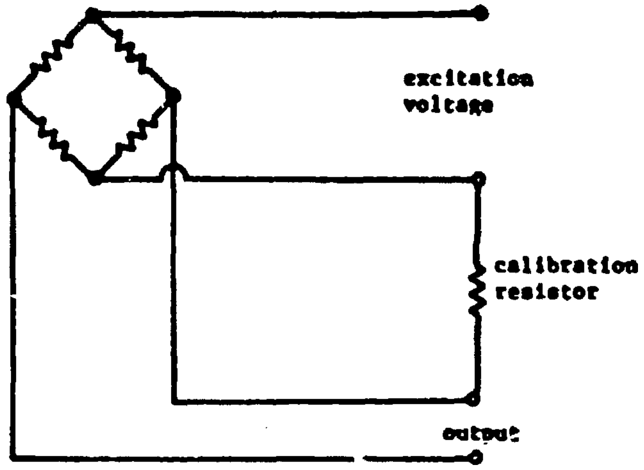


Figure 7-12. Pre-fire System Calibration for Bridge Circuit Showing Electronic Simulation of a Physical Load

rare-gas filled thyratron tube. When the thyratron turns on, the grid loses all control until the plate voltage goes negative. The thyratron is cut off by a self-quenching circuit (using C_4) that reduces the plate voltage.

A basic silicon controlled rectifier, or thyristor, circuit is shown in Fig. 7-16. The thyristor is a four-layer diode consisting of three junctions. The center junction is reverse biased and normally blocks current. One of

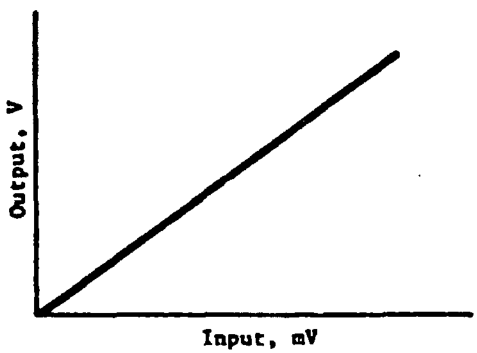
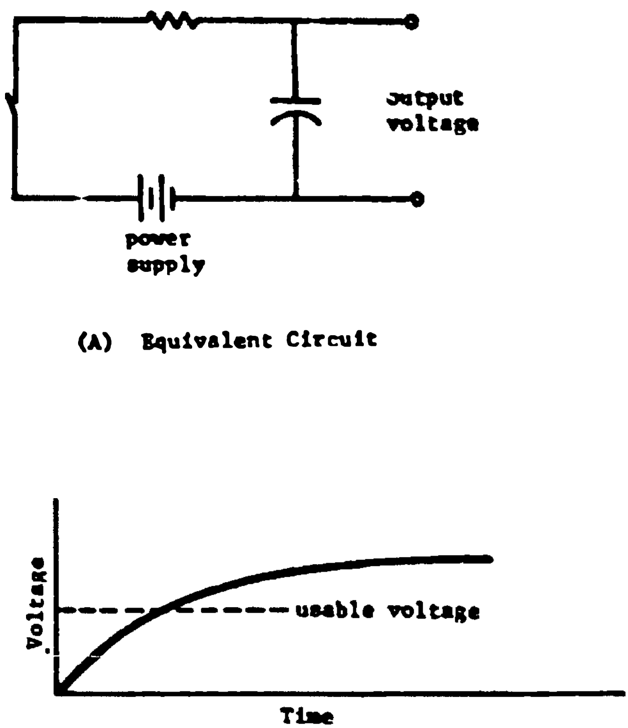


Figure 7-13. Example of Linear Amplification

the intermediate layers is called the gate and is used to control conduction. The current injected into the gate layer by applied potential breaks down the reverse bias of the center junction. As in the case of the thyratron, this causes rapid conduction. It also can be made self-quenching by reducing anode current.

7-2.2.2.6 ANALOG-TO-DIGITAL CONVERSION

The voltage signals coming from transducers and amplifiers are generally continuously variable (analog). Therefore, a preliminary function of a digital minicomputer is to change the expression of the information from analog to digital, so it can be automatically processed. The digital expression consists of the unambiguous binary language of yes (1) and no (0), corresponding to the conducting and not-conducting states of a switching device. Since the analog input changes continuously, the converter must ignore variations in input while each sequential computation is completed. This process of referring to the input intermittently is called sampling.



(A) Equivalent Circuit

(B) Voltage-Time Trace

Figure 7-14. Equivalent Circuit for "RC" Effect of Long Cable and Voltage-time Trace

7-2.2.2.7 DIGITAL PROCESSING

Digital processing consists of a sequence of arithmetic, logic, and control operations that manipulate the data. This sequence of operations is controlled by a "program". Minicomputers can be programmed to recognize points on a curve, to integrate, etc. Many simplified computer languages are available that resemble the English language and hence make programming easy. These languages must, however, be used with a standard translating program and this, unfortunately, occupies computer space.

As mentioned in par. 7-2.1.2, automatic digital processing is economically advantageous for repetitious data reduction, but it also has disadvantages: (1) may not be economical for R&D testing and (2) is more difficult to repair than nonautomatic analog equipment.

7-2.2.3 OUTPUT DEVICES

The purpose of an output device is to convert instrumentation data into a form (usually visible) designed for human understanding. Generally speaking, there are two categories of output devices (1) display (temporary indication, as on a counter), and (2) record (permanent record, as on a chart).

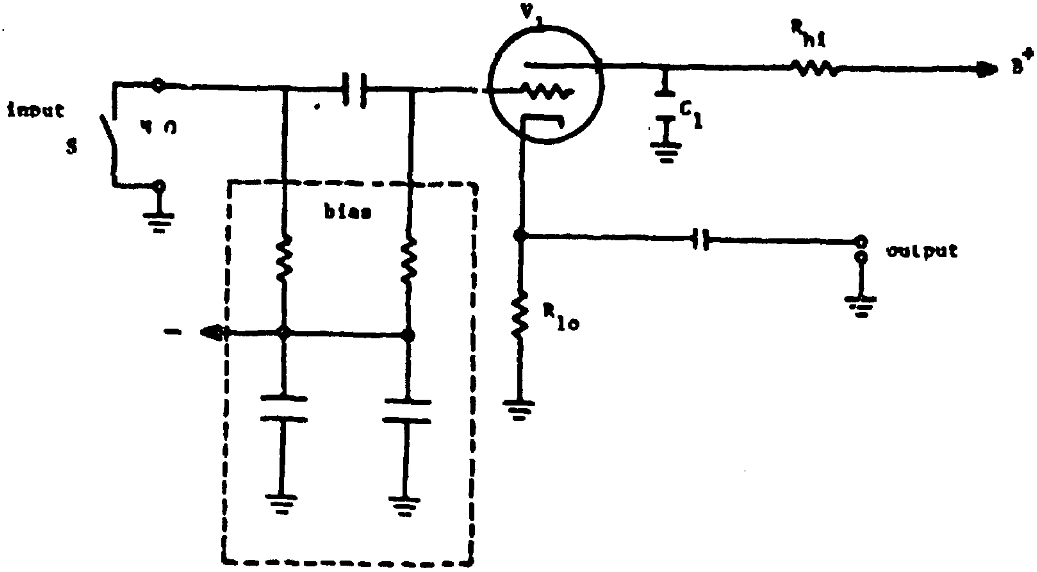


Figure 7-15. Simplified Self-quenching Cathode Follower Thyratron

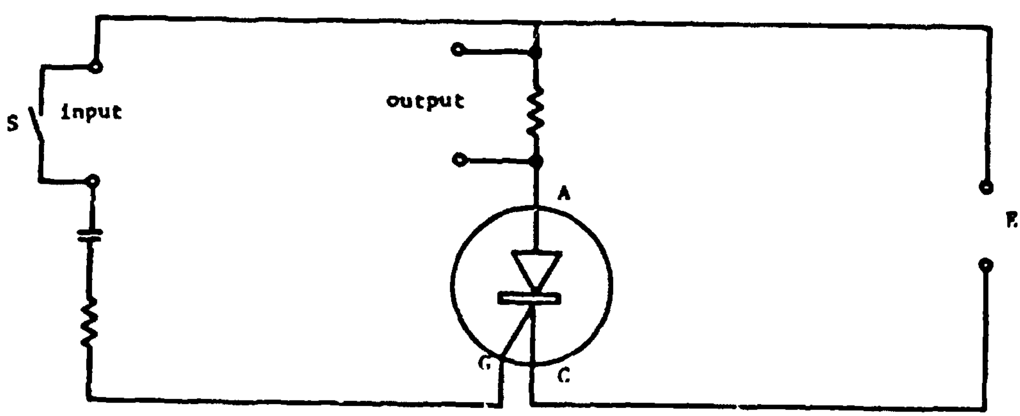


Figure 7-16. Simplified Thyristor Circuit

The most common output devices will now be discussed.

7-2.2.3.1 COUNTER

A counter is an electronic device that will display frequency, period, and time interval. Its most frequent PAD uses are to: (1) monitor oscillator signals to an oscillograph, and (2) monitor time intervals to obtain delay times and velocities. A typical counter is shown in Fig. 7-17.

To measure time intervals, channel A is fed the "start" signal and channel B the "stop" signal.

The counter functions as follows. Input signals are amplified, limited, and shaped into suitable pulses. A time interval is measured by counting the pulses of an internal generator occurring between the beginning and end of the interval. The internal generator is extremely stable and its frequency is set very precisely.

7-2.2.3.2 OSCILLOGRAPH

An oscillograph creates a permanent graphic record of a test. The medium is a strip of paper that is ultraviolet light sensitive and receives such light from reflecting galvanometers. These ballistic galvanometers consist of a coil (with a mirror attached) that is free to rotate within a magnetic field. As current is applied to the coil, the magnetism thus generated interacts with the stationary magnetic field and the coil-mirror rotates. In oscillographs, ultraviolet light is radiated toward the mirror and the reflected light beam shines on the graph paper. The system is designed so that the deflection on the paper is proportional to the input current (see Fig. 7-18).

Twelve or more of these galvanometers are placed in a graph and hence multichannel data may be recorded; for an example, see Fig. 7-19. The recording is produced by the galvanometer system just described plus a precision speed motor that drives the paper.

7-2.2.3.3 PRINTER

This is a typewriter printer that receives output from a minicomputer. It will printout in any format to which it has been programmed. Printers usually are programmed only to print data summaries.

7-2.2.3.4 OSCILLOSCOPE

This is an output device that displays a visual trace of incoming voltages on the face of a cathode ray tube. An electron beam in the tube is controlled precisely by horizontal and vertical deflection plates as electrical signals are applied to their terminals. The electron beam creates a visible trace when it strikes the face of the tube and activates the phosphor there. The oscilloscope has high input impedance and high frequency re-

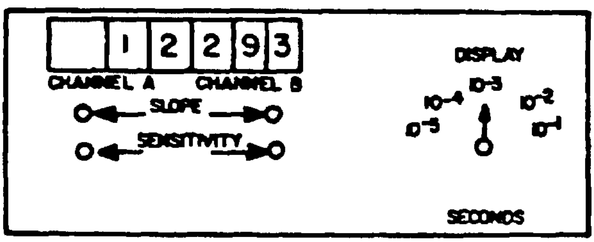


Figure 7-17. Typical Counter

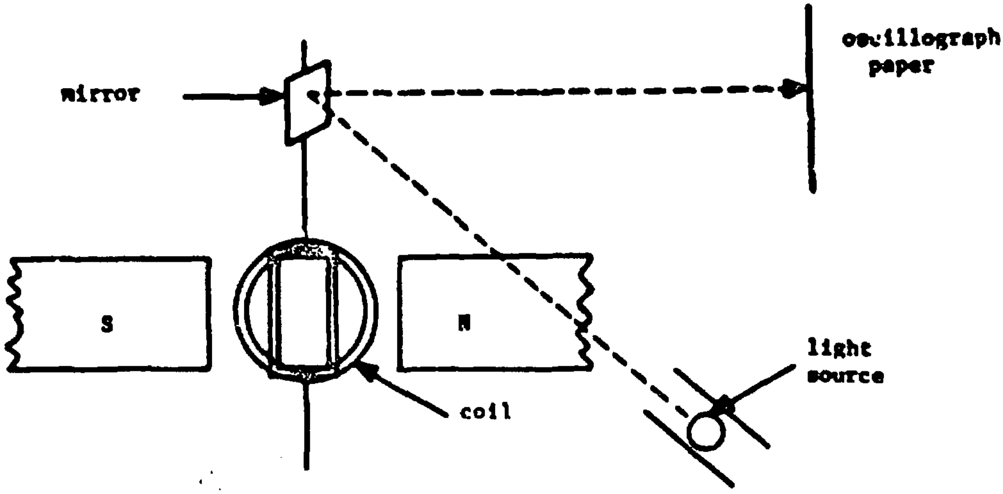


Figure 7-18. Oscillograph Galvanometer System

sponse, and is quite versatile in use. Its major drawback is the temporary nature of its display. This can be overcome by use of a camera.

7-2.2.3.5 OTHER OUTPUT DEVICES

Other output devices, such as peak readers, are available but have limited use in PAD. The oscillograph is the most essential PAD output device since it produces a complete, analog, and permanent record of a ballistics test.

7-2.3 FIRING SYSTEM

All items fired in PAD ranges are actuated remotely by means of an electric firing system. This system consists of a power supply and switch, a firing line and connectors, a firing signal monitor, and safety breaks in the line.

7-2.3.1 POWER SUPPLY AND SWITCH

Gas-actuated PAD's generally are fired by releasing highly compressed air (1300 psi) into the firing pin chamber. This air duplicates the action of gases from an initiator. The compressed air is fed from a tank through hose and air reservoir to a solenoid valve. When the solenoid is actuated (by a 26 V electric signal for approximately 50 msec) it passes the air into a hose and then into the PAD firing pin chamber (see Fig.

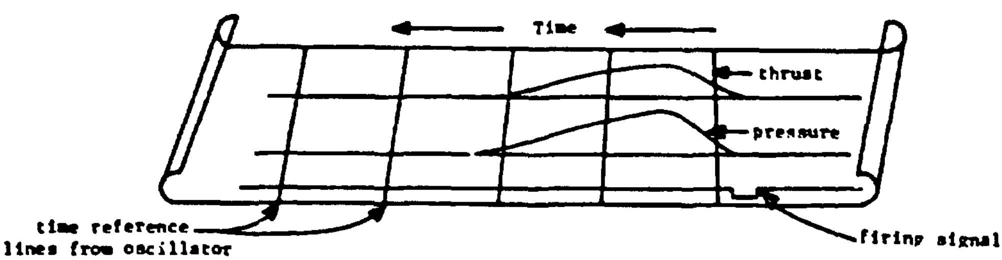


Figure 7-13. An Oscillograph Record

7-20). The solenoid selected should be such that the hose line to the PAD is vented to the atmosphere when the solenoid is not actuated. This is a safety precaution so pressure can't accidentally accumulate behind the firing pin.

Mechanically actuated PAD's are designed to be operated by pull of a cable. In testing, however, an air piston pulls the cable. Low pressure (300 psi) compressed air is released through a solenoid (as described in preceding paragraph) into an air cylinder in front of an air piston. This pressure acting on the piston area produces the force necessary (usually about 30 lb) to activate the PAD (see Fig. 7-21).

Electrically actuated PAD's are fired either by transient or steady power. In the first case, a capacitor with high voltage (over 100 V) in storage is discharged across the electric element. Although the energy applied is momentary, it will suffice to actuate most ignition elements. In the other case, a constant voltage or current can be applied by a regulated power supply. This introduces more control and is specified in some ignition element tests. In some cases, it is required that the current be applied for a maximum time period, such as 50 msec, and thus, interval timers must be added in the firing circuit.

The power supply is connected to the firing line by a switch marked "off-fire". In the "off" position, every wire in the firing line must be open as a safety feature. A "momentary" switch is preferable for the firing switch.

7-2.3.2 FIRING LINE AND CONNECTORS

The firing line (usually a two-wire shielded cable) should be run in trays apart from AC power lines and should be isolated from strong electrostatic and electromagnetic fields. Insulation should be of good quality and conform to manufacturer's meg-ohm requirements. The connectors should be in good condition and be shielded effectively.

7-2.3.3 FIRING SIGNAL MONITOR

The firing signal is monitored by a pulse being sent to the oscillograph when the firing switch is closed. Ignition of electric elements can be monitored completely by directing a small, but proportionate, amount of the firing current to the graph.

7-2.3.4 SAFETY BREAKS IN THE FIRING LINE

There should be at least three safety breaks in the firing line. One safety break is controlled by the instrument operator, the one who throws the "fire" switch. The "break" consists of an open circuit in the form of a (female) jack. When the instrument operator inserts his "safety plug" into this receptacle, he completes the circuit. The operator should insert this plug only when the PAD is ready to be tested and the range is clear of personnel.

A second safety break is controlled by the proof technician, the person who connects the firing line to the PAD or actuation device. The "break" is located in the instrument room (not the test area) and opens all wires in

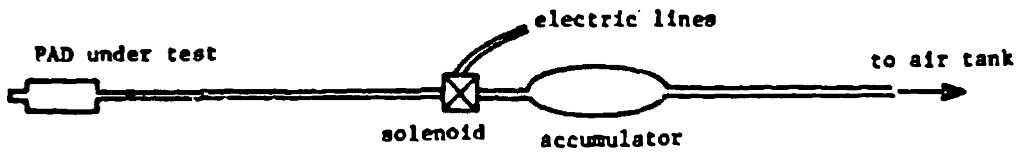


Figure 7-20. Gas Actuated PAD Firing Apparatus

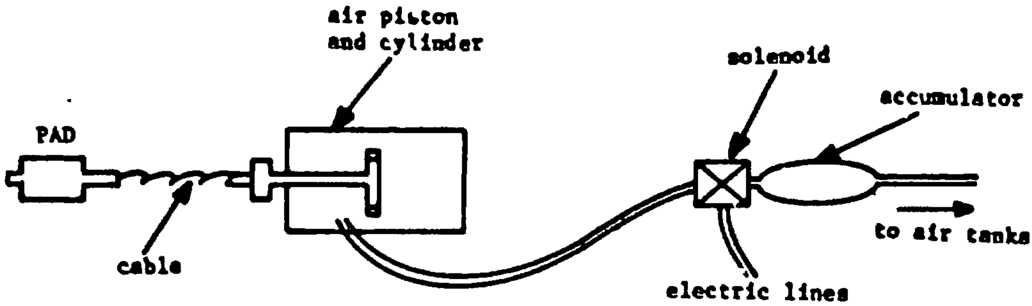


Figure 7-21. Mechanically Actuated PAD Firing Apparatus

the firing circuit. The matching safety plug is carried by the proof technician and is inserted into the jack only after the firing line has been connected and the range is clear of personnel.

Finally, a safety break is located on the exit door from the firing range. This break is automatic: When the door is open the firing circuit is open; when the door is closed, the firing circuit is closed. Once again, all wires in the firing line are open at this break. The purpose of this break is to open the circuit when personnel are in the range (since the door will be open under this circumstance). When the personnel leave the test area before the test, they will close the door and also close the firing circuit.

7-2.3.5 SEQUENCING SYSTEM

Timers can be arranged to sequence several normally manual operations. This eliminates operator sequencing mistakes. For example, by the push of a single button, the following events automatically transpire: (1) warning siren is triggered, (2) oscillograph starts running, and (3) the PAD is sent a firing pulse.

7-2.4 TEST FIXTURES

A variety of test fixtures are in use, and fall into two basic categories by function: (1) static fixtures (involving no motion) for gas generating devices, and (2) dynamic fixtures for stroking devices.

7-2.4.1 FIXTURE DESIGN CONSIDERATIONS

Test fixtures generally are fabricated from standard structural steel members and mechanical components. Safety factors are quite high because the fixtures will be used repeatedly and must withstand the stresses due to both R & D and production testing. Furthermore, since the fixtures are used frequently, they must be capable of rapid reemployment.

Moving parts should be as frictionless as possible. They should be supported in such a way that they don't twist and bind. The most common test fixture element is the holding apparatus that holds the PAD (or stationary section of PAD) in place during the test. Sometimes an accelerometer or magnetic pickup is attached in order to sense vibration when the PAD actuates and, hence, produce a "start" time signal.

7-2.4.2 COMMON TEST FIXTURES

The three fixtures most frequently used are: (1) the pressure chamber, a static fixture for initiators, (2) constant load cylinder, a dynamic fixture for thrusters, and (3) carriage and track, a dynamic fixture for catapults.

7-2.4.2.1 PRESSURE CHAMBER

Pressure chambers are used for testing gas-generating devices such as initiators. The fixture is a cylindrical chamber of a specified volume, usually 0.062 in.^{3} or 1 in.^{3} (see Fig. 7-22). The chamber is provided with at least two ports: one for the hose which leads the gas into the chamber, and the other to permit insertion of a pressure transducer. Sometimes a third port is used with a valve for rapid and convenient release of pressure after firing. If a pulse indicating start of rise of pressure is desired, then a pressure switch can also be added. Care must be taken not to change the system volume with these additional features. This can be accomplished by taking up added volume with incompressible grease, reducing volume of basic chamber, etc. Any of these changes must be examined to insure they are not detrimental to instrumentation accuracy.

7-2.4.2.2 CONSTANT LOAD CYLINDERS

Constant load cylinders are designed for PAD's (thrusters) which have short strokes and operate against constant loads of thousands of pounds. The thruster is positioned (see Fig. 7-23) so that its stroking member moves a piston in a cylinder against pressurized air. The initial volume of the cylinder is so large that the change in volume resulting from the moving piston is negligible. Since the volume is constant so is the pressure which acts on the piston area and hence a constant load is produced which opposes the motion of the thruster. Some cylinders are designed so that air pressure can be built up on either side of the piston. This method allows evaluation of retracting type thrusters (where the piston withdraws into the device) as well as pushing type thrusters. Load cells, pressure gages, velocity switches, etc. can be mounted on this fixture.

7-2.4.2.3 TRACK AND CARRIAGE

The track can be vertically mounted on a tower (Fig. 7-24) or horizontally mounted. Catapults and removers stroke against a load (carriage) and propel it. By use of different carriages and various weighted attachments, the total carriage weight can range between 60 lb and 1200 lb. One end of the PAD is secured to the base of the fixture and the other end is attached to the carriage. When the device strokes, it propels the carriage up the track. In the case of the vertical track, a pair of brake shoes on the carriage contacts the rails and decelerates the carriage.

The carriage is held at its maximum height and lowered as follows. An endless chain,

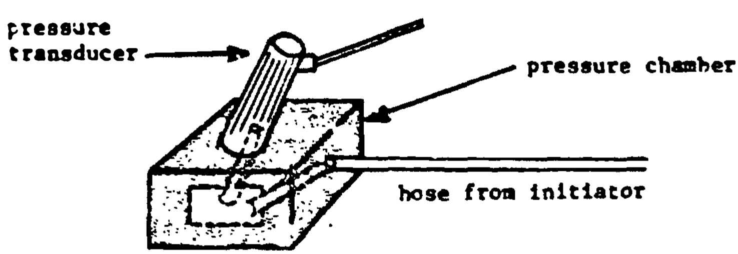


Figure 7-22. Pressure Chamber Fixture

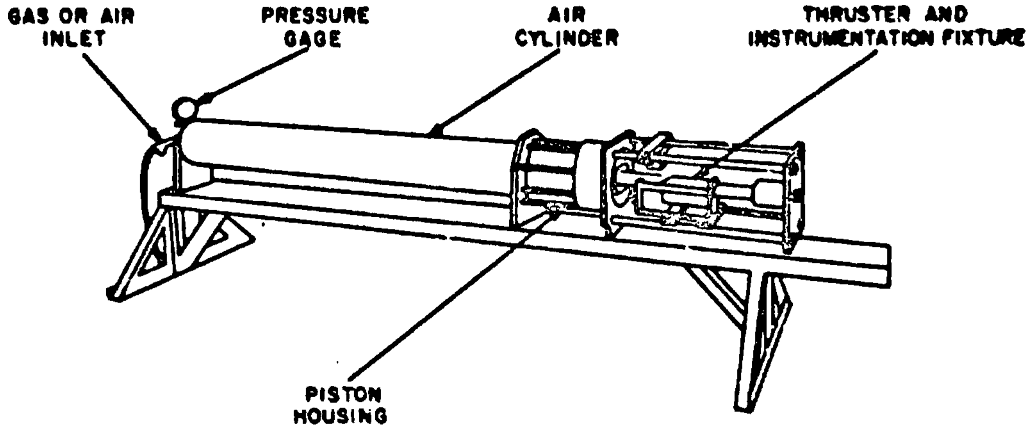


Figure 7-23. Constant Load Cylinder

running the length of the tower, normally is held fixed but may be driven upward or downward by an electric motor. The sprocket on the carriage engages this chain and, by virtue of an included clutch, may spin freely as the carriage ascends but it is prevented from spinning in the opposite direction; therefore, when the carriage has reached its maximum height, it will be held there by the sprocket chain combination. To lower the carriage, the chain is driven in the downward direction, permitting the carriage to fall as rapidly as the chain descends. The chain also may be driven upward to raise the carriage for adjusting the PAD under test.

On the horizontal fixture the track is short and the carriage travels about 15 ft before it is decelerated and stopped by a spring and hydraulic buffer. It is returned to starting position manually.

7-2.4.2.4 OTHER FIXTURES

Other PAD testing facilities include the bomb ejector rack, water recovery fixture, seals tester, parachute ejector fixture, rotary actuator test fixture, grenade launcher, etc. Their use is for specific PAD's.

7-2.5 PAD PARAMETERS

Direct measurement of PAD parameters is preferable to inferential since there is less chance for error. Hence, many PAD variables are monitored in order to avoid inferential treatment. For example, catapult acceleration can be computed from the thrust monitored on a load cell; but it can be more directly measured by use of an accelerometer. The paragraphs that follow will list the most important measured PAD parameters.

7-2.5.1 DIMENSION PARAMETERS

7-2.5.1.1 LENGTH

Length is measured to insure correct dimensional alignment on fixture, to obtain travel distance, to insure precision spacing of magnetic pickups (for velocity measurements), to determine wear and corrosion on parts due to firing, and to reduce data accurately on instrument graphic output devices. Dimension gages, steel rules, and steel tapes are used to measure length.

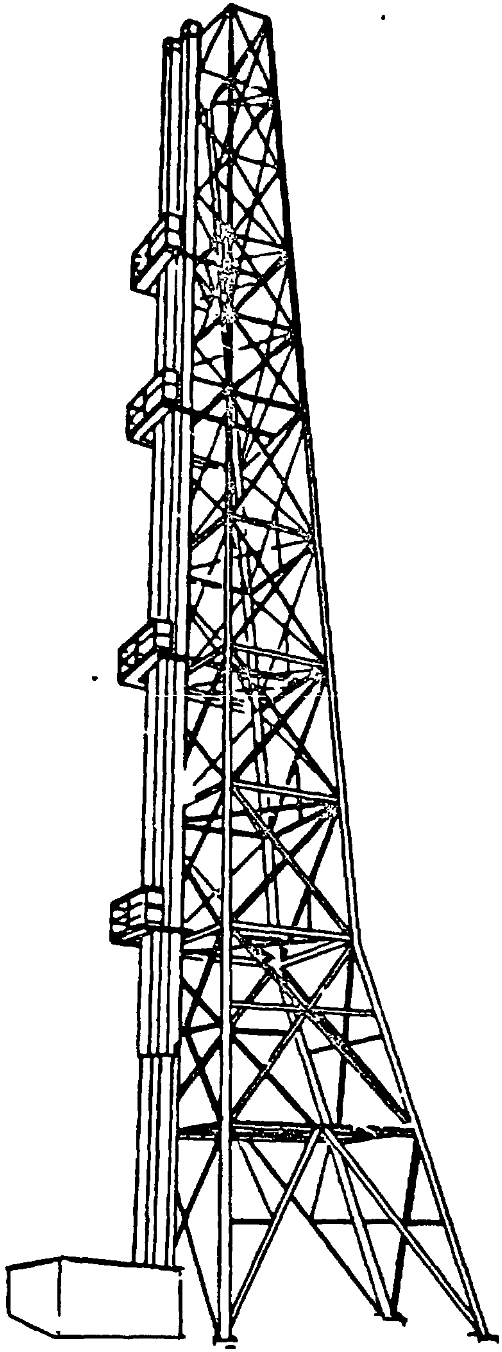


Figure 7-24. Vertical Test Tower

7-2.5.1.2 AREA

Areas of cross sections are measured to establish dimensional changes due to firing of PAD's, to integrate oscillograph traces, etc. Telescoping gages, dimension gages, and planimeters are used.

7-2.5.1.3 VOLUME

Volumes of fittings and chambers used in tests need to be known because pressure is a function of system volume. Occasionally, liquid agents are employed in PAD work and their volume must be measured. Dimension gages and graduated cylinders determine volume.

7-2.5.1.4 ANGLE

The machined angle of rocket nozzles is very useful information since it is related directly to the effective thrust angle. A level protractor or angle transducer can be used.

7-2.5.2 TIME PARAMETERS

7-2.5.2.1 TIME INTERVALS

Time interval measurements are necessary to compute velocity using travel sensors. Time intervals also determine delay times, period measurements, etc. Counters are used to monitor time intervals.

7-2.5.2.2 FREQUENCY

Sometimes it is desirable to measure frequency, such as for galvanometer calibration. Frequency can be produced by an oscillator and monitored by a counter.

7-2.5.3 MOTION PARAMETERS

7-2.5.3.1 VELOCITY

This is a required measurement on most stroking PAD's such as catapults. It is obtained indirectly by dividing a known distance between sensors by the time it takes for the moving item to travel that distance. Therefore, a steel rule and a counter must both be used.

7-2.5.3.2 ACCELERATION

This is a required measurement on catapult tests. A strain gage accelerometer monitors this parameter.

7-2.5.3.3 RATE OF CHANGE OF ACCELERATION $\dot{g}$

This is a requirement on older type catapults. It was used as an indication of dynamic effects on a pilot but has been superceded by the Dynamic Response Index (DRI) on newer type catapults. Rate of charge of acceleration is measured from the acceleration-time curve.

7-2.5.3.4 ACCELERATION-TIME INTEGRAL $\int a dt$

This is a requirement on catapults. It is determined by integrating the acceleration-time curve.

7-2.5.3.5 DYNAMIC RESPONSE INDEX (DRI)

It is a requirement on newer type catapults and is a single numerical indicator of the physiological response of a pilot to ejection dynamics. Since the DRI is a solution of a second order differential equation with equation acceleration as the driving function, manual derivation is difficult, and hence a minicomputer is programmed to sample acceleration and compute the DRI.

7-2.5.4 FORCE DERIVED PARAMETER

7-2.5.4.1 FORCE

Force is a requirement on all stroking

PAD's. It defines the thrust available to move a seat-man combination or an aircraft component. Load cells are used for its determination.

7-2.5.4.2 WEIGHT

Propellant is weighed carefully since this weight is an important determinant of other ballistic parameters. Weight of carriages is important in catapult, remover, and some thruster fixtures since this represents the specified resistance load that must be overcome. Generally, weights are measured with precision scales.

7-2.5.4.3 FORCE-TIME INTEGRAL $\int Fdt$

This is the total impulse and in some cases is the most important characteristic of a stroking device. It is obtained by integrating the force-time curve.

7-2.5.4.4 PRESSURE

Chamber pressure is always an important consideration regarding structural strength of the PAD hardware. It is the prime parameter in initiator tests and an important additional parameter of rocket catapult firings. It is measured by a strain gage pressure transducer. For extremely fast response a piezoelectric pressure gage can be used.

7-2.5.4.5 PRESSURE-TIME INTEGRAL $\int Pdt$

The pressure-time integral is the pressure analog to the impulse. It is determined through integration of the pressure-time curve.

7-2.5.4.6 TORQUE

Torques are specified for assembly and disassembly of PAD's, and a torque wrench is used to meet requirements. On most stroking PAD's, zero torque should be produced during ballistic tests. This zero condition can be checked by load cells properly arranged.

7-2.5.5 ELECTRICAL PARAMETERS

7-2.5.5.1 CURRENT

Current entering ignition elements can be monitored continuously by use of a current proportioner that selects a small, proportionate (< 1%) amount of the total current and directs it to a galvanometer. The current also can be passed directly through an ammeter.

7-2.5.5.2 VOLTAGE

Voltage often must be monitored in a firing system, etc. As with the case of current, a small, proportionable amount can be applied to a galvanometer, or it can be measured directly by a voltmeter.

7-2.5.5.3 RESISTANCE

Resistance usually is checked before and after firing of electric ignition elements. An ordinary meter should not be used to check the resistance since it may pass a significant current and set off the element accidentally. Only igniter testers should be used since they limit the current to less than 5 mA.

7-2.5.5.4 AMPLIFIER CHARACTERISTICS

This involves measurement of gain, linearity, and flatness of frequency response. This is accomplished by use of digital voltmeters, oscillators, etc.

7-2.5.6 OTHER PARAMETERS

7-2.5.6.1 CASE TEMPERATURE

This is sometimes used to indicate heat loss in a PAD. A thermocouple system is employed.

7-2.5.6.2 FLAME TEMPERATURE

This is an accessory thermodynamic parameter for rockets. It can be measured by remote sensing instruments.

7-2.5.6.3 FLOW

Occasionally air flow studies are conducted. Electronic or visually indicating equipment is used.

7-2.5.6.4 ACOUSTICAL PARAMETERS

Frequency and amplitude of sound emitted from a PAD during a ballistic test provide an additional method of accessing firing characteristics.

7-2.6 INITIATOR TESTING

7-2.6.1 PARAMETERS

Usually two parameters are measured: pressure and time. The peak pressure is important because it is the best single indication of the ability of the initiator to activate another device such as a catapult. The rise time is monitored to insure firing with minimum hesitation ($<$ 50 msec). The exception is the delay initiator that is purposely designed to pause between its actuation and firing.

7-2.6.2 FIXTURES

The initiator is mounted on a block that has a magnetic sensor inserted against a steel pin. When the initiator is activated, the pin vibrates and this induces the sensor to generate a start pulse (par. 7-2.2.1.3). Behind the initiator is placed the firing mechanism (par. 7-2.3.1). A hose leads from the initiator (Fig. 7-25) and enters the pressure chamber (par. 7-2.4.2.1) where a pressure transducer and a pressure switch are located.

7-2.6.3 INSTRUMENTATION

As mentioned in par. 7-2.6.2, the magnetic sensor generates a start signal that is transmitted to the graph and counter. The stop signal is generated by a pressure switch electrically connected to a thyratron. This pulse goes directly to the counter and through an impedance matching attenuating network into a galvanometer. Both the graph and counter, therefore, will display the time interval from activation of the initiator to start of pressure rise in the pressure chamber. In the case of delay initiators, this time will be the delay time of the initiator. The pressure transducer at the pressure chamber is connected to an oscillograph (through an amplifier) and provides a continuous pressure-time trace (see Fig. 7-26) which is used to determine peak pressure and time to peak.

7-2.6.4 REPORT

The report lists identifying information, peak pressure, and ignition or delay time.

7-2.6.5 SPECIAL CONSIDERATIONS

It is imperative that there be no gas leaks in the system. Before firing, all fittings and valves should be tightened. Evidence of gas leak is (1) propellant ash or dust around fittings or (2) rapid decrease of pressure-time curve on oscillograph trace.

7-2.7 THRUSTER TESTING

7-2.7.1 PARAMETERS

Four characteristics are of interest: peak thrust, stroke length, velocity, and ignition delay. The peak thrust is important because it is the best single indication of the ability of the thruster to move a load. The stroke length determines that the thruster move the load a sufficient distance. The velocity indicates the quickness with which it accomplishes its task, and the ignition delay must be monitored to insure that the time between ignition pulse and development of thrust is not excessive. (should be less than 25 msec).

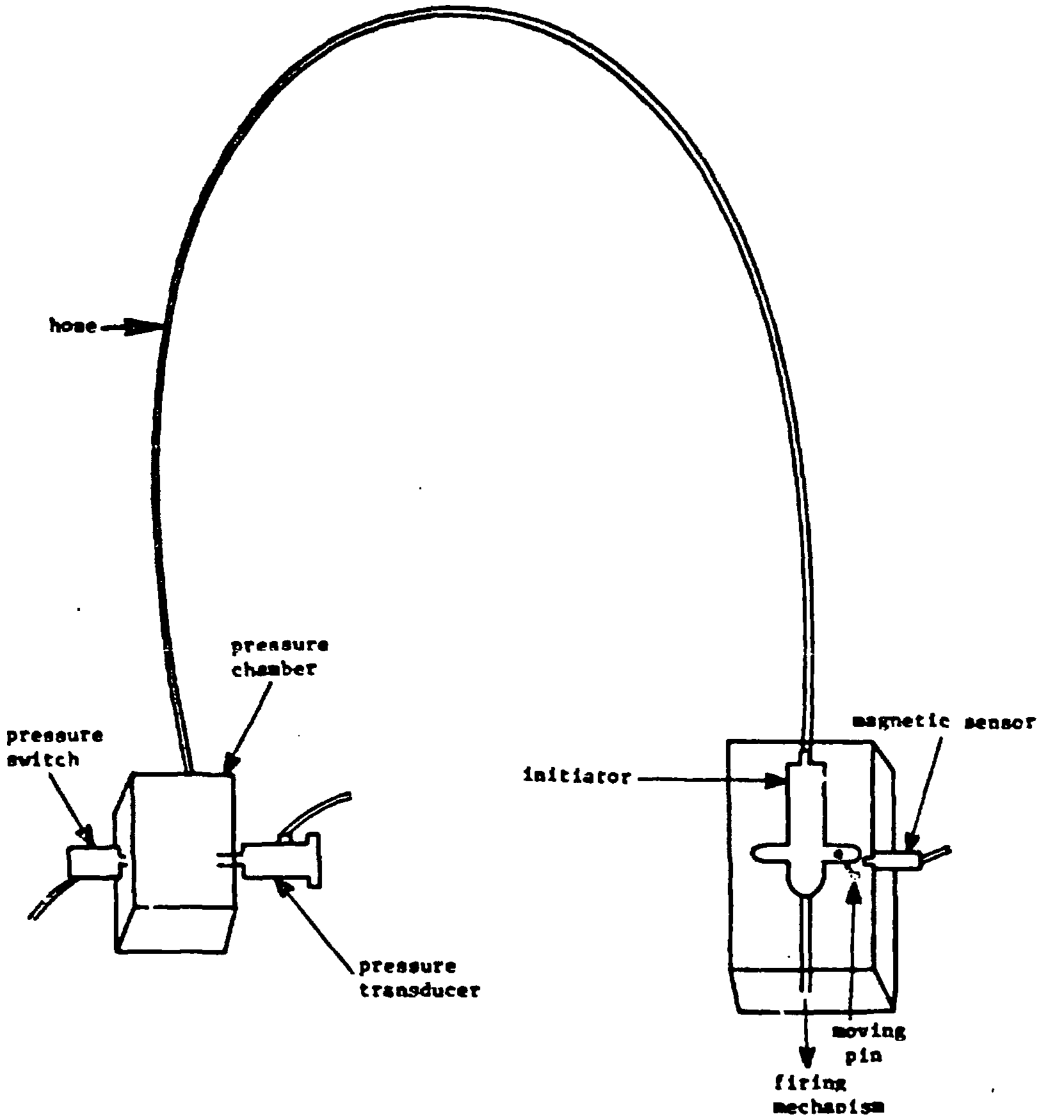


Figure 7-25. Initiator With Instrumentation Fixture

7-2.7.2 FIXTURES

The constant load cylinder (par. 7-2.4.2.2) is used with thrusters since their specifications usually call for a constant resistive load.

7-2.7.3 INSTRUMENTATION

Instrumentation on the thruster fixture is shown in Fig. 7-27. Completion of stroke is noted by magnetic sensor or lead break (using

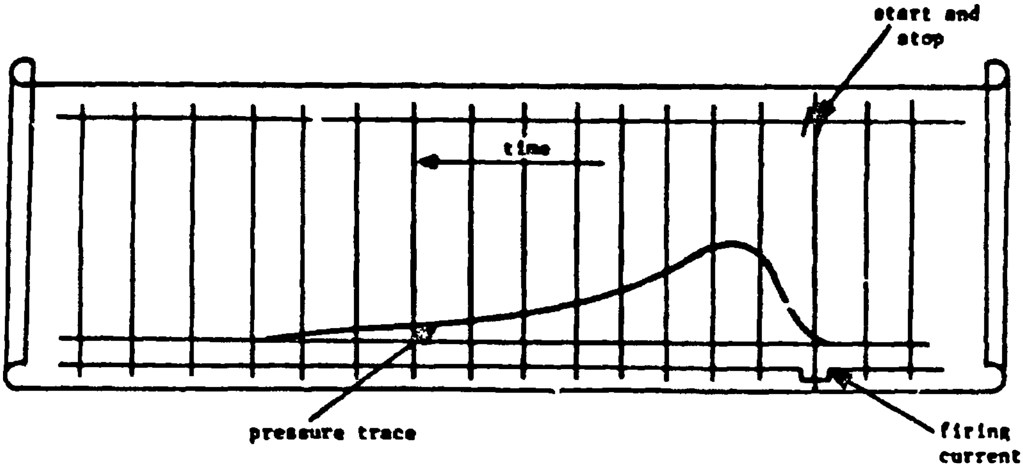


Figure 7-26. Initiator Trace

thyratron). The thrust is monitored continuously by a load cell (which generates a thrust-time curve). When velocity is measured it is done by means of magnetic sensor signals. For sample thruster curve, see Fig. 7-28.

7-2.7.4 RECORD

Besides identifying information; thrust (peak), velocity, stroke, and ignition delay are reported.

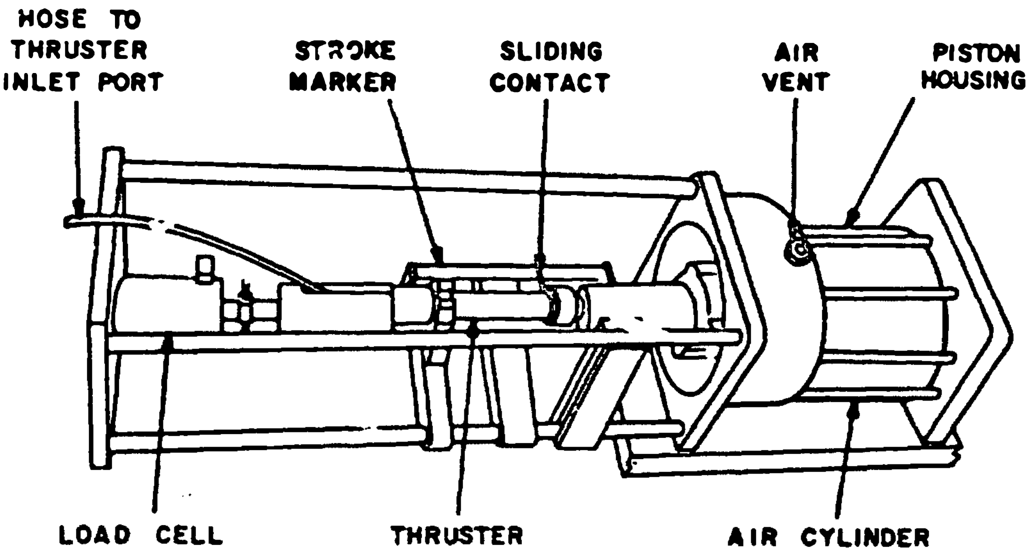


Figure 7-27. Thruster and Instrumentation Fixture

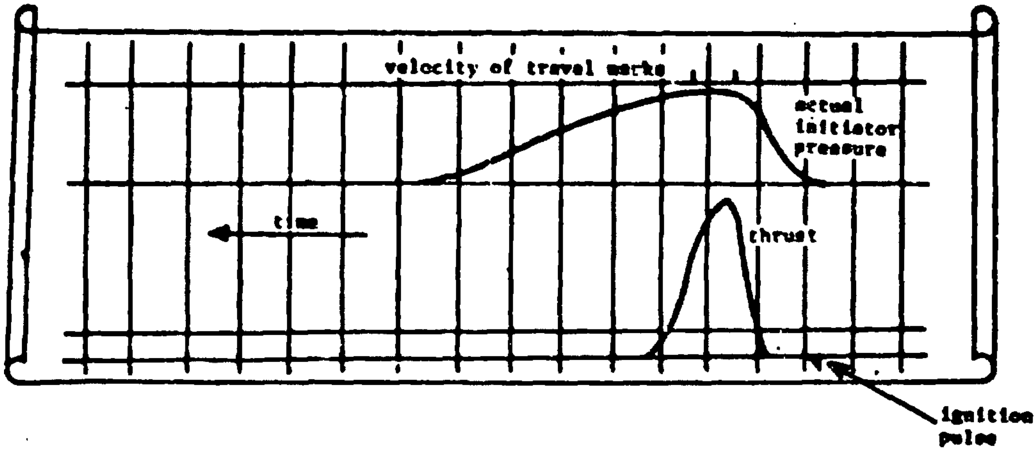


Figure 7-28. Thruster Trace

7-2.7.5 SPECIAL CONSIDERATION

Sliding parts in fixture must be kept lubricated. If shearpins are used, care must be taken to insure proper dimension.

7-2.8 ROCKET CATAPULT TESTING

7-2.8.1 PARAMETERS

The single best indicator of catapult performance is the DRI. The single best indicator of rocket performance is impulse $\int Fdt$. The other parameters measured (pressure, thrust, time, acceleration, velocity) are important supplements to the two basic parameters.

7-2.8.2 FIXTURES

The carriage and horizontal track are used (par. 7-2.4.2.3). Whereas in the aircraft the "stationary" section of the rocket catapult is attached to the aircraft, in testing in ballistic tracks the same section is attached to the carriage. This is done so the rocket (sustainer) section will remain affixed to the stationary fixture so it can be measured on a load cell.

7-2.8.3 INSTRUMENTATION

The instruments are attached to the track as in Fig. 7-29. Pressure gages, accelerometer, and load cells measure the parameters. The carriage contains a rack with gear teeth which, when passing fixed magnetic sensors, will induce in the sensors signals that indicate "travel" and velocity. Automatic data processing equipment is needed to compute DRI conveniently. A typical oscillograph trace of a rocket catapult test is shown in Fig. 7-30. The curves that occur first (to the right) are catapult curves. These curves should, and do, look the same because they are merely different aspects of the same phenomenon. Above them occur the travel marks indicating inches of travel and the two velocity marks. To the left occur the curves due to firing of the rocket motor. Again all these are similar. One load cell measures axial thrust and the other normal to axial thrust. The resultant thrust can be calculated by vectoral addition.

7-2.8.4 REPORT

The report states identifying data, ignition and delay times, $\int Pdt$, $\int Fdt$, acceleration, velocity, and DRI.

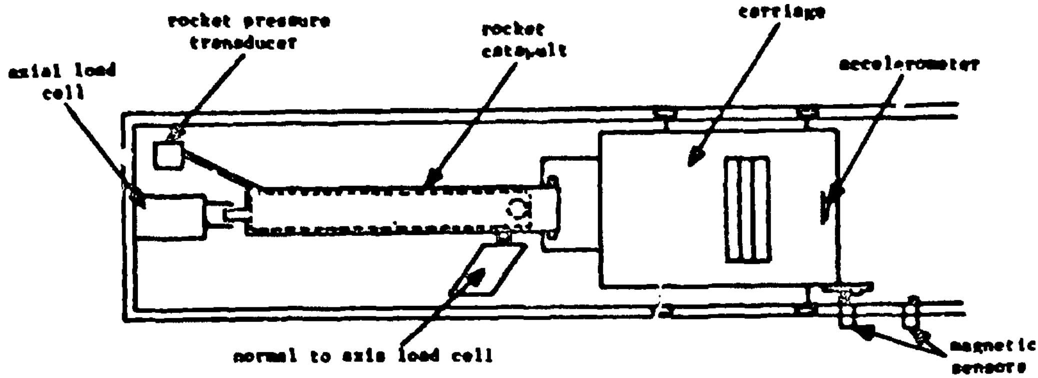


Figure 7-29. Instrumentation on Horizontal Track for Rocket Catapult Test

7-2.8.5 SPECIAL CONSIDERATIONS

Catapult tubes must be aligned to prevent binding and side loading. The deceleration buffer, if one is used, should be gentle enough so that ballistic tests will not damage PAD hardware or instruments attached to the carriage.

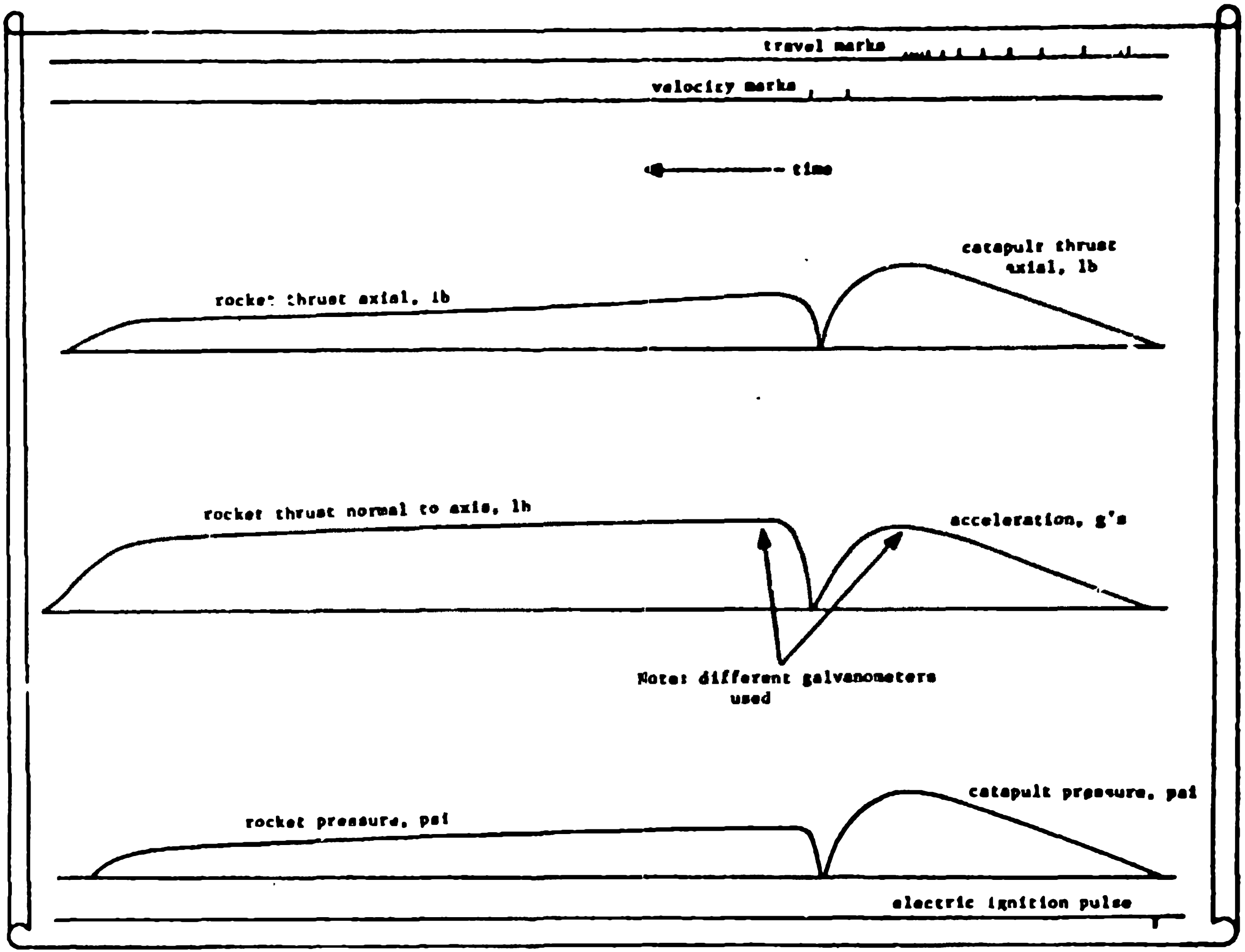


Figure 30. Rocket Catapult Trace

APPENDIX A

CONVERSION OF DISTORTION ENERGY EQUATION TO MORE USEFUL FORMS FOR PROPELLANT ACTUATED DEVICES

A-1 TRIAXIAL STRESSES

A-1.1 GENERAL

$$2\sigma_e^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 \qquad (4\text{-}33)$$

where

σ_e = minimum yield stress = Y

σ_1 = radial stress = $-P$

σ_2 = tangential stress

σ_3 = axial stress

P = maximum internal pressure

† Lame's Formula.

A-1.2 TANGENTIAL STRESS†

$$\sigma_2 = P\left(\frac{W'^2 + 1}{W'^2 - 1}\right) = P\left(\frac{D^2 + d^2}{D^2 - d^2}\right) \qquad (A\text{-}1)$$

where

W' = wall ratio of tube $\left(\frac{D}{d}\right)$

d = inside diameter

D = outside diameter

A-1.3 AXIAL STRESS

$$\sigma_3 = \frac{F}{A_{out} - A_{in}} = \frac{\frac{P\pi d^2}{4}}{\frac{\pi D^2}{4} - \frac{\pi d^2}{4}} \qquad (A\text{-}2)$$

$$= P\left(\frac{d^2}{D^2 - d^2}\right)$$

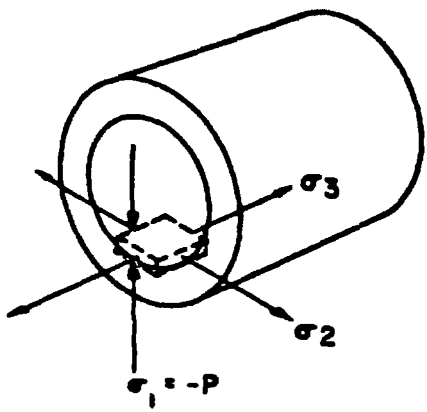


Figure A-1. Stress Parameters

where

F = force delivered to end

A = cross-sectional area

Substituting the values of σ_1, σ_2, and σ_3 from Eqs. A-1 and A-2 into Eq. 4-33 yields

$$2Y^2 = \left[-P - P\left(\frac{D^2 + d^2}{D^2 - d^2}\right)\right]^2$$

$$+ \left[P\left(\frac{D^2 + d^2}{D^2 - d^2}\right) - P\left(\frac{d^2}{D^2 - d^2}\right)\right]^2$$

$$+ \left[-P - P\left(\frac{d^2}{D^2 - d^2}\right)\right]^2$$

$$2Y^2 = \frac{6P^2 D^4}{(D^2 - d^2)^2}$$

$$\therefore P^2 = \frac{Y^2(D^2 - d^2)^2}{3D^4}$$

$$P = \frac{Y}{\sqrt{3}}\left[1 - \left(\frac{d^2}{D^2}\right)\right]$$

$$P = \frac{Y}{\sqrt{3}}\left(1 - \frac{1}{W'^2}\right)$$

$$\frac{P}{Y} = \frac{1}{\sqrt{3}}\left(\frac{W'^2 - 1}{W'^2}\right) \qquad (4\text{-}33)$$

A-2 BIAXIAL STRESSES

$$\frac{P}{Y} = \frac{W'^2 - 1}{(3W'^4 + 1)^{1/2}} \qquad (4\text{-}35)$$

The derivation of equation 4-36 is identical with that of equation 4-34, except that the axial stress σ_3 is zero. A derivation of this equation and tables of values of W' for values of P/Y are presented in a report on the design of gun tubes.

APPENDIX B

TABLE OF WALL RATIOS

where

P = maximum internal pressure (psi)

Y = minimum strength of material (psi)

W' = wall ratio (outside dia/inside dia)

P/Y	W'	
	Biaxial	Triaxial
0.010	1.0101	1.0088
0.011	1.0111	1.0097
0.012	1.0122	1.0106
0.013	1.0132	1.0114
0.014	1.0142	1.0123
0.015	1.0153	1.0132
0.016	1.0163	1.0141
0.017	1.0173	1.0151
0.018	1.0183	1.0160
0.019	1.0194	1.0169
0.020	1.0204	1.0178
0.021	1.0215	1.0187
0.022	1.0225	1.0196
0.023	1.0236	1.0205
0.024	1.0246	1.0214
0.025	1.0257	1.0224
0.026	1.0267	1.0233
0.027	1.0278	1.0242
0.028	1.0288	1.0251
0.029	1.0299	1.0261
0.030	1.0309	1.0270
0.031	1.0320	1.0280
0.032	1.0331	1.0289
0.033	1.0342	1.0299
0.034	1.0352	1.0308
0.035	1.0363	1.0318
0.036	1.0374	1.0327
0.037	1.0385	1.0337
0.038	1.0396	1.0346
0.039	1.0406	1.0354
0.040	1.0417	1.0365
0.041	1.0428	1.0375
0.042	1.0439	1.0385
0.043	1.0450	1.0395
0.044	1.0461	1.0404
0.045	1.0472	1.0414
0.046	1.0482	1.0424
0.047	1.0493	1.0434
0.048	1.0504	1.0443
0.049	1.0515	1.0453

P/Y	W'	
	Biaxial	Triaxial
0.050	1.0526	1.0463
0.051	1.0537	1.0473
0.052	1.0549	1.0483
0.053	1.0560	1.0493
0.054	1.0571	1.0503
0.055	1.0582	1.0513
0.056	1.0594	1.0523
0.057	1.0605	1.0533
0.058	1.0616	1.0543
0.059	1.0628	1.0554
0.060	1.0639	1.0564
0.061	1.0651	1.0574
0.062	1.0662	1.0584
0.063	1.0674	1.0595
0.064	1.0685	1.0605
0.065	1.0697	1.0615
0.066	1.0709	1.0626
0.067	1.0720	1.0636
0.068	1.0732	1.0647
0.069	1.0743	1.0657
0.070	1.0755	1.0668
0.071	1.0767	1.0678
0.072	1.0779	1.0688
0.073	1.0790	1.0699
0.074	1.0802	1.0710
0.075	1.0814	1.0721
0.076	1.0826	1.0731
0.077	1.0838	1.0742
0.078	1.0849	1.0753
0.079	1.0861	1.0763
0.080	1.0873	1.0774
0.081	1.0885	1.0785
0.082	1.0897	1.0796
0.083	1.0910	1.0807
0.084	1.0922	1.0818
0.085	1.0934	1.0829
0.086	1.0946	1.0840
0.087	1.0958	1.0851
0.088	1.0971	1.0862
0.089	1.0983	1.0873

P/Y	W'	
	Biaxial	Triaxial
0.090	1.0995	1.0884
0.091	1.1007	1.0895
0.092	1.1020	1.0907
0.093	1.1032	1.0918
0.094	1.1045	1.0929
0.095	1.1058	1.0940
0.096	1.1069	1.0952
0.097	1.1082	1.0963
0.098	1.1094	1.0975
0.099	1.1107	1.0986
0.100	1.1119	1.0998
0.101	1.1132	1.1009
0.102	1.1145	1.1021
0.103	1.1157	1.1032
0.104	1.1170	1.1044
0.105	1.1183	1.1056
0.106	1.1196	1.1067
0.107	1.1209	1.1079
0.108	1.1221	1.1091
0.109	1.1234	1.1103
0.110	1.1247	1.1115
0.111	1.1260	1.1127
0.112	1.1273	1.1139
0.113	1.1286	1.1151
0.114	1.1299	1.1163
0.115	1.1312	1.1175
0.116	1.1326	1.1187
0.117	1.1339	1.1199
0.118	1.1352	1.1211
0.119	1.1365	1.1223
0.120	1.1378	1.1236
0.121	1.1392	1.1248
0.122	1.1405	1.1260
0.123	1.1419	1.1273
0.124	1.1432	1.1285
0.125	1.1446	1.1297
0.126	1.1459	1.1310
0.127	1.1473	1.1322
0.128	1.1486	1.1335
0.129	1.1500	1.1348
0.130	1.1513	1.1360
0.131	1.1527	1.1373
0.132	1.1541	1.1386
0.133	1.1555	1.1399
0.134	1.1569	1.1412
0.135	1.1583	1.1424
0.136	1.1596	1.1437
0.137	1.1610	1.1450
0.138	1.1624	1.1463
0.139	1.1638	1.1476
0.140	1.1652	1.1489
0.141	1.1666	1.1503
0.142	1.1680	1.1516
0.143	1.1695	1.1529
0.144	1.1710	1.1542
0.145	1.1724	1.1556
0.146	1.1738	1.1569
0.147	1.1752	1.1583
0.148	1.1767	1.1596
0.149	1.1782	1.1610
0.150	1.1796	1.1623
0.151	1.1811	1.1637
0.152	1.1825	1.1650
0.153	1.1840	1.1664
0.154	1.1855	1.1678
0.155	1.1870	1.1692
0.156	1.1884	1.1706
0.157	1.1899	1.1720
0.158	1.1914	1.1734
0.159	1.1928	1.1748
0.160	1.1943	1.1762
0.161	1.1958	1.1776
0.162	1.1974	1.1790
0.163	1.1989	1.1804
0.164	1.2004	1.1818
0.165	1.2020	1.1833
0.166	1.2035	1.1847
0.167	1.2050	1.1861
0.168	1.2065	1.1876
0.169	1.2081	1.1891
0.170	1.2096	1.1905
0.171	1.2112	1.1920
0.172	1.2127	1.1934
0.173	1.2142	1.1949
0.174	1.2158	1.1964
0.175	1.2174	1.1979
0.176	1.2190	1.1994
0.177	1.2206	1.2009
0.178	1.2222	1.2024
0.179	1.2237	1.2039
0.180	1.2253	1.2054
0.181	1.2269	1.2069
0.182	1.2286	1.2084
0.183	1.2302	1.2100
0.184	1.2319	1.2115
0.185	1.2335	1.2131
0.186	1.2351	1.2146
0.187	1.2368	1.2162
0.188	1.2384	1.2177
0.189	1.2400	1.2193
0.190	1.2417	1.2209
0.191	1.2434	1.2224
0.192	1.2451	1.2240
0.193	1.2468	1.2256
0.194	1.2485	1.2272
0.195	1.2502	1.2288
0.196	1.2518	1.2304
0.197	1.2535	1.2320
0.198	1.2552	1.2337
0.199	1.2569	1.2353
0.200	1.2586	1.2369

APPENDIX C

DERIVATION OF EQUATION USED IN DETERMINING LENGTH OF ENGAGEMENT OF THREADS

Shear force of male = Force on female

$$S_s A_1 = P A_2$$

$$S_s \pi d \frac{L^{\dagger}}{2} = P \pi R^2$$

$$L = \frac{2PR^2}{S_s d}$$

where

A_1 = cylindrical shear area at assumed diameter

d = minimum minor diameter of screw

R = maximum major radius of nut

S_s = shear stress

L = length of engagement

P = pressure

Applying a safety factor of 1.5 yields

$$L = \frac{3PR^2}{S_s d} \qquad (4\text{-}37)$$

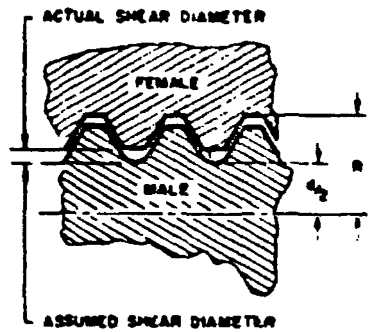


Figure C-1. Thread Parameters

†$L/2$ is substituted for L since only one-half (approximately) of the thread length actually is loaded in shear while resisting the internal pressure.

APPENDIX D

COMPUTER PROGRAM FOR SIMULATION OF DIRECT STROKING DEVICE

```
      PROGRAM SPBSD (INPUT,OUTPUT,TAPE1=INPUT,TAPE3=OUTPUT)
C     SOLID PROPELLANT DIRECT BALLISTIC STROKING DEVICE
C     LEONARD A DESTEFANO      CC JS100      CXT 6889
      DIMENSIONP(5),R(5),W(5),A(5),D(17),X(8),U(8),C(4,8),REX(4),S(4)
  100 FORMAT(1H140X,49HSOLID PROPELLANT DIRECT BALLISTIC STROKING DEVICE
     1//)
  101 FORMAT(5F16.5
  102 FORMAT(1H //)
  103 FORMAT(2X,10HTIME (SEC),3X,14HBURN DIST (IN),3X,19HCHARGE WEIGHT (
     1LBS),3X,15HPRESSURE (PSIA),3X,24HACCELERATION (FT/SEC SQ),3X,17HVE
     2LOCITY (FT/SEC),3X,11HSTROKE (FT))
  104 FORMAT(AX,4F10.3)
  105 FORMAT(5F16.3)
  106 FORMAT(14X,1HP,11X,1HR,9X,1HW,8X,1HA)
  107 FORMAT(3X,F7.4,F14.4,F19.3,2F22.2,F23.2,F17.3)
  108 FORMAT(8X,46H 1 COMPUTE INTERVAL (SEC) ....................F16.5)
  109 FORMAT(8X,46H 2 PRINT INTERVAL (SEC) ......................F16.5)
  110 FORMAT(8X,46H 3 STROKE (FT) ...............................F16.5)
  111 FORMAT(8X,46H 4 SHOT START PRESSURE (PSIA) ................F16.5)
  112 FORMAT(AX,46H 5 PISTON AREA (SQ IN) .......................F16.5)
  113 FORMAT(8X,46H 6 VENT AREA (SQ IN) .........................F16.5)
  114 FORMAT(8X,46H 7 PROPELLED LOAD (LBM) ......................F16.5)
  115 FORMAT(8X,46H 8 ANGLE OF ELEVATION (DEGREES) ..............F16.5)
  116 FORMAT(AX,46H 9 RETARDATION COEFFICIENT (LBF/FT) ..........F16.5)
  117 FORMAT(8X,46H10 THERMAL EFFICIENCY (DIMENSIONLESS) ........F16.5)
  118 FORMAT(8X,46H11 RATIO OF SPECIFIC HEATS (DIMENSIONLESS) ....F16.5)
  119 FORMAT(8X,46H12 PROPELLANT DENSITY (LBM/CU IN) .............F16.5)
  120 FORMAT(8X,46H13 PROPELLANT IMPETUS (FT-LBF/LBM) ............F16.5)
  121 FORMAT(8X,46H14 ADIABATIC ISOCHORIC FLAME TEMPERATURE (R) ..F16.5)
  122 FORMAT(AX,46H15 INITIAL PRESSURE (PSIA) ....................F16.5)
  123 FORMAT(8X,46H16 INITIAL FREE VOLUME (CU IN) ................F16.5)
    1 WRITE(3,100)
      READ(1,105)P,R,W,A
      WRITE(3,106)
      WRITE(3,104)(P(I),R(I),W(I),A(I),I=1,5)
      WRITE(3,102)
      DO2I=1,4
      REX(I)=(ALOG(R(I+1)/R(I)))/(ALOG(P(I+1)/P(I)))
    2 S(I)=(A(I+1)-A(I))/(W(I+1)-W(I))
      READ(1,101)D
      WRITE(3,108)D(1)
      WRITE(3,109)D(2)
      WRITE(3,110)D(3)
      WRITE(3,111)D(4)
      WRITE(3,112)D(5)
      WRITE(3,113)D(6)
      WRITE(3,114)D(7)
      WRITE(3,115)D(8)
      WRITE(3,116)D(9)
      WRITE(3,117)D(10)
```

```
      WRITE(3,118)D(11)
      WRITE(3,119)D(12)
      WRITE(3,120)D(13)
      WRITE(3,121)D(14)
      WRITE(3,122)D(15)
      WRITE(3,123)D(16)
      WRITE(3,102)
      WRITE(3,103)
      X(1)=W(1)
      X(2)=A(1)
      X(3)=D(15)*D(16)*D(11)/(12.*D(13)*D(10))
      X(4)=D(15)
      X(5)=0.
      X(6)=0.
      X(7)=D(14)*D(10)/D(11)
      X(8)=0.
      SINT=32.2*SIN(D(8)/57.2958)
      C1=D(1)/2.
      C2=C1/3.
      C3=12.*D(13)/D(14)
      C4=32.2*D(5)/D(7)
      C5=14.7*C4+SINT
      C6=-D(14)*(D(11)-1.)*D(7)/(32.2*D(13))
      C7=28.-1./D(12)
      AP12=12.*D(5)
      FR=32.2*D(9)/D(7)
      AMU2=.5*D(9)
      CD1=SQRT(32.2*D(11)*D(14)/D(13)*(2./(D(11)+1.))**((D(11)+1.)/(D(11
     1)-1.)))*D(6)
      TMAX=500.*D(1)
      M=1
      T=0.
      TC=0.
      CK=0.
      DO15I=1,4
      C(I,8)=0.
   15 C(I,7)=0.
    3 C8=C1
      DO4I=1,4
      VL=D(16)+AP12*X(6)-C7*X(3)
      GWT=X(3)+X(8)
      CD=CD1/SQRT(X(7))
      AF=X(4)*C4-C5
      N=0
    5 N=N+1
      IF(P(N)-X(4))5,6,6
    6 N=N-1
      C(I,1)=R(N)*(X(4)/P(N))**REX(N)
      IF(W(5)-X(1))7,8,8
    7 C(I,2)=0.
      X(2)=0.
      X(1)=W(5)
      GOTO9
    8 IF(W(M)-X(1))10,10,11
   10 M=M+1
      GOTO8
   11 C(I,2)=S(M-1)*C(I,1)
    9 C(I,3)=D(12)*X(2)*C(I,1)-C(I,8)
      C(I,4)=C3*(X(7)*VL*C(I,3)+VL*X(3)*C(I,7)-X(3)*X(7)*(AP12*X(5)-C7*C
     1(I,3)))/(VL*VL)
```

```
      IF(AF)12,12,13
   13 IF(X(4)-D(4))28,28,14
   28 IF(X(6))12,12,14
   12 C(I,5)=0.
      GOTO26
   14 C(I,5)=AF-FR*X(6)
   26 C(I,6)=X(5)
      C(I,7)=(C6/(X(3)*X(3)))*(X(3)*(X(5)*(C(I,5)+SINT+D(9)*X(6)))-C(I,3
     1)*(.5*X(5)*X(5)+X(6)*(SINT+ANU2*X(6))))
      C(I,8)=CD*X(4)
      IF(I-2)18,19,20
   20 IF(I-4)21,4,4
   18 IF(X(6)-D(3))31,29,29
   31 TPRINT=T-CK*D(2)
      IF(ABS(TPRINT).LE..000001)GO TO 29
      GO TO 30
   29 CK=CK+1.
      WRITE(3,107)T,X(1),GWT,X(4),C(I,5),X(5),X(6)
   30 IF(T-TMAX)32,32,17
   32 IF(X(6)-D(3))16,16,17
   17 IF(D(17))1,1,27
   27 STOP
   16 DO25J=1,8
   25 U(J)=X(J)
      GOTO23
   21 C8=D(1)
   23 T=T+C1
   19 DO22J=1,8
   22 X(J)=U(J)+C8*C(I,J)
    4 CONTINUE
      DO24J=1,8
   24 X(J)=U(J)+(C(1,J)+2.*(C(2,J)+C(3,J))+C(4,J))*C2
      GOTO3
      END
```

APPENDIX E

COMPUTER PROGRAM FOR HIGH-LOW STROKING DEVICE

```
      PROGRAM HLBSD(INPUT,OUTPUT,TAPE1=INPUT,TAPE3=OUTPUT)
C     SOLID PROPELLANT HIGH LOW BALLISTIC STROKING DEVICE
C     LEONARD A DESTEFANO      CC 05100      EXT 6849
      DIMENSIONP(5),R(5),W(5),A(5),D(19),X(12),U(12),REX(4),S(4),C(4,12)
  100 FORMAT(1H1)
  101 FORMAT(8X,F7.4,F14.4,F18.3,F23.2,F21.2,F18.2,F17.3)
  102 FORMAT(5F16.5)
  103 FORMAT(8X,10HTIME (SEC),2X,14HBURN DIST (IN),2X,19HCHARGE WEIGHT (
     1LBM),2X,20HHIGH PRESSURE (PSIA),2X,19HLOW PRESSURE (PSIA),2X,17HVE
     2LOCITY (FT/SEC),2X,11HSTROKE (FT))
  104 FORMAT(8X,4F10.3)
  105 FORMAT(5F16.3)
  106 FORMAT(1H //)
  107 FORMAT(40X,51HSOLID PROPELLANT HIGH-LOW BALLISTIC STROKING DEVICE/
     1//14X,1HP,11X,1HR,9X,1HW,8X,1HA)
  108 FORMAT(8X,46H 1 COMPUTE INTERVAL (SEC) .....................F16.5)
  109 FORMAT(8X,46H 2 PRINT INTERVAL (SEC) .......................F16.5)
  110 FORMAT(8X,46H 3 STROKE (FT) ................................F16.5)
  111 FORMAT(8X,46H 4 SHOT START PRESSURE (PSIA) .................F16.5)
  112 FORMAT(8X,46H 5 PISTON AREA (SQ IN) ........................F16.5)
  113 FORMAT(8X,46H 6 ORIFICE AREA (SQ IN) .......................F16.5)
  114 FORMAT(8X,46H 7 PROPELLED LOAD (LBM) .......................F16.5)
  115 FORMAT(8X,46H 8 ANGLE OF ELEVATION (DEGREES) ...............F16.5)
  116 FORMAT(8X,46H 9 RETARDATION COEFFICIENT (LBF/FT) ...........F16.5)
  117 FORMAT(8X,46H10 THERMAL EFFICIENCY (DIMENSIONLESS) .........F16.5)
  118 FORMAT(8X,46H11 RATIO OF SPECIFIC HEATS (DIMENSIONLESS) ....F16.5)
  119 FORMAT(8X,46H12 PROPELLANT DENSITY (LBM/CU IN) .............F16.5)
  120 FORMAT(8X,46H13 PROPELLANT IMPETUS (FT-LBF/LBM) ............F16.5)
  121 FORMAT(8X,46H14 ADIABATIC ISOCHORIC FLAME TEMPERATURE (R) ..F16.5)
  122 FORMAT(8X,46H15 INITIAL LOW SIDE PRESSURE (PSIA) ...........F16.5)
  123 FORMAT(8X,46H16 INITIAL LOW SIDE FREE VOLUME (CU IN) .......F16.5)
  124 FORMAT(8X,46H17 INITIAL HIGH SIDE PRESSURE (PSIA) ..........F16.5)
  125 FORMAT(8X,46H18 INITIAL HIGH SIDE FREE VOLUME (CU IN) ......F16.5)
    1 WRITE(3,100)
      WRITE(3,107)
      READ(1,105)P,R,W,A
      WRITE(3,104)(P(I),R(I),W(I),A(I),I=1,5)
      WRITE(3,106)
      DO2I=1,4
      REX(I)=ALOG(R(I+1)/R(I))/ALOG(P(I+1)/P(I))
    2 S(I)=(A(I+1)-A(I))/(W(I+1)-W(I))
      READ(1,102)D
      WRITE(3,108)D(1)
      WRITE(3,109)D(2)
      WRITE(3,110)D(3)
      WRITE(3,111)D(4)
      WRITE(3,112)D(5)
      WRITE(3,113)D(6)
      WRITE(3,114)D(7)
      WRITE(3,115)D(8)
```

```
      WRITE(3,116)D(9)
      WRITE(3,117)D(10)
      WRITE(3,118)D(11)
      WRITE(3,119)D(12)
      WRITE(3,120)D(13)
      WRITE(3,121)D(14)
      WRITE(3,122)D(15)
      WRITE(3,123)D(16)
      WRITE(3,124)D(17)
      WRITE(3,125)D(18)
      WRITE(3,106)
      WRITE(3,103)
      SINT=32.2*SIN(D(8)/57.2958)
      C1=D(1)/2.
      C2=C1/3.
      C3=12.*D(13)/D(11)
      C4=12.*D(13)/D(14)
      C5=12.*D(5)
      C6=-D(14)*(D(11)-1.)*D(7)/(32.2*D(13))
      C7=32.2*D(5)/D(7)
      C8=14.7*C7+SINT
      C9=32.2*D(9)/D(7)
      C10=2./D(11)
      C11=(D(11)+1.)/D(11)
      C12=5.39*D(6)*D(11)/SQRT(D(13))*(C10/C11)**(C11/(C10*(D(11)-1.)))
      C13=1./SQRT(((D(11)-1.)/2.)*(C10/C11)**((D(11)+1.)/(D(11)-1.)))
      X(1)=A(1)
      X(2)=A(1)
      X(5)=D(17)+D(18)/C3
      X(6)=D(18)
      X(7)=D(17)
      X(9)=D(16)
      X(10)=D(15)
      IF(D(15)-14.7)4,4,5
    4 X(4)=0.
      X(8)=530.
      GOTO6
    5 X(8)=D(14)*D(10)/D(11)
      X(4)=(D(15)-14.7)*D(16)/(C3*D(10))
    6 X(3)=X(4)+X(5)
      X(11)=0.
      X(12)=0.
      TMAX=500.*D(1)
      ANU2=.5*D(9)
      L=0
      T=0.
      CK=0.
      TC=0.
      PRC=(2./(D(11)+1.))**(D(11)/(D(11)-1.))
      M=1
      DO22I=1,4
   22 C(I,11)=0.
    7 C14=C1
      DO8I=1,4
      N=0
    9 N=N+1
      IF(P(N)-X(7))9,10,10
```

```
10 M=M-1
   C(I,1)=R(N)*(X(7)/P(N))**NEX(N)
   IF(W(5)-X(1))11,11,12
11 C(I,2)=0.
   X(2)=0.
   X(1)=W(5)
   GOTO13
12 IF(W(M)-X(1))14,14,15
14 M=M+1
   GOTO12
15 C(I,2)=S(M-1)*C(I,1)
13 C(I,3)=D(12)*X(2)*C(I,1)
   PR=X(10)/X(7)
   IF(PR-1.)38,39,39
39 SI=0.
   GOTO18
38 IF(PR-PPC)16,16,17
16 SI=1.
   GOTO18
17 SI=C13*SQRT(PR**C10-PR**C11)
18 C(I,4)=SI*C12*X(7)
   C(I,5)=C(I,3)-C(I,4)
   C(I,6)=C(I,3)/D(12)-28.*C(I,3)
   C(I,7)=(C3/(X(6)*X(6)))*(X(6)*C(I,5)-X(5)*C(I,6))
   IF(X(4))19,19,44
19 C(I,8)=0.0
   GO TO 21
44 IF(L-1)20,45,20
45 X(8)=D(14)*D(10)/D(11)
20 C(I,8)=(C8/(X(4)*X(4)))*(X(4)*(X(11)*(C(I,1)+SINT-D(9)*X(12)))-C
  1I,4)*(.5*X(11)*X(11)+X(12)*(SINT+AMU2*X(12))))
21 C(I,9)=C5*X(11,-28.*C(I,4)
   C(I,10)=(C4/(X(9)*X(9)))*(X(9)*X(2)*C(I,4)+X 9)*X(4)*C(I,8)-X(4)*
 . 1(8)*C(I,9))
   AF=X(10)*C7-C8
   IF(AF)23,23,24
24 IF(X(10)-D(4))25,25,26
25 IF(X(12))23,23,26
23 C(I,11)=0.
   GOTO27
26 C(I,11)=AF-C9*X(12)
27 C(I,12)=X(11)
   IF(I-2)29,29,30
30 IF(I-4)31,8,8
28 IF(X(12)-D(3))42,43,43
42 TPRINT=T-CK*D(2)
   IF(ABS(TPRINT).LE..000001)GO TO 43
   GO TO 40
43 CK=CK+1.
   WRITE(3,101)T,X(1),X(3),X(7),X(10),X(11),X(12)
   L=L+1
40 IF(T-TMAX)41,41,33
41 IF(X(12)-D(3))32,32,33
33 IF(D(19))1,1,3
 3 STOP
32 DO34J=1,12
34 U(J)=X(J)
   GOTO35
```

```
31 C14=D(I)
35 T=T+C1
29 DO36J=1,12
36 X(J)=U(J)+C14*C(I,J)
 8 CONTINUE
   DO37J=1,12
37 X(J)=U(J)+(C(1,J)+2.*(C(2,J)+C(3,J))+C(4,J))*C2
   GOTO7
   END
```

APPENDIX F

COMPUTER PROGRAM FOR HIGH-LOW GRAIN DESIGN

```
      PROGRAM HLGDP (INPUT,OUTPUT,TAPE1=INPUT,TAPE3=OUTPUT)
C     SOLID PROPELLANT HIGH LOW GRAIN DESIGN PROGRAM
C     LEONARD A DESTEFANO      CL JS13J      EXT 6489
      DIMENSIONC(4,13),D(21),U(10),X(10)
      DIMENSIONMD(3),AL(3),EF(3),GW(3),HEFF(3),PCD(3)
  100 FORMAT(1H1,50X,29HHIGH LOW GRAIN DESIGN PROGRAM///)
  101 FORMAT(5F16.5)
  102 FORMAT(1H /15X,34HALL OUTER GRAIN SURFACES INHIBITED)
  103 FORMAT(1H //6X,16HBURN DIST (IN),2X,20HSURFACE AREA (SQ IN),2X,10H
     1TIME (SEC),2X,19HLOW PRESSURE (PSIA),2X,20HHIGH PRESSURE (PSIA),2X
     2,17HVELOCITY (FT/SEC),2X,11HSTROKE (FT))
  104 FORMAT(7X,F7.4,12X,F9.4,9X,F7.4,9X,F8.2,14X,F8.2,12X,F8.3,9X,F4.3)
  105 FORMAT(1H ///////////)
  106 FORMAT(1X,13HTHROAT AREA =,F8.5)
  107 FORMAT(////10X,22HLEAST SQUARES ANALYSIS//15X,33HINITIAL PROPELLAN
     1T SURFACE AREA =F9.4,6H SQ IN/15X,31HFINAL PROPELLANT SURFACE AREA
     2 =F11.4,6H SQ IN)
  108 FORMAT(1H //7X,12HNO. OF PERFS,2X,14HGRAIN DIA (IN),2X,13HPERF DI
     1 (IN),2X,21HPERF CIRCLE DIA (IN),2X,17HGRAIN LENGTH (IN),2X,14HG
     2IN WT (LBS),2X,20HBALLISTIC EFFICIENCY)
  109 FORMAT(12X,I1,F19.4,F15.4,F19.4,F21.4,F17.4,F17.4)
  110 FORMAT(8X,46H 1 BURN DISTANCE COMPUTE INTERVAL (IN) ........F16.5)
  111 FORMAT(8X,46H 2 BURN DISTANCE PRINT INTERVAL (IN) ..........F16.5)
  112 FORMAT(8X,46H 3 STROKE (FT) .................................F16.5)
  113 FORMAT(8X,46H 4 SHOT START PRESSURE (PSIA) .................F16.5)
  114 FORMAT(8X,46H 5 EQUILIBRIUM PRESSURE (PSIA) ................F16.5)
  115 FORMAT(8X,46H 6 RISE TIME (SEC) .............................F16.5)
  116 FORMAT(8X,46H 7 ORIFICE AREA (SQ IN) ........................F16.5)
  117 FORMAT(8X,46H 8 PISTON AREA (SQ IN) .........................F16.5)
  118 FORMAT(8X,46H 9 PROPELLED LOAD (LBM) .........................F16.5)
  119 FORMAT(8X,46H10 ANGLE OF ELEVATION (DEGREES) ................F16.5)
  120 FORMAT(8X,46H11 BURN RATE COEFFICIENT (IN/SEC*PSIA**M) .....F16.5)
  121 FORMAT(8X,46H12 BURN RATE EXPONENT (DIMENSIONLESS) .........F16.5)
  122 FORMAT(8X,46H13 THERMAL EFFICIENCY (DIMENSIONLESS) .........F16.5)
  123 FORMAT(8X,46H14 RATIO OF SPECIFIC HEATS (DIMENSIONLESS) ....F16.5)
  124 FORMAT(8X,46H15 ADIABATIC ISOCHORIC FLAME TEMPERATURE (R) ..F16.5)
  125 FORMAT(8X,46H16 PROPELLANT IMPETUS (FT-LBF/LBM) ............F16.5)
  126 FORMAT(8X,46H17 PROPELLANT DENSITY (LBM/CU IN) .............F16.5)
  127 FORMAT(8X,46H18 INITIAL LOW SIDE PRESSURE (PSIA) ...........F16.5)
  128 FORMAT(8X,46H19 INITIAL LOW SIDE FREE VOLUME (CU IN) .......F16.5)
  129 FORMAT(8X,46H20 INITIAL HIGH SIDE FREE VOLUME (CU IN) ......F16.5)
   25 WRITE(3,100)
      READ(1,101)D
      WRITE(3,110)D(1)
      WRITE(3,111)D(2)
      WRITE(3,112)D(3)
      WRITE(3,113)D(4)
      WRITE(3,114)D(5)
      WRITE(3,115)D(6)
      WRITE(3,116)D(7)
```

```
      WRITE(3,117)D(8)
      WRITE(3,118)D(9)
      WRITE(3,119)D(10)
      WRITE(3,120)D(11)
      WRITE(3,121)D(12)
      WRITE(3,122)D(13)
      WRITE(3,123)D(14)
      WRITE(3,124)D(15)
      WRITE(3,125)D(16)
      WRITE(3,126)D(17)
      WRITE(3,127)D(18)
      WRITE(3,128)D(19)
      WRITE(3,129)D(20)
      WRITE(3,103)
      K=0
   24 DO 3 I=1,4
      DO 3 J=1,10
    3 C(I,J)=0.0
      CD=5.39*D(14)*SQRT((2./(D(14)+1.))**((D(14)+1.)/(D(14)-1.))/D(16))
      C1=D(1)/2.
      C2=C1/3.
      C3=(D(5)-D(18))/(D(6)*D(11))
      C4=C3*D(11)
      C5=.0833*D(15)/D(16)
      C6=12.*D(8)
      C7=-D(15)*D(9)*(D(14)-1.)/D(16)
      C8=C5*D(14)/D(15)
      C9=SIN(D(10)/57.29576)
      C10=32.2*D(8)/(D(11)*D(9))
      C11=32.2*C3/D(11)
      C12=D(11)/(D(7)*CD)
      C13=2./D(14)
      C14=(D(14)+1.)/D(14)
      C15=1./SQRT(((D(14)-1.)/2.)*((2./(D(14)+1.))**((D(14)+1.)/(D(14)-1
     1.))))
      PM=D(19)*C4*C4/(D(13)*D(7)*CD)
      PMC=(2./(D(14)+1.))**(D(14)/(D(14)-1.))
      WP=D(9)*C9/D(8)+14.7
      DECF=D(9)*(D(14)-1.)/D(16)
      PMNEX=1./(1.-D(12))
      X(1)=D(14)
      X(2)=0.0
      X(5)=D(13)*D(15)/D(14)
      X(3)=(X(1)-14.7)*D(19)*C5/X(5)+.0001
      X(4)=D(19)
      X(6)=C8*PM*D(20)
      X(7)=D(20)
      X(8)=X(6)+X(3)
      X(9)=0.0
      X(10)=0.0
      W0=0.
      SUMA=0.0
      SUM1A=0.0
      AN=-1.
      DPMDX=C3*D(14)/(D(20)*D(13)*PM**D(12))
      CK=1.
      PLSF1=2.5*C3
      PLSF2=2.   3/D(6)
      TSF1=.75*D(5)
      TSF2=1.25*D(6)
```

```
    6 C16=C1
      DO6I=1,4
      PHD12=PH**D(12)
      IF(X(2)-TSF1)7,35,35
    7 C(I,1)=C3/PHD12
      GO TO 9
   35 IF(X(2)-TSF2)5,5,8
    5 C(I,1)=(PLSF1-PLSF2*X(2))/PHD12
      GOTO9
    8 C(I,1)=0.
      A(1)=D(5)
    9 C(I,2)=1./(D(11)*PHD12)
      C(I,3)=C5*(X(5)*X(4)*C(I,1)+X(5)*A(1)*C(I,4)-X(4)*X(1)*C(I,5))/(X(
     15)*X(5))
      C(I,4)=C6*C(I,10)-28.*C(I,3)
      C(I,5)=C7*(X(3)*(.0311*X(9)*C(I,9)+C9*X(9))-(.0155*X(9)*X(9)+C9*X(
     110))*C(I,3))/(X(3)*X(3))
      C(I,6)=C8*(X(7)*DPHD+PH*C(I,7))
      C(I,8)=C(I,3)+C(I,6)
      C(I,7)=C(I,8)/D(17)-28.*C(I,6)
      IF(X(1)- P)10,30,30
   30 IF(X(1)-D(4))10,11,11
   10 C(I,9)=0.0
      GO TO 12
   11 C(I,9)=(C10*(X(1)-14.7)-C11)/PHD12
   12 C(I,10)=X(4)/(D(11)*PHD12)
      IF(I-2)13,14,15
   15 IF(I-4 )16,6,6
   13 IF((X(1)/PH)-PRC)18,18,19
   18 SI=1.
      GO TO 20
   19 IF(X(1)-PH)21,22,22
   21 SI=C15*SQRT((X(1)/PH)**C13-(X(1)/PH)**C14)
      GO TO 20
   22 IF(K-4)28,28,25
   28 D(7)=.8*D(7)
      K=K+1
      WRITE(3,105)
      WRITE(3,106)D(7)
      WRITE(3,103)
      GO TO 29
   20 PHN=(C(I,3)*C12/SI)**PHNEX
      DPHD=(PHN-PH)/D(1)
      PH=PHN
      IF(AN)36,37,37
   36 AS=0.0
      GOTO38
   37 AS=C(I,9)/D(17)
   38 IF(X(10)-D(3))34,33,33
   34 WPRINT=WH-CK*D(2)
      IF(ABS(WPRINT).LE..00001)GO TO 33
      GO TO 32
   33 CK=CK+1.
      WRITE(3,104)WH,AS,X(2),X(1),PH,X(9),X(10)
   32 AN=AN+1.
      SUMA=SUMA+AS
      SUMIA=SUMIA+AN*AS
      IF(X(10)-D(3))23,24,24
   24 SLOPE=(12./(D(1)*AN*(AN*AN-1.)))*(SUMIA-((AN+1.)/2.)*SUMA)
      ASI=SUMA/AN-SLOPE*(AN+1.)*C1
```

```
      ASF=ASI*SLOPE*WB
      WRITE(3,107)ASI,ASF
      EPS2=(ASF*ASF)/(ASI*ASI)
      EF(1)=1.0
      EF(2)=(EPS2-1.)/(1.5476*EPS2-1.)
      EF(3)=(EPS2-1.)/(1.2857*EPS2-1.)
      BD(1)=2.*ASF/SLOPE
      BD(2)=2.1547*BD(1)
      BD(3)=3.*BD(1)
      ALD=2.*ASI/SLOPE
      GWF=.5*D(17)*(ASF*ASF-ASI*ASI)/SLOPE
      WRITE(3,104)
      DO31M=1,3
      AM=M
      L=M*M-M+1
      AL(M)=SLOPE/(6.2832*(AM*AM-AM+1.))
      PCD(M)=BD(M)-BD(1)
      GWT(M)=GWF/EF(M)
      BEFF(M)=BECF*(X(9)*X(9)/64.4+C9*X(10))/GWT(M)
      WRITE(3,105)L,BD(M),ALD,PCD(M),AL(M),GWT(M),BEFF(M)
   31 CONTINUE
      WRITE(3,102)
      IF(D(21))25,25,1
    1 STOP
   25 DO 26 J=1,10
   26 U(J)=X(J)
      GO TO 27
   16 C16=D(1)
   27 WB=WB+C1
   14 DO 17 J=1,10
   17 X(J)=U(J)+C16*C(I,J)
    6 CONTINUE
      DO 2 J=1,10
    2 X(J)=U(J)+(C(1,J)+2.*(C(2,J)+C(3,J))+C(4,J))*C2
      GO TO 6
      END
```

INDEX

INDEX (Con't.)

INDEX (Con't.)

INDEX (Con't.)

INDEX (Con't.)

INDEX (Con't.)

INDEX (Con't.)