DEPARTMENT OF THE ARMY TECHNICAL BULLETIN TB 9-1377-200

DEPARTMENT OF THE AIR FORCE TECHNICAL ORDER TO 11P-14

PROPELLANT
ACTUATED DEVICES

DEPARTMENTS OF THE ARMY AND THE AIR FORCE

NOVEMBER 1965

WARNING

The propellant charges contained in propellant actuated devices function at various burning rates, and yield relatively large amounts of energy and impetus, according to design.

The same degree of caution should be exercised when handling propellant actuated devices as is used when standard ammunitions are handled. Inadvertent functioning, forcing, dropping, severe jarring, or throwing could result in damage to equipment and/or injury to personnel.

TECHNICAL BULLETIN
No. No. 9-1377-200
TECHNICAL ORDER
No. 11P-1-4

DEPARTMENTS OF THE ARMY
AND THE AIR FORCE

WASHINGTON, D.C., *8 November 1965*

PROPELLANT ACTUATED DEVICES

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CHAPTER 1

INTRODUCTION

1. Purpose and Scope. This bulletin is intended for the dissemination of such general and technical information concerning Propellant Actuated Devices .is may be necessary for their care, handling and utilization. It may also be used as a reference book for all using arms and services. This bulletin is the first publication of its type and pertains to the history and basic fundamentals of Propellant Actuated Devices. It discusses only the basic theory and principles underlying the functioning and design of most devices in this class; it does not attempt to discuss the mechanical details or operating procedures that differentiate one model from another. General reference is made to specific models to give the reader an overall picture of the development of Propellant Actuated Devices from the earliest date of concept.

2. Reporting of Bulletin Improvements. The direct reporting by the individual user of errors. omissions and recommendations for improving this bulletin is authorized and encouraged. DA Form 2028 (Recommended Changes to DA Publications) will be used for reporting these improvements and forwarded direct to the Commanding Officer, Frankford Arsenal, ATTN: SMUFA-M 4320, Philadelphia, Pa., 19137.

3. References. Appendix VI contains a list of references pertaining to Propellant Actuated Devices. Detailed information relative to specific applications can be obtained from applicable technical manuals, as listed in DA Pam 3104.

4. History. *a*. 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 when trouble occurred. The technique of turning the ship onto its back, sliding open the canopy, releasing one's safety belt, and falling out was no longer feasible.

b. In 1943, the U.S. 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.

c. The Germans were the first to take effective 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.

d. The problems of escape from pusher-type airplanes were studied by the Aircraft Laboratory at Wright Field as early as 1940. At least one experimental airplane made during the war 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 formation of the Air Research and Development Command in 1950, these laboratories were assigned to Wright Air Development Center.

e. Before gun-type devices could be used on personnel ejection seats, it was necessary to determine tolerable acceleration levels for the human body and the minimum velocity of separation necessary for ejected personnel to clear the aircraft structure in flight. The Aero-Medical Laboratory had been conducting a continuing study to determine the physiological limitations of the human body in the various flight suits which have been developed. Table I summarizes the present limitations outlined in the military specification covering the design of propellant actuated devices.

Table I. Physiological Limitations for Personnel Ejection

Direction of ejection	Maximum acceleration (g)	Maximum rate of change of acceleration (g/sec)
Upward	20	250
Downward	12	125
Rearward (seat positioning)	6	60

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 mechanically initiated; 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.

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

h. With the advent of the B-52 airplane and its requirements for multi-crew, multi-functional, integrated escape system, it was realized that a new form of propellant actuated device (PAD) could furnish thrust to position ejection seats, unlock hatches, stow control columns, etc. In 1951, with the enthusiastic support of the airframe contractors and Wright Air Development Center, Frankford Arsenal commenced the design and development of the first series of thrusters, designated M1, M2, M3, and M5. Since that time many new and varied applications for propellant actuated devices have been found in the escape system and other weapons systems for various services.

i. Propellant actuated devices are commonly supplied by the Air Force as Government Furnished Equipment (GFE). Current development and manufacture is accomplished primarily by the Munitions Command at Frankford Arsenal. Approximately 175 propellant actuated devices and cartridges are fabricated and over one-half have been standardized and are available off the shelf.

5. Uses. *a*. Although propellant actuated devices were developed originally for emergency escape from aircraft, they have been used for many other short-duration, high-force applications, such as ejecting radio beacons in the event of a crash, supplying gas pressure to operate hydraulic pumps in missiles, releasing bombs or jettisoning stores from aircraft, and ramming projectiles into the breech of a howitzer. Propellant actuated devices are useful in these 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.

b. Propellant actuated devices have been proposed for parachute and cargo separation, reduction of landing shock, landing gear extenders, Gatling gun and missile rotators, and life raft inflators. Applications in the form of rotational motors for augmenting or starting standard engines and operation of a varied family of such devices in space, where weight and bulk are at a premium, is also practicable. In addition, gas servo mechanisms would eliminate some of the common problems inherent in hydraulic systems by substitution of gas which is more suitable to applications involving high temperatures and radiation. All such devices are capable of full output on command and may be time phased after triggering as desired.

CHAPTER 2

DESCRIPTION OF PROPELLANT ACTUATED DEVICES

6. General. *a.* The first aircraft pilot catapults and associated devices powered by propellants were called "Cartridge Actuated Devices" (CAD), a name which arose from the similarity in appearance between their propellant containers and the cartridge case for an ordinary rifle. As new applications were developed, this similarity disappeared, but the name continued to be used. Many of the older records will show this name. OTCM 37418 dated 12 April 60 was published to change the name of future developments of these items to "Propellant Actuated Devices" (PAD), it being considered that this name more nearly expresses their principal characteristic.

b. 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 be classified as essentially gas generators or stroking devices, they have been separated because, of specific applications.

c. Various tables list data on the physical and performance characteristics of propellant actuated devices already developed. Although rocket-assisted catapults are beyond the scope of this manual, the performance possible with these devices is compared to that of conventional catapults.

d. Some propellant actuated devices combine the operations of several subdevices. Such a device is the T28 initiator which combines release with a mechanically operated initiator. The operation of this and other devices incorporating separate functions is not described, since an understanding of the individual functions is all that is necessary to understand the most complex of these devices.

e. Several aircraft escape systems and missile systems are described in order to illustrate the application of propellant actuated devices and demonstrate their interrelationship in actual systems. The various means of transmitting energy from device to device in a system and proposed energy transmission methods also are discussed.

7. Gas-Generating Devices. *a.* 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 firing mechanisms may be operated electrically, by gas pressure, or mechanically.

b. Initiators are designed primarily to supply gas pressure to operate the firing mechanisms of other propellant actuated devices, but they may be used as sources of energy for operating piston devices such as safety-belt releases and safety-pin extractors. Initiators are used extensively in aircraft to operate the firing mechanisms of propellant actuated devices, since they eliminate cumbersome cable-pulley systems and provide a more reliable method of triggering. In systems where the propellant actuated device is remote from the initiator, intermediate initiators (gas-actuated) are used as boosters. For systems where propellant actuated devices are fired in a sequence, initiators or other PAD's may contain combustion train elements (delay elements) to delay propellant ignition for a specific time to permit completion of another operation. A typical initiator is shown in figure 1. Comparative data for several existing initiators are given in table II.

c. Gas generators differ from initiators since an initiator supplies gas for much less than 1 second, while a gas generator may supply gas for several minutes. Gas generators (fig. 2) have been used to supply gas flow to spin turbines as well as for supplying pressure to operate pumps which supply hydraulic pressure to missile controls. Comparative data for gas generators are given in table III.

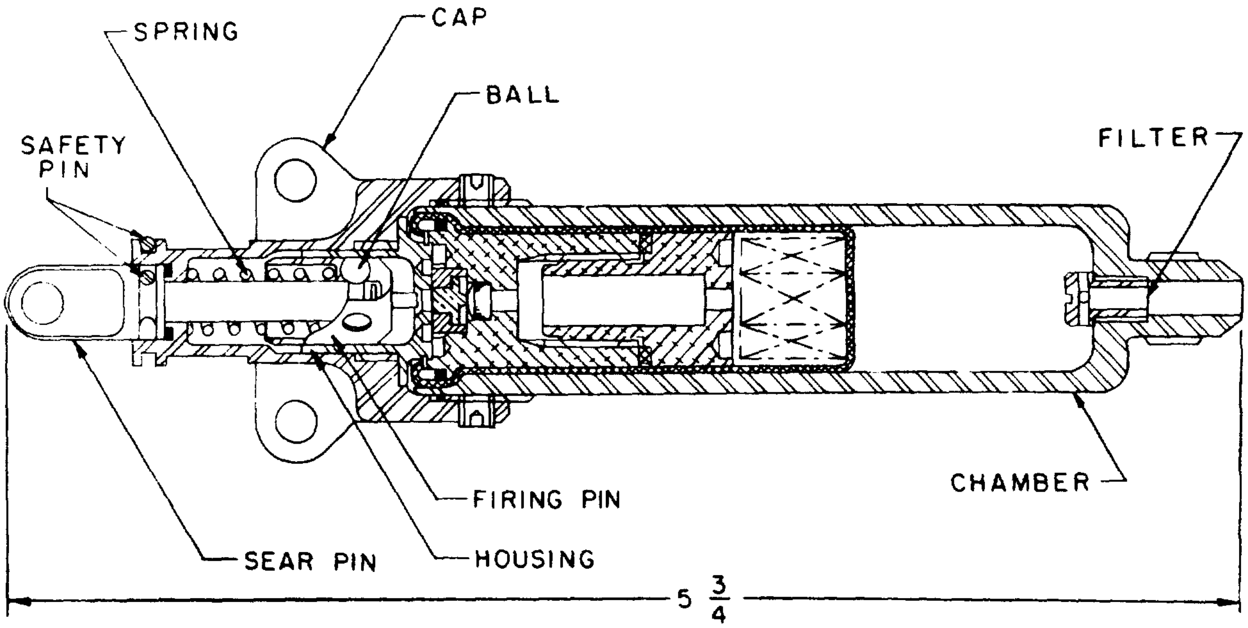


Figure 1. Mechanically operated initiator.

Table II. Comparative Data for Initiators

Model	Weight (lb)	Chamber volume (in.*)	Delay (sec)	Peak pressure† (psi)
Mechanically operated				
M4	1.0	2.4	2	600(12)
M12	1.0	2.4	1	600(12)
M3	0.9	2.3		1000(16)
M29	1.6	2.3		1000(15)
M27	0.3	0.6		1200(15)
T30E1	0.3	0.6		1200(15)
M30	1.1	2.6	2	1500(15)
M32	1.1	2.6	1	1500(15)
M8	2.2	4.3		1800(30)
Gas operated				
M6	1.0	2.4	2	600(12)
M33	1.0	2.4	1	600(12)
M5	0.9	2.3		1000(15)
M28	0.3	0.6		1200(15)
T31E1	0.3	0.6		1200(15)
M10	1.1	2.6	2	1500(15)
M31	1.1	2.6	1	1500(15)
M9	1.8	4.3		1600(30)

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

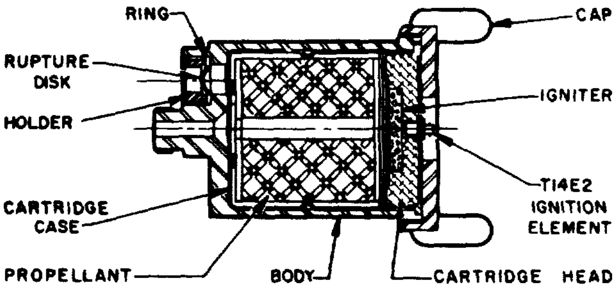


Figure 2. Gas generator.

Table III. Comparative Data for Gas Generators

Model	Weight (lb)	Chamber volume (in.^{3})	Operating pressure (psi)	Operating time (sec)
T3	25	100	2,000	90
T4	30	50	1,500	480
XM7	0.75	0.3	†500	0.9

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

d. In the past few years, considerable progress has been made in miniaturizing initiators. For example, a typical initiator, the M3, has a chamber volume of 2.3 cubic inches and weighs 0.9 pound. This device has been miniaturized in the form of the T25 initiator which has a chamber volume of only 0.65 cubic inch and weighs 0.33 pound. This miniature initiator duplicates the performance of the M3 initiator when used with hose lengths between 3 and 15 feet.

8. Stroking Devices. *a. General.*

(1) Stroking devices include catapults, removers, thrusters, and ejectors. These devices can be divided into two groups: those which separate permitting the escape of propellant gasses (open devices) and those that do not separate (closed devices).

(2) Closed devices are more difficult to design since a method of stopping the piston or stroking member at the end of stroke is required. The unit also must be able to withstand the maximum pressure developed as no gas escapes from the system.

b. Catapults.

(1) The catapult was developed for emergency ejection of personnel from aircraft. In this application, it serves is a connecting member between the crewman's seat and the aircraft structure. The catapult is a telescoping "open" assembly which is mounted in the aircraft on trunnions. The firing mechanism is mounted in one end of the catapult along with a cartridge containing at primer, igniter, and propellant. When the cartridge functions, the propellant gas fills the catapult and causes it to extend (fig. 3). As the catapult extends, it ejects the seat from the aircraft. Table IV lists the existing catapults and presents performance data for these devices as a guide to what has already proved practicable in catapult design.

(2) Rocket-assisted catapults sustain thrust and thus increase ejection height, without exceeding acceleration maximums. Performance data for several rocket-assisted (catapults are presented in table V.

Table IV. Comparative Data for Conventional Catapults

	Stroke (in.)	Weight propelled (lb)	Maximum velocity (fps)	Maximum acceleration (g)	Rate of change of acceleration (g/sec)	Weight of device (lb)
M6†	21	350	26	9	120	32
M4A1	45	412	37	8	70	7
T15	50	340	60	17		11
M2†	60	312	48	13	100	15
M1A1	66	312	64	15	160	8
M5A1	66	312	64	15	160	8
T16E2	71	600	23	14		24
T10	72	363	71	17	130	16
T18	76	350	80	20		31
M3A1	88	465	72	15	100	25

†Multi-shot training catapult.

Table V. Comparative Data for Rocket-Assisted Catapults

	Catapult stroke (In.)	Weight propelled (1b)	Total Impulse (lb sec)	Maximum velocity (fps)	Maximum acceleration (g)	Rocket grain weight (lb)	Weight of device (lb)
T20	23	325	1,100	35	15	2.8	22
XM10	34	350	1,650	35	12	6.0	26
XM9	36	350	1,650	35	12	5.8	24
XM12	40	350	1,800	40	12	6.6	29
XM8	40	350	1,800	40	12	6.6	27
XM7	(†)	595	6,300	120	15	30.4	65

† An all-rocket catapult.

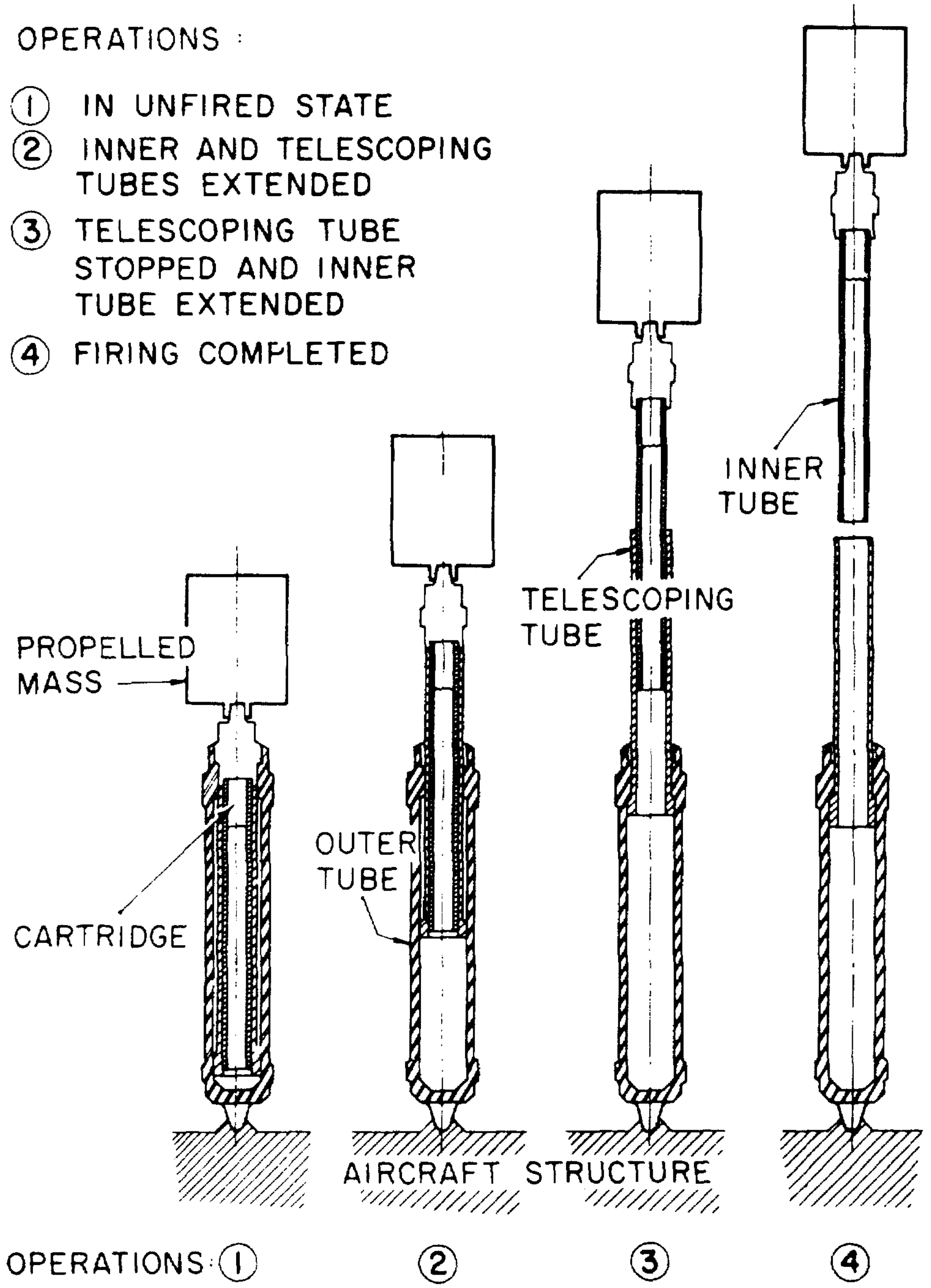
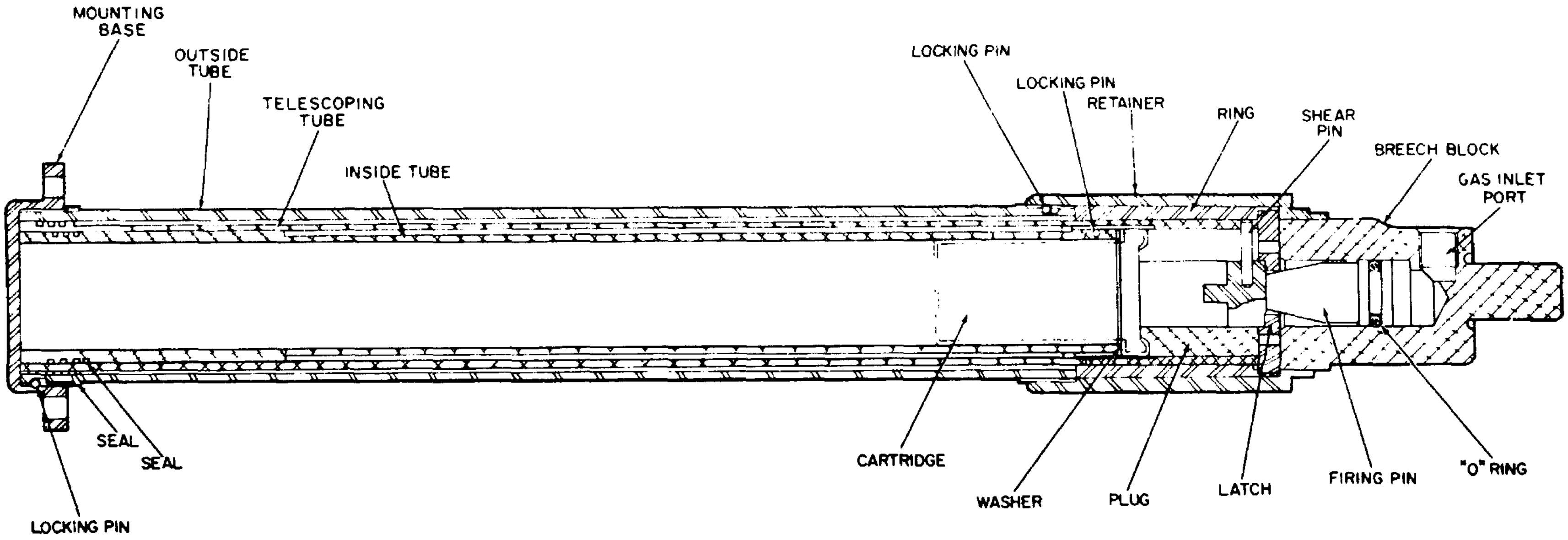


Figure 3. Operation of a conventional catapult.

c. *Removers.*

(1) Removers (fig. 4) are "open" telescoping devices developed to remove the canopies from aircraft prior to personnel ejection. Comparative data for various removers are presented in table VI. These devices are similar in design to catapults with one important exception: removers are de-maximum pressure produced by the burning propellant in the event of restrained motion of the propelled load. This feature is described as being able to withstand "locked-shut" firings. Also, greater acceleration is permissible with signed to be capable of retaining the removers (table VI) since



REMOVER

Figure 4. Typical remover.

Table VI. Comparative Data for Removers

	Stroke (in.)	Weight propelled (lb)	Peak thrust (lb)	Stroke time (sec)	Method of initiation	Weight of device (lb)
T18†	12	320	6,000	------	Gas	19.0
M4	19	300	4,100	0.1	Gas	3.8
M5	19	1,000	8,100	0.15	Gas	3.9
M1A1	23	311	3,040	0.13	Mechanical	2.1
T13E1	23	1,000	5,500	0.2	Gas	------
T19†	24	230	6,000	------	Gas	25.5
M3	26	311	3,145	0.15	Gas	4.4
T8	26	300	3,100	0.15	Gas	4.3
M2A1	28	311	3,145	0.15	Gas	4.4

† Electromechanical-ballistic canopy remover-actuator.

human physiological limitations are not a factor. The only limit on acceleration and rate of change of acceleration is the strength of the aircraft structure.

(2) Electro-mechanical removers, not illustrated, utilize an aircraft's electrical power system to allow operation of the canopy in normal use. In emergencies, jettisoning of the canopy is accomplished by means of a ballistic system initiated by the pilot or other crew member.

d. Thrusters.

(1) The thruster was developed to exert a thrust, through a short stroke, to move a weight or to oppose a force. The device consists of a chamber, piston, firing mechanism, and a cartridge. Thrusters have been used for operations such as seat positioning, stowing of equipment, hatch or canopy unlock, and canopy ejection. Thrusters are closed devices; that is, the main piston does not separate from the device under any operating condition including "locked-shut" and "no-load" firings.

(2) Buffer or damper mechanisms (fig. 5) are used occasionally in conjunction with thrusters and, in some cases, are made an integral part of the thruster. They are used to restrict the velocity and acceleration of the propelled load because of structural or human physiological limitations. Thrusters have been developed that function in their usual manner, but also at the end of a stroke, bypass gas through high-pressure flexible hose or tubing to initiate other propellant actuated devices. In this application, the thruster ensures the proper sequencing of operations. An example is one of the T25 thrusters used in the F-106B aircraft escape system. This thruster unlocks the canopy and, at the completion of stroke (after the canopy is unlocked), bypasses gas to fire the canopy remover (fig. 6). Each thruster is designed to operate against specific constant or varying forces.

e. Ejectors. These devices (fig. 7) consist of a body, an outside tube (slug), a firing mechanism, and a cartridge. When the cartridge fires, the expanding propellant gas ejects the slug and extracts the load to which it is attached. A series of electrically and gas initiated ejectors has been developed to eject drag parachutes. Table VII presents comparative data on the size and performance of existing ejectors. This table like all of the others, is presented merely to show the range of devices already developed as a guide for determining the feasibility of proposed devices. Ejectors are applicable to many missile and drone recovery systems and have potential Use as automatic mortar, grenade, or rocket launchers and for chest type reserve parachute deployment.

9. Special Purpose Devices. *a. General*. A number of propellant actuated devices have been developed for "special" applications. Included in this category are cutters, releases, and electric ignition elements.

b. Cutter. Cable cutters have been developed that sever cables (such as electrical cables) prior to the removal or ejection of a canopy or seat, or the firing of a missile. Although most cable cutters were developed to sever a single cable, a cutter (T3) was designed to sever

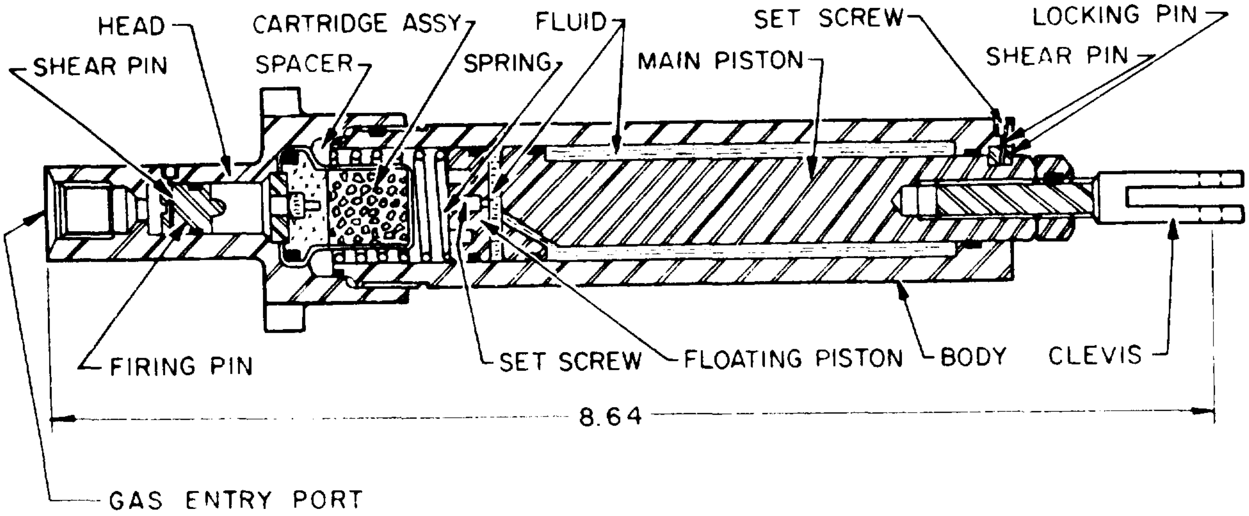


Figure 5. Oil damped thruster.

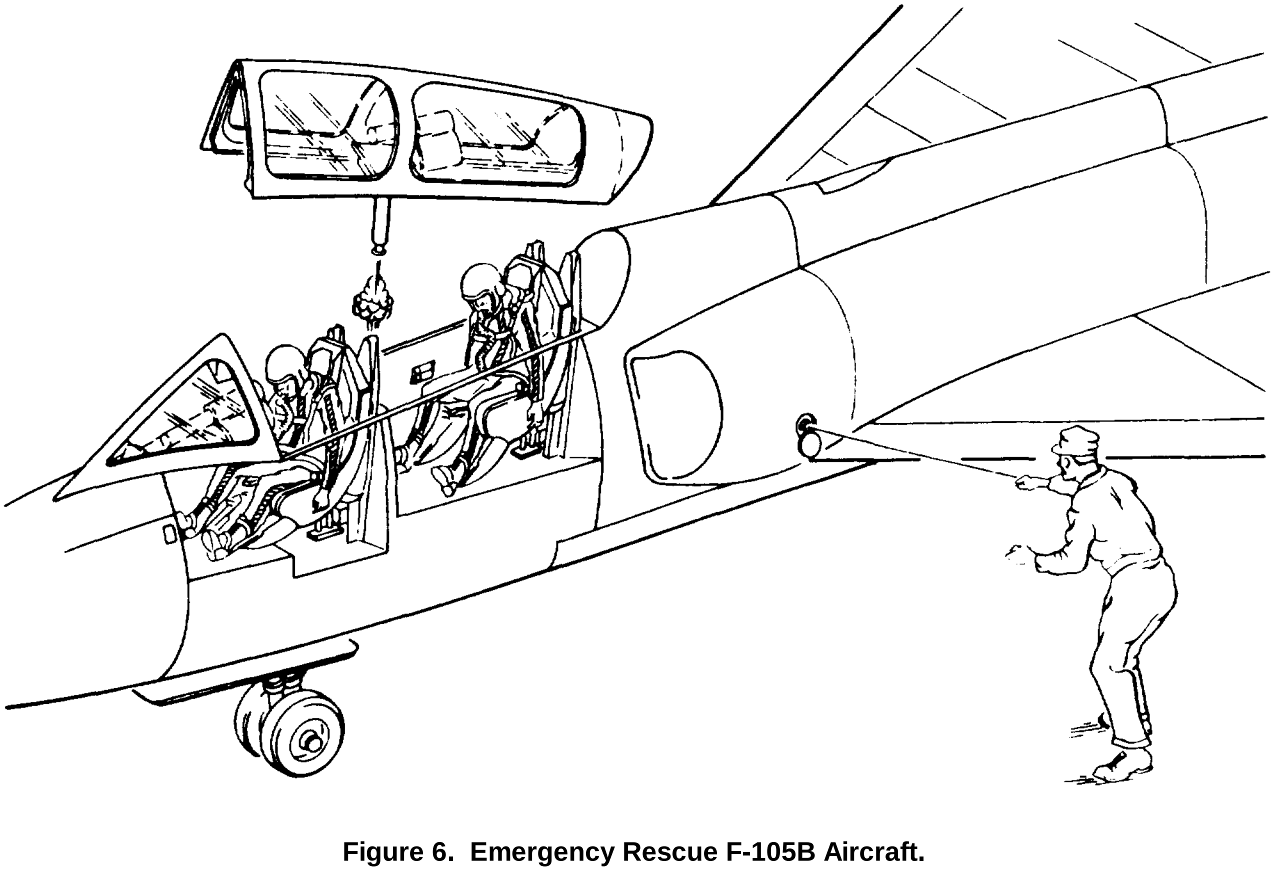


Figure 6. Emergency Rescue F-105B Aircraft.

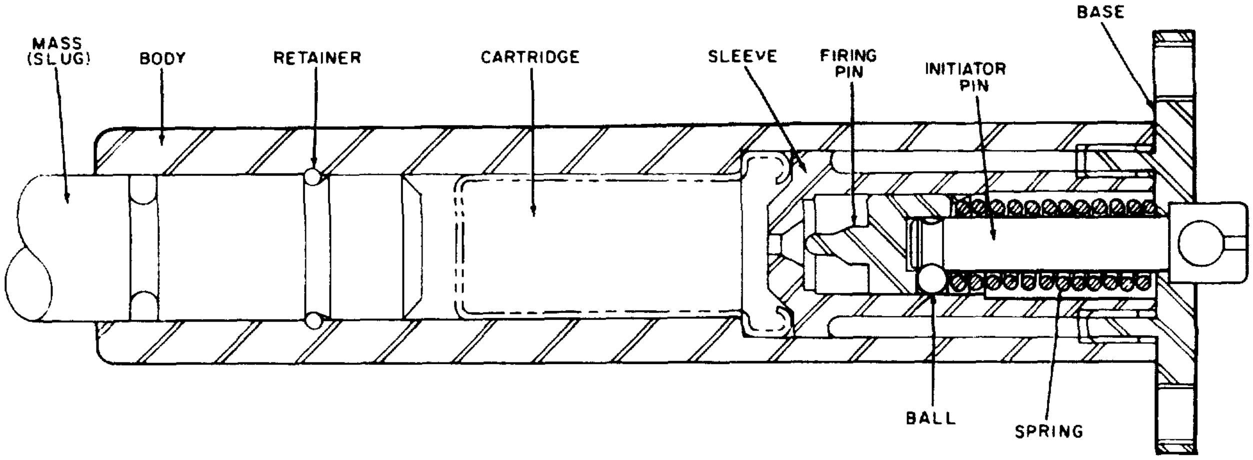
a bundle of 41 electrical wires prior to the removal of the aircraft canopy. The T3 cutter has a blade attached to the forward end of the piston. Gas produced by burning propellant in the cartridge in the cutter propels the piston forward, driving the blade into the wires which are to be severed. The blade of the cutter may be coated to prevent electrical shorting as the blade passes through the current-carrying wires. Other cutters have been designed to sever the reefing lines of parachutes. Unlike cable cutters, reefing line cutters are

Table VII. Comparative Data for Ejectors

	Weight of device (lb.)	Ejected Weight (lb)	Length (in)	Maximum velocity (fps)	Method of initiation	Stroke (in)
T1E1	1.0	0.3	5	125	Mechanical	5.0
T7	2.0	1.0	6	340	Gas	3.0
T8†	2.6	1.0	5.5	375	Gas	3.0
T9†	2.6	1.0	5.5	375	Gas	3.0
T10†	2.6	1.0	5.5	375	Electrical	3.0
T11†	2.6	1.0	5.5	375	Electrical	3.0

† These units differ only in the mounting angle of the base plates.

mechanically initiated. (Fig. 8 shows a typical reefing line cutter.) The firing mechanism of the reefing line cutter is attached by lanyard to the shroud of a parachute. When the shroud lines are pulled taut by the opening 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 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, passing through the hole in the end of the cutter. A whole family of cartridges has been developed to provide different delay times (2-, 4-, 6-, 8-, and 10-second delays). The sear-type firing mechanism may be operated by pulling the cable (sear) from any angle up to and including 180° to the cutter main axis.



EJECTOR, PARACHUTE

Figure 7. Parachute ejector.

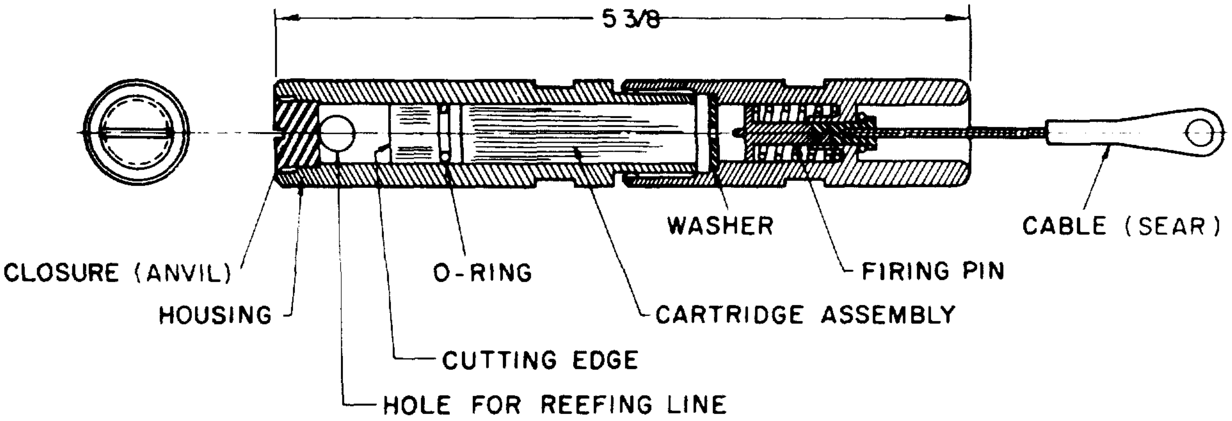


Figure 8. Typical reefing line cutter.

c. Releases.

(1) Releases have been developed that disconnect the parachute from a crash-locator beacon, suspend and release single lug bombs, release external stores front aircraft, and pull safety pins from other propellant actuated devices.

(2) The release designed to pull the safety pin of another propellant actuated device is shown in figure 9. 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 device does not contain a cartridge. Propellant gas supplied to the release unlocks the piston and causes it to retract and withdraw its pin from the firing mechanism of the device assembled to it, thereby arming the device.

(3) The type of release shown in figure 9 is commonly used in aircraft escape systems to unlock the firing mechanisms of initiators used to fire catapults. In these systems, the release is actuated automatically at the end of the pre-ejection cycle. This prevents personnel ejection prior to performing such operations as seat positioning and canopy removal.

d. Ignition Elements.

(1) The electric ignition element is a device designed to replace the firing pins and percussion primers used with gas or mechanically fired propellant actuated devices. Ignition elements have been developed that are capable of being fired by an electrical power source such as an aircraft 28-volt dc supply. The first ignition elements developed were designed to pass 0.5 ampere without firing and to fire when the current was 1.0 ampere. This early series of ignition elements used the body of the element for a ground. A later series of ignition elements was designed with 4 internal pins, insulated from the body of the device (fig. 10). Two pins are interconnected and provide a testing circuit separate from the firing circuit. The other two pins are connected to the firing circuit. This device is designed with a 1.5 ampere no-fire and a 3.5 ampere all-fire qualification.

(2) The two pins in the firing circuit are connected to a wire filament in the element. This wire is coated with an ignition bead which is ignited when the filament is heated by passing the required current through it. Ignition of the bead sets off the main charge of the element.

(3) To improve the reliability of electrically initiated systems, auxiliary firing sources, such as electromagnetic impulse generators, have been developed. Electromagnetic impulse generators contain several bar magnets and a coil. Movement of the handle or trigger on the generator changes the reluctance in the magnetic circuit, generating a current in the coil. These units have indefinite life, are unaffected by environmental extremes, and present a fixed impedance for circuit checking.

10. Systems. *a. Aircraft Escape Systems.*

(1) *Seat escape systems*.

(*a*) Initially, relatively simple systems for canopy removal and seat ejection provided for the escape of

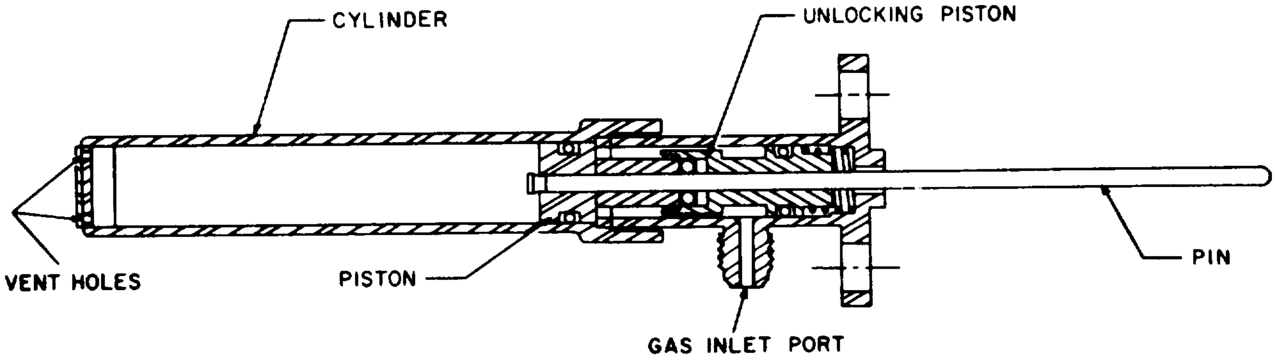


Figure 9. Release.

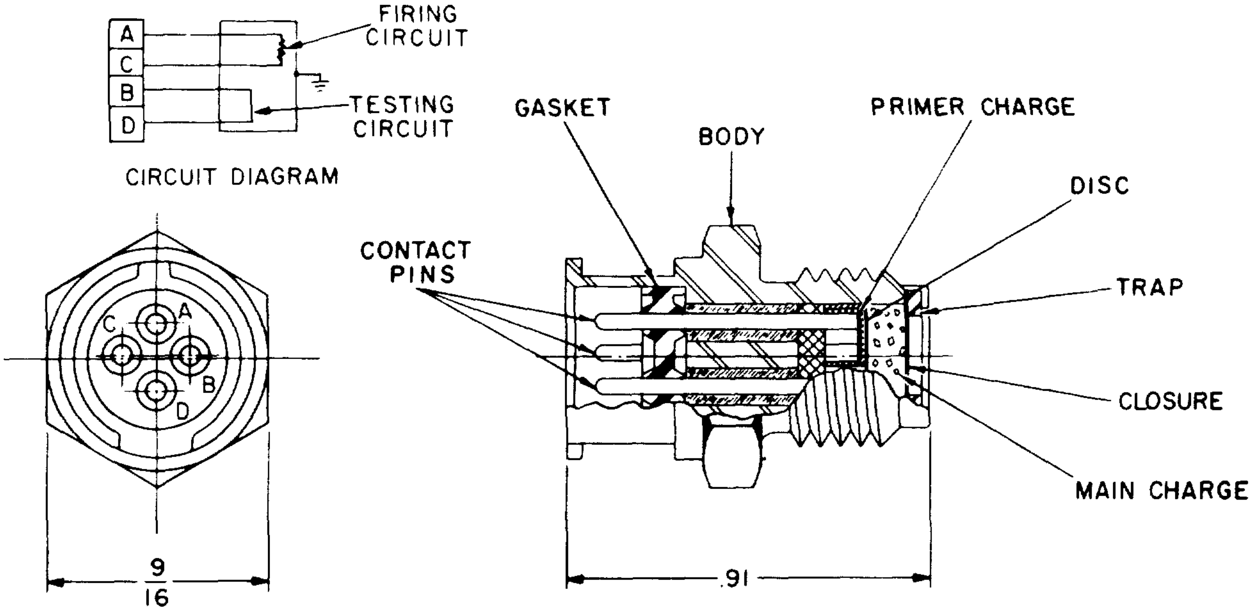


Figure 10. Electric ignition element.

personnel from fighter aircraft. In these systems, two separate operations were required, and mechanical interlock ensured the order of actuation. As the operation of aircraft became more complex, escape systems were expanded to include pre-ejection operations, such as stowing the control column or positioning the seat, thus freeing the pilot from these operations. The development of escape systems for bomber aircraft necessitated that initiation be possible from several points, provision be made for the escape of many crewmen and for the stowage of equipment, crewmen be oriented with respect to the escape exit, and delays or pauses be part of the escape sequence.

(b) A schematic of an escape system used in the F104B aircraft is presented in figure 11. When the dee ring (1) is pulled, three cables attached to it are pulled actuating four initiators. One M27 initiator (2) supplies gas pressure to fire the XM13 thruster (3). The XM13 thruster unlocks the aircraft canopy and also twists a torque tube which actuates an M27 initiator (4). This miniature initiator supplies gas pressure to fire two XM11 thrusters (5) which jettison the aircraft canopy.

(c) Concurrently, a second M27 initiator (6), actuated by pulling the dee ring (1), supplies gas pressure to initiate an M15 thruster (7). This retracting type thruster positions the pilot's legs by tightening cables attached to the pilot's ankles; as the piston of the thruster retracts, it actuates an M27 initiator (8), supplying gas pressure to initiate the XM10 catapult (9) which ejects the pilot from the aircraft.

(d) The third initiator actuated by pulling the dee ring (1) is an M32 delay initiator (10) which supplies gas to fire the XM10 catapult (9) after a 1-second delay. This initiator is insurance against failure of the M27 initiator actuated by the leg-positioning thruster to fire the catapult.

(e) The fourth initiator actuated by the original pull on the dee ring is an M30 delay initiator (11) which contains a 2-second delay element. After the delay element burns, the propellant charge in the initiator is ignited and supplies gas pressure through the manifold (12) to cable cutters (13), which release the pilot's legs. To insure that the cables retaining the pilot's legs are

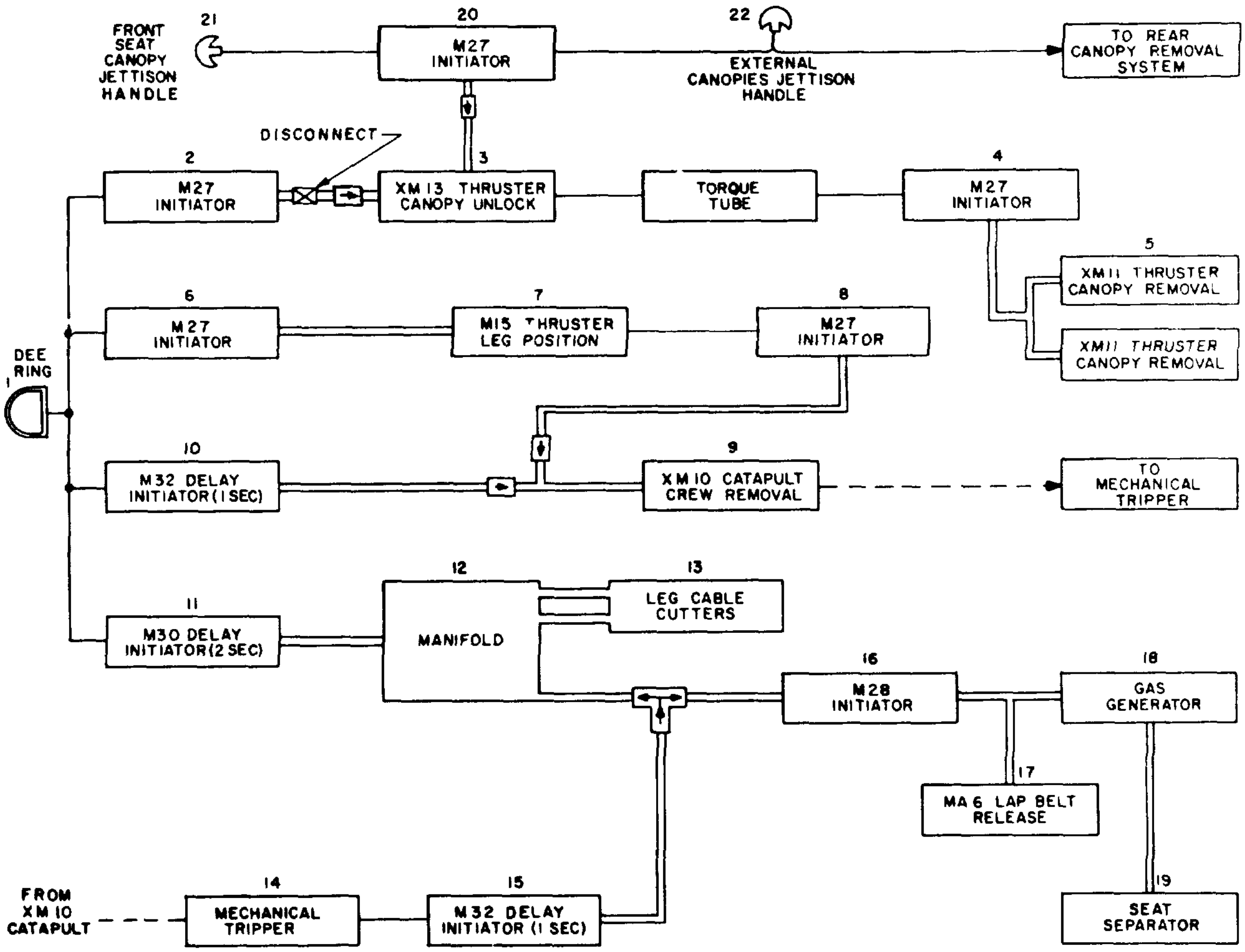


Figure 11. F-104B Escape System, schematic diagram.

severed, a mechanical tripper ignites an M32 initiator (15) containing a 1-second delay element. After the delay, gas pressure from the initiator is supplied through the manifold (12) to the cable cutters (13). Gas from the M32 initiator (15) is also supplied to an M28 initiator (16) which acts as a booster and supplies gas to operate the pilot's MA-6 lap belt release (17) and a gas generator (18). The gas generator supplies gas to an actuator (19) which separates the pilot from the seat.

(*f*) To summarize, the pilot pulls a dee ring and the canopy is unlocked and ejected, his legs positioned, the seat ejected, his legs freed, the lap belt opened, and he is separated from the seat, all in the proper sequence, and with parallel systems to insure operation of the catapult and leg-positioning cable cutters.

(*g*) As part of the complete system, a separate M27 initiator (20) is provided so that the canopy can be unlocked and jettisoned, without initiating the seat-ejection system. This initiator may be actuated by the pilot (21) or from outside the aircraft (22).

(*h*) The F104D aircraft is a two-seat aircraft with two independent escape systems. Each system is identical to that described above with one exception. As in the single-seat aircraft, the external canopy jettison ring (22) is connected to an M27 initiator (20) in the front seat to remove the front canopy; however, the ring also is connected to an M45 delay initiator, which delays 3 seconds and removes the aft canopy.

The delay avoids any possibility of the forward canopy striking the rear canopy as may occur should they be jettisoned simultaneously.

(2) *Capsule escape systems*.

(a) An escape system should allow the crewmen to separate safely from the aircraft throughout the aircraft's altitude and speed range, and to descend, with the necessary survival equipment, to the earth's surface in a physical condition permitting him to survive and, if necessary, evade or escape enemy forces. The ejection-seat escape system is effective in the region below 600 knots IAS (indicated air speed). Beyond 600 knots, the probability of a safe escape with an ejection-seat escape system rapidly decreases. The Air Research and Development Command requires that escape capsules with protective and survival devices be used in all new aircraft with speeds exceeding 600 knots EAS (equivalent air speed) † and operational altitudes exceeding 50,000 feet.

(b) Figure 12 shows a nose capsule design based on the configuration of an F104 type aircraft. The ejectable nose capsule is stabilized by three swept-back, thick-wedge airfoils.

(c) The complete escape system (fig. 13) is set into operation by a single operation of the pilot, the raising of his seat handle or handles (1). This action starts a dual initiation system for all units which absolutely must work for a successful escape. Either or both initiators (2 and 3) fire a gas generator (4) which supplies gas pressure to actuate the pilot's body and foot restraint systems (5). The gas generator also supplies pressure to extend the stabilizing wedges (6, 7, and 8). The movement of the upper wedge unlocks the capsule air vent (9). As soon as the top wedge (6) and either of the lower wedges (7 or 8) are fully extended, they remove stops in a valve (10). Gas from the generator (4) then forces a shuttle in the valve forward and actuates four exploding bolts A (11 and 12), a 0.5-second delay initiator (13), and the rocket motor (14). The four exploding bolts are the only structural connections between the nose capsule and the rest of the airframe. If for some reason the valving system (10) does not operate satisfactorily, a 1-second delay initiator (15), previously actuated by the dual initiators (2 and 3), will fire the rocket motor, structural disconnects (exploding bolts), and a 0.5-second delay initiator (16). The rocket motor thrust insures separation and sufficient trajectory for parachute deployment, even in "off the runway" escapes (fig. 14).

(d) The purpose of the two 0.5-second delay initiators (13 and 16) is to postpone arming the parachute launching sensor (17) action until the rocket has propelled the capsule to maximum speed. If the capsule has not exceeded the safe parachute launching speed at that time, the pilot chute ejector (19) is fired, pulling the high and low speed drogue chutes (19) out into the airstream. The drogue chutes extract the heavy main parachute box and the main parachute is deployed. At initial deployment, the main parachute is reefed so that its opening shock will not be too great. After suspension line stretch, cutting of the reefing line allows full parachute deployment. If the pilot senses a failure of the parachute launching system, he can fire a second ejector cartridge manually (20). This is the end of the dual initiation sequence.

(e) The remaining phases which enhance safe escape, but are not, absolutely necessary, are actuated from single sources. At the time the capsule starts away from the parent aircraft, a lanyard from the aircraft pulls on a valve (21) in the capsule allowing pressure remaining in the

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† Equivalent air speed is the Indicated air speed corrected for compressibility. Though the difference between IAS and EAS is negligible at low speeds and low altitudes, impact pressure upon the pitot tube at high speeds increases, causing the airspeed indicator to show values above normal.

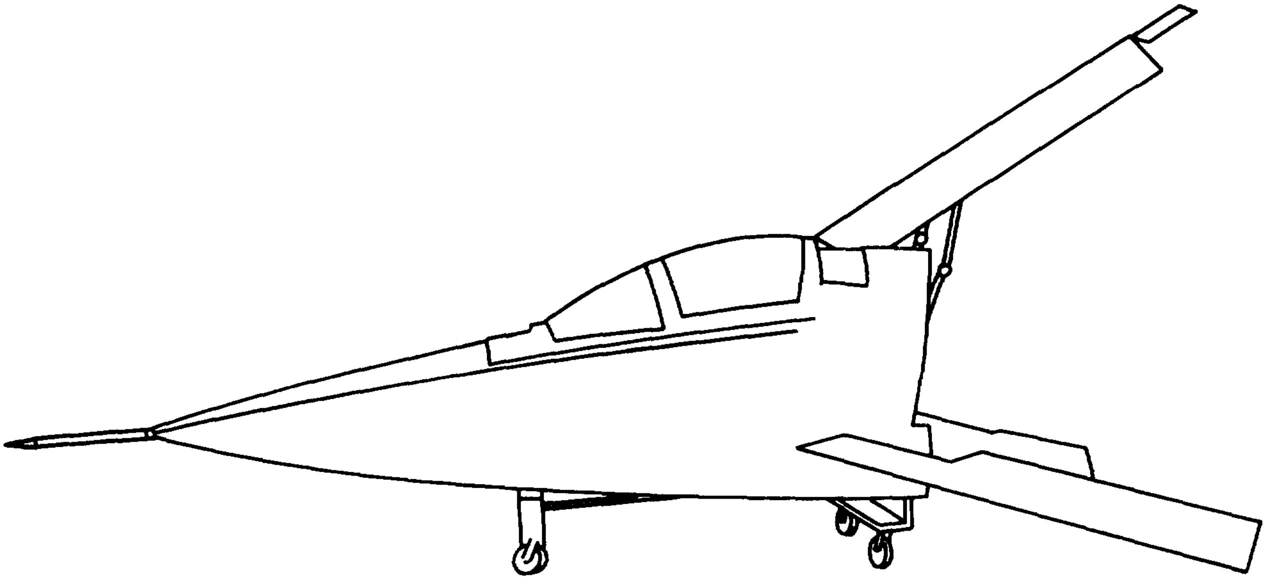

Figure 12. Nose capsule.

gas generator to operate the head restraint device (22). Another lanyard from the parachute riser starts a 6-second delay initiator (23) at the time of parachute launch. This initiator releases pressure from a bottle (24) to prepare the capsule for a landing on land or in the water. The pressure from the bottle actuates a propellant charge to shatter the glass-like radome (25), exposing a sheet metal structure with predictable shock-absorbing characteristics, and allowing the capsule's center of gravity to be closer to the ground at the time of contact. This reduces the capsule's tumbling tendencies in the wind. Simultaneously, gas from the pressure bottle releases the lower riser of the parachute (26), positioning the capsule for the most desirable landing attitude, and gas from the bottle also inflates floats in the stabilizing wedges (27). The floats at the ends of the lower stabilizing wedges support the aft end of the capsule so that it is approximately level, and reasonably stable in the water.

(f) After the capsule contacts the ground or water, the pilot can, at his discretion, pull a handle (28) in the cockpit to release the parachute riser (29).

b. Missile Systems.

(1) A propellant gas generator was developed to replace the compressed gas bottle used to pressurize the hydraulic fluid in the NIKE-AJAX guided 'missile. It was installed in a missile and successfully tested on the ground.

(2) Another gas-generating system has been developed for possible use in the NIKE-HERCULES guided missile. It was developed as a backup for the current, ethylene-oxide system. It has not as yet been used, although it has been ground tested. It is described here as an example of missile applications.

(3) In this system, propellant gas from the T4 gas generator in the auxiliary power supply is used to operate a double-acting pump which supplies fluid to the actuators at 3,000±250 psi at a flow rate to meet tactical demands for all anticipated missile maneuvers. The system is relatively light in weight, simple in design, requires little ground maintenance, and may be stored for long periods of time.

(4) The auxiliary power supply for the NIKE-HERCULES guided missile operates in the following manner: Prior to launching, the T4 gas generator (fig. 15) is initiated by the T14E2 electric ignition element. The ignition element ignites the igniter which, in turn, ignites the fast-burning

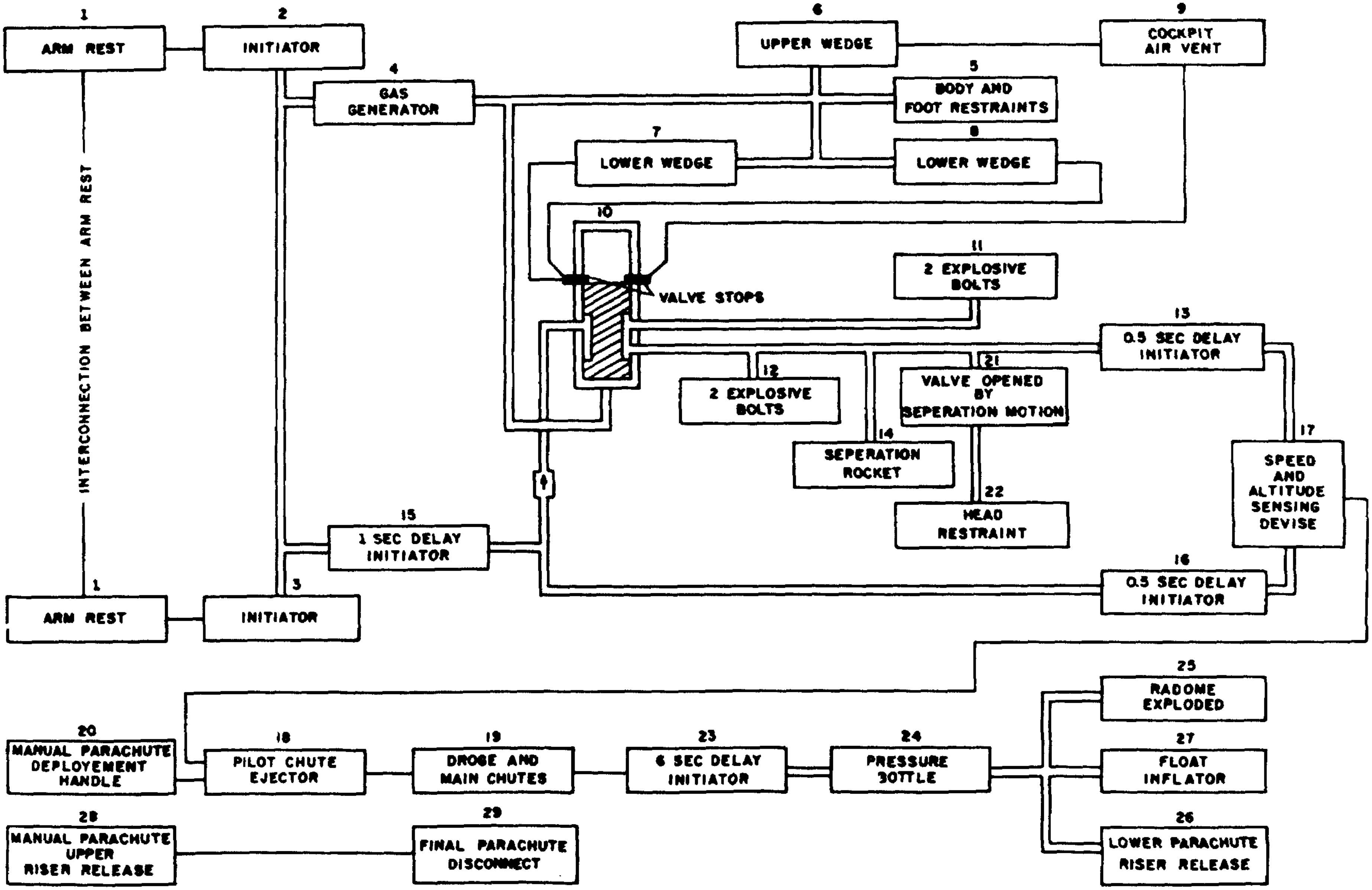

Figure 13. Nose capsule escape system, schematic diagram.

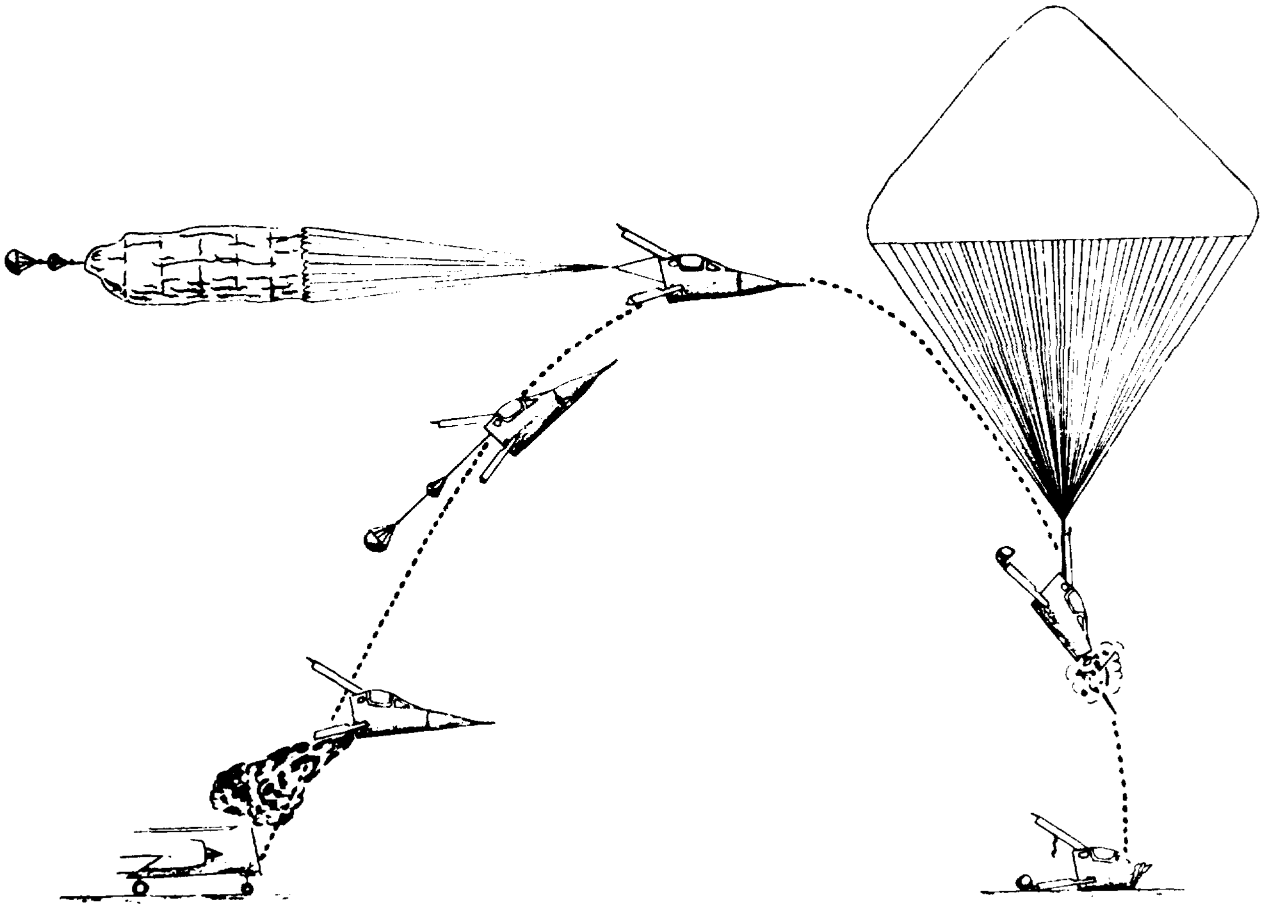

Figure 14. "Off the runway" ejection sequence.

propellant contained in the chamber. As this propellant burns, it ignites the main propellant charge (sustainer) contained in the series of tubes which makes up the gas generator. The walls of the propellant grains are inhibited so the propellant must burn from end to end as a cigarette. As the stub end of the propellant stick burns, it ignites a primer cord which ignites the propellant in the next tube, and so the burning continues for 8 minutes.

(5) Figure 16 shows the entire auxiliary power supply system. The gas produced by the burning propellant passes through a filter in the gas generator, through an external filter and pressure release valve, into a shift valve (2), where it is directed into one end of a double-acting pump. The double-acting pump transforms gas energy (3) to hydraulic fluid energy (4). By means of a 2 to 1 differential piston area, the hydraulic fluid is pressurized to 3,000 psi as the piston is stroked. The fluid is forced through the actuating mechanism (5) and the spent fluid is returned to the opposite side of the piston at a low pressure. When the piston bottoms, the shift valve (2) exhausts the high pressure gas and reverses the direction of the gas piston. The hydraulic fluid becomes pressurized in the opposite direction, and these cycles continue until burnout of propellant in the gas generator occurs (approximately 8 minutes).

(6) The surge accumulator (6) absorbs surges of fluid and maintains a constant flow when the pump reverses direction. The oil reservoir (7) contains the fluid displaced when the piston rod is in the pump chamber and provides back pressure in the system.

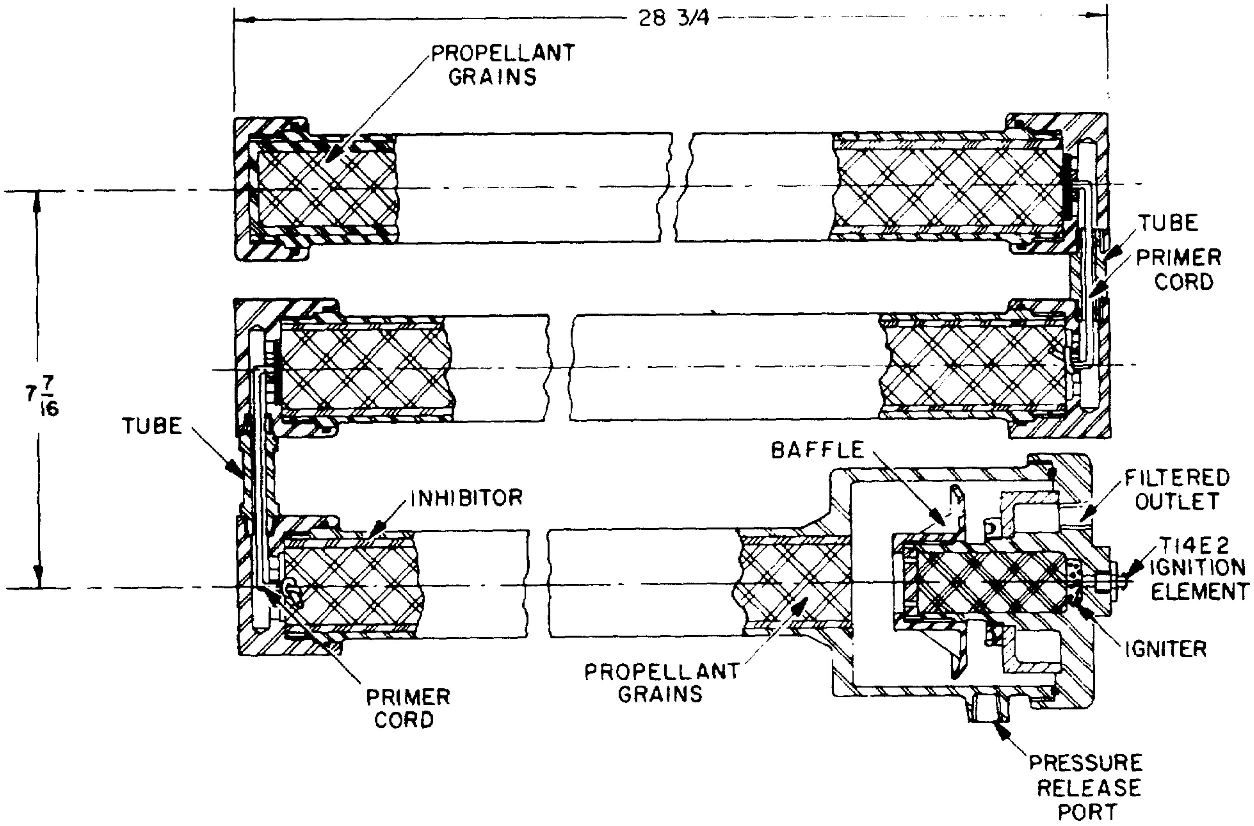

Figure 15. T4 gas generator.

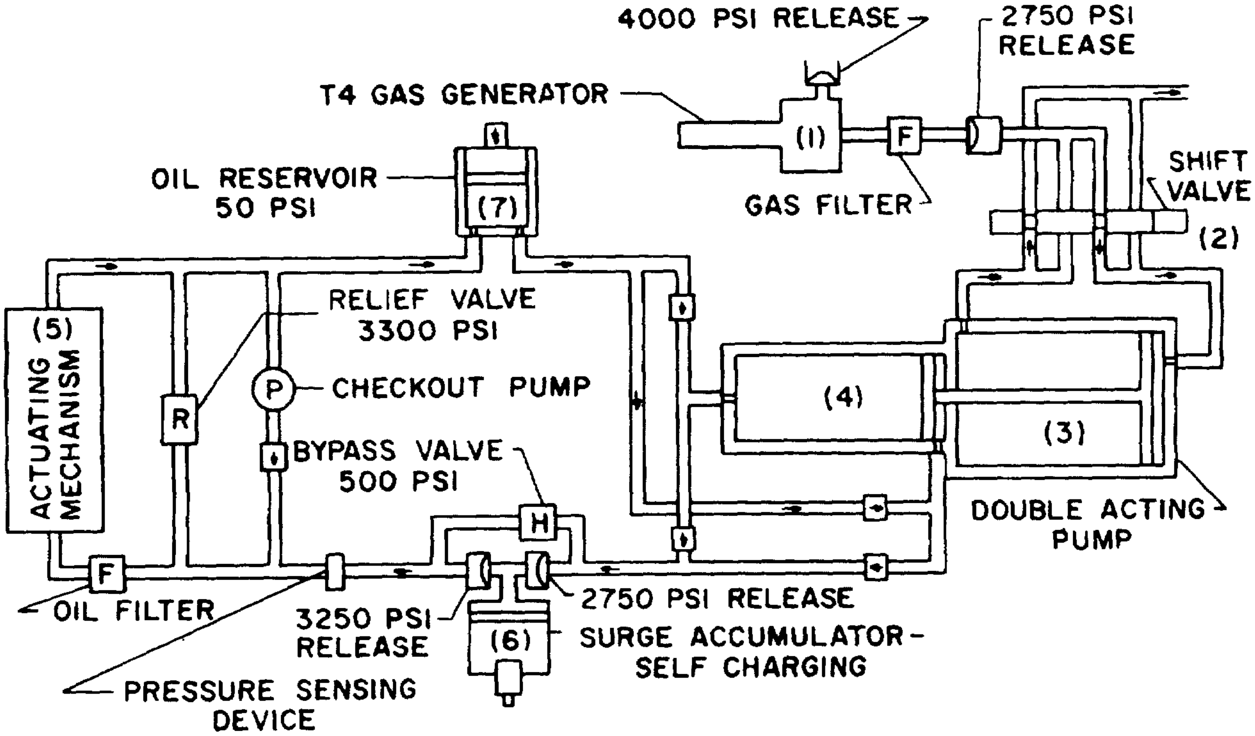

Figure 16. NIKE-HERCULES auxiliary power supply system.

c. Energy Transmission in Systems.

(1) In early aircraft escape systems, all propellant actuated devices were mechanically initiated. This mechanical initiation required elaborate cable pulley arrangements to release cocked firing pins by rotating or withdrawing sears. The drawbacks of this system are obvious.

(2) Gas-initiated systems gradually replaced these early systems. Gas systems use teflon-lined, steel-braided hose 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.

(3) 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, no booster initiators are needed. 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 possible danger of accidental firing caused by stray radiation, etc.

CHAPTER 3

BASIC DESIGN

11. General. *a*. 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 burning the propellant they contain. The materials selected for use in these parts are compatible with the propellant, igniter, and primer at various temperatures and in the functional and storage conditions to which the parts are exposed.

b. Constant awareness of basic concepts must be maintained when designing propellant actuated devices. Certainly the most important concept is that of 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.

c. Standard parts are used wherever possible, and when special parts are necessary, they are designed so that they are manufactured easily. All parts 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 so that it is impossible to assemble a component backwards.

12. Motion or Time Functions. *a.* The function time for propellant actuated stroking devices is the time interval from initiation of operation to the completion of a stroke. This interval may vary from as little as a few milliseconds (some thrusters) to a quarter of a second (some catapults). Thrusters containing damping devices may take more than one-half a second to complete a stroke.

b. In the system shown in figure 17, 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 which 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 in the thruster chamber increases and causes the thruster piston to extend, moving a body (load). A curve showing the relationship of pressure to time within the thruster is presented in figure 18.

c. Point A in figure 18 represents the instant the initiator functions and point B represents the moment the thruster firing mechanism is operated. Point C is the time internal gas pressure is first noted in the thruster, and point D is the time peak pressure occurs. Point E represents the instant the thruster piston is fully extended.

d. If it is assumed that piston motion starts at point C (when pressure is first developed in the thruster), the actual work cycle of the device extends from point C to point E. However, thrusters normally have initial locking arrangements (to prevent the piston from extending prior to the time the thruster cartridge fires), and the initial lock is released when the pressure reaches some intermediate point between C and D.

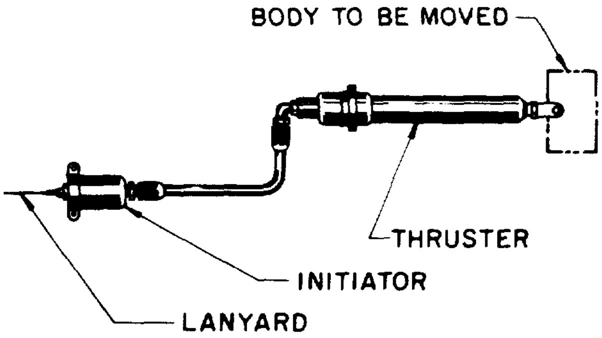

Figure 17. A simple PAD system.

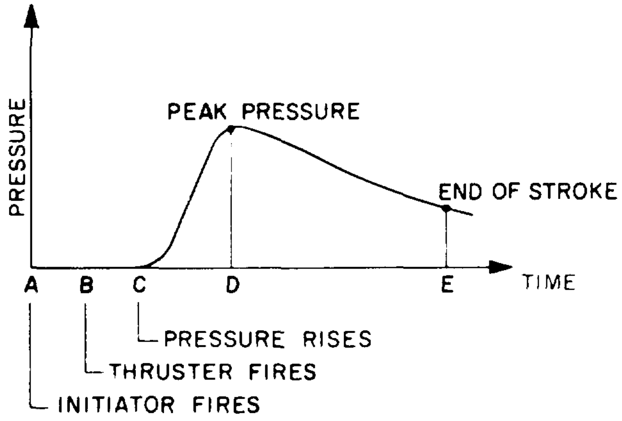

Figure 18. Pressure-time curve for system of figure 17.

e. Every effort is made to minimize the time from point A to point C. The exception to this is in the design of the delay initiator. 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 designing elaborate systems. The span of time from B to C is referred to as ignition delay (the interval between actuating the firing mechanism and the beginning of sustained rise of pressure in the propellant chamber).

f. The C to D span may be the most important for it is during this pressure rise time that such important performance characteristics as rate of change of acceleration are determined. Furthermore, this C to D span affects the selection of propellant, propellant geometry (perforations and web, etc.), internal volume, and expansion ratio (the ratio of final internal volume to initial internal volume). The time from C to D varies from a few milliseconds for releases and initiators to 100 or more milliseconds for some catapults. The ballistic design chapter 5 of this manual discusses this important interval in detail.

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

h. Finally, the interval from point D to point E 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 E, the end of the stroke.

i. Acceleration and rate of change of acceleration of a device are controlled by the selection of internal ballistic parameters. Occasionally, further control is effected by the addition of a buffer or damper. External dampers were used in earlier propellant actuated devices, and internal dampers have been used successfully in several recently designed thrusters. Figure 5 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 its stroke when the pressure buildup is sufficient to shear the locking pin (fig. 5). The fluid surrounding the main piston is then 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.

j. Motion is not only controlled by grain design and by the addition of dampers but may also be controlled ballistically by metering the flow of propellant gas through an orifice. A high-low system is an example of ballistic control. In a high-low system, the propellant is burned in a chamber and the gas is bled from this chamber into a much larger chamber through an orifice. Thus, the propellant is burned at high pressures (which are conducive to good burning) while the stroke is controlled by the low pressure gas in the large chamber.

k. A pressure relief valve can also be used to control the motion of a propellant actuated device ballistically by dumping the gas that would cause excessive acceleration. Throughout the stroke, the valve opens and closes to maintain a nearly constant pressure within the device.

13. Load. The load experienced by the piston of a thruster is the total of all forces acting on the thruster. Propellant actuated devices may be subject to loads which assist as well as resist motion. These loads include the inertia forces of the mass of the body being propelled and the moving parts of the propellant actuated device, initial and final locks (if used), friction forces, and damping forces (if a damper is used). In aircraft installations, friction and bending forces may be present in the tubes of catapults and removers as a result of aircraft maneuvers and aerodynamic loads.

14. Weight and Size (Envelope). *a*. Weight and size, although subordinate to reliability, generally are critical considerations in aircraft or missile installations. 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 devices which could be fabricated easily from a single long 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 shown in figure 19.

b. To reduce weight, it is necessary to operate with working stresses which approach the yield stresses of the materials used. The sizes of the parts are adjusted and readjusted to provide safety factors which experience has indicated will produce a reliable item. The safety factors used are covered in paragraph 28.

c. 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.

15. Environment. *a*. In aircraft applications, propellant actuated devices are exposed to temperatures within the range of -65° to +200°F. Propellant, primers, and all mechanical parts 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 which may age and cease to function properly. The coefficient of expansion and the viscosity of damping and buffing fluids also are important considerations because of this wide temperature range.

b. Propellant actuated devices are supplied as sealed units to prevent moisture or dirt entering during long storage periods (as long as 3 years either on a shelf or mounted in an aircraft). As added insurance, cartridges are hermetically sealed, and are replaced periodically to prevent propellant aging from adversely affecting performance.

c. Threaded connections must be capable of withstanding torque tests as insurance against loosening when exposed to vibrations encountered in handling, shipment, or installation. A Nylok pellet, 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 if the device contains a cartridge, since the device may require disassembly.

d. If a propellant actuated device can survive a 6-foot drop onto concrete, it can withstand the maximum shock which 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 the shock. The design of shear pins used to retain the firing pins in

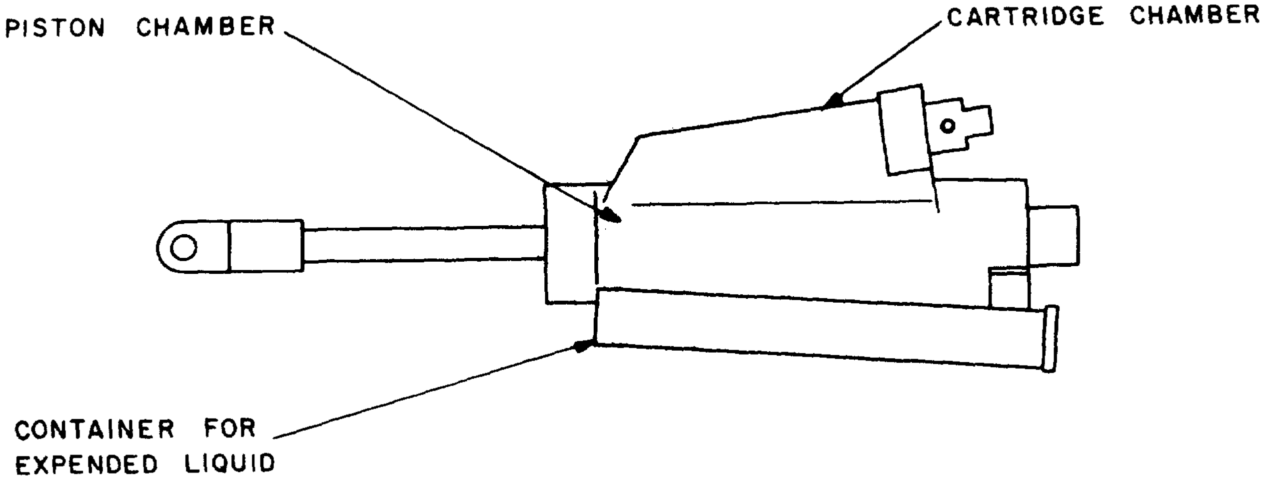

Figure 19. Thruster with stacked configuration.

gas-actuated device is critical: the pins must withstand the shock of the drop test and yet shear when the firing pin is subjected to a specific gas pressure. The concept of shear pins is presented in chapter 4.

16. Heat Loss. *a*. A highly theoretical discussion of heat loss is unnecessary in the design of propellant actuated devices. 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 the chamber volume required. Heat loss has a great effect on devices which retain or produce hot propellant gas for a long period of time (gas generators) ; the chamber walls absorb heat, thus lowering the temperature of the gas in the chamber and, consequently, reducing the pressure of the gas remaining in the chamber.

b. In transferring hot gas from one chamber 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.

c. In preliminary designs of propellant actuated devices, it is common to assume the devices to be 8 to 10 percent efficient. No attempt is made to calculate the actual losses due to heat and friction, but rather, the above efficiency is assumed and adjustments in energy requirements are made during testing.

CHAPTER 4

DESIGN TECHNIQUES

Section I. INTRODUCTION

17. General. This chapter provides 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 in propellant actuated devices are discussed. The design of individual components of the devices is described, and the use of protective finishes and dissimilar metals is outlined.

18. Design Requirements. The customary starting point in the design of propellant actuated devices is the requirements which list in detail the size, weight, strength, and performance of the device. A typical list of design requirements includes the following.

a. Maximum envelope dimensions.

b. Maximum weight.

c. Method of initiation.

d. Minimum mounting strength (structural loads).

e. Open or closed type system.

f. Initial and/or final lock requirements.

g. Propelled mass.

h. Velocity.

i. Maximum acceleration.

j. Maximum rate of change of acceleration.

k. Ignition delay.

l. Resisting or assisting forces.

m. Strokes (must be compatible with *h*, *i*, and *j* above).

n. Special requirements such as bypass and buffer or damper requirements.

Section II. METHOD OF FIRST ORDER APPROXIMATIONS

19. General. Not all significant parameters are defined in design requirements. The design requirements may specify acceleration, rate of change of acceleration, and velocity, but, not the stroke necessary to satisfy these requirements. Stroke and velocity but not acceleration may be specified for thrusters. The envelope specifications may give exterior dimensions but not the internal volume and expansion ratio nor the propellant charge and cartridge size. The unspecified parameters must be determined by the designer in conjunction with the ballistician. Methods of approximating stroke, stroke time, working pressures, and propellant charges are presented here. The last parameter is treated in greater detail in chapter 5.

20. Stroke to Separation. *a.* The requirements for catapults, removers, and occasionally thrusters specify terminal velocity, v, maximum acceleration, a_m, and maximum rate of change of acceleration, a°. The stroke, S, of such devices can be estimated by using the following equation, the derivation of which is contained in chapter 5.

$$S = 0.6\frac{v^2}{a_m} \qquad (1)$$

b. The M5 catapult, for example, has the following performance characteristics when fired at 70°F.:

$v = 64$ fps †

$a_m = 14g$ (451 ft/sec^2) †

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† The quantities used here are the actual quantities measured during the development of the M5 Catapult. They are used in these equations to illustrate the usability of the equations. The acceleration and rate of change of acceleration are usually given as specified maxima. The values of these two quantities to be used in these equations for preliminary design are chosen by the designer from experience. Chapter 6 gives step-by-step use of the equations for some examples.

Using equation (1) to determine the necessary stroke,

$$S = 0.6\frac{(64\ \text{ft/sec})^2}{451\ \text{ft/sec}^2} = 5.45\ \text{ft} = 65.4\ \text{in.}$$

The actual stroke of the M5 catapult is 66 inches.

c. The relationship of stroke and velocity for several values of acceleration also is shown graphically in figure 20. The performance curves were plotted using equation (1). The maximum acceleration curves shown were chosen near those which are acceptable for pilot ejection catapults. Using the 15*g* curve of figure 20 instead of the equation would have yielded a similar result. To use the curve, locate the intersection of the desired final velocity (abscissa) with the curve representing the allowable acceleration. The ordinate of this intersection is the required stroke, which in the example is 65 inches.

21. Stroke Time. The time t_m, required for a propellant actuated device to complete its stroke may be estimated from the equation:

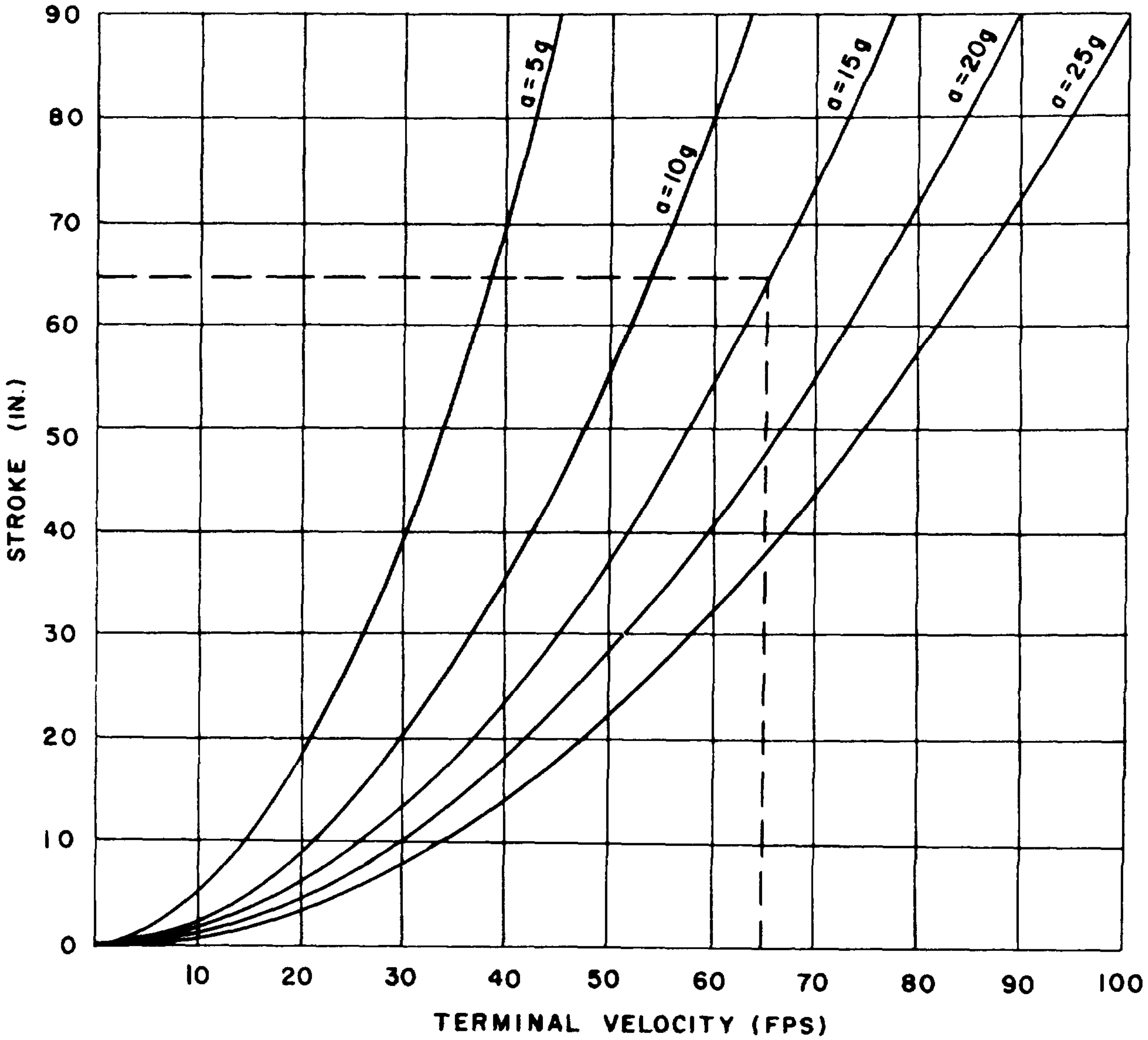

Figure 20. Curves for estimating performance.

$$t_m = \frac{v}{a_m} + \frac{a_m}{2\mathring{a}} \qquad (2)$$

Where a° is the maximum rate of change of acceleration. The use of equation (2) is demonstrated by the following calculation which was made to determine the stroke time of the M5 catapult. The M5 catapult has the following performance characteristics:

$v = 64$ fps

$a_m = 14g$ (451 ft/sec^2)†

$\mathring{a} = 109g$/sec†

Using equation (2),

$$t_m = \frac{64 \text{ ft/sec}}{451 \text{ ft/sec}^2} + \frac{14g}{2 \times 109g/\text{sec}}$$
$$= 0.142 + 0.064 = 0.206 \text{ sec}$$

The stroke for the M5 catapult actually is 0.220 seconds.

22. Peak Pressure. *a*. The relationship between peak pressure, P, and piston area or tube area, A, may be estimated by using Newton's Law ($F=ma$) and substituting PA for force, F, where m is the propelled mass and a_m the maximum acceleration.

$$PA = ma_m \qquad (3)$$

Equation (3) may be used to determine the piston or tube area if a specific pressure is desired, or it may be used to determine the peak pressure if the area is established.

b. The characteristics of the M5 catapult are used again in the following calculation as an example of how to use equation (3). The propelled mass is 312/*g* slugs and the tube area is 2.65† + square inches. Therefore:

$$P = \frac{ma_m}{A} = \frac{\frac{312}{g} \times 14g^{‡}}{2.64} = 1{,}650 \text{ psi}$$

The actual peak pressure in the M5 catapult is 1800 psi.

23. Propellant Charge Weight. *a. Catapults and Removers*.

(1) A first order design approximation of the propellant charge weight for catapults and removers may be found by using figure 21. This figure is based on the equation:

$$c = Wkv^2 \qquad (4)$$

Where:

c=charge weight (grams)
W=propelled weight (pounds)
k=a constant (6.25X10^{-5} for catapults and 5.38X 10^{-5} for removers)
v=terminal velocity (fps)

(2) Equation (4) is a simplification of equation (31) presented in Chapter 5. The derivation of the constants§ used in equation (4) is presented in "Refinements to First Order Equations," in Chapter 5.

(3) To use the curves of figure 21 in approximating the propellant charge in a catapult (the M5 catapult for example) find the intersection of the terminal velocity (64 fps) abscissa and the catapult curve. The ordinate of this point (0.26 gm/lb) is the ratio of the charge weight to the propelled weight. Since the propelled weight is 312 pounds, multiply the ratio found in figure 21 by 312 pounds and the approximate charge weight is found to be 81 grams. This is a reasonable estimate since the actual charge weight of the M5 catapult is 84.5 grams.

(4) A similar procedure is followed when estimating the charge weight of a remover, except the remover curve is used.

b. Thrusters.

(1) Figure 22 is used, in a manner similar to that outlined above, to estimate the propellant charge for a thruster. Two curves are presented in figure 23, showing two groups of propellants of different impetus which are used in stroking devices. The curves are plotted from equation (5) which is derived in chapter 5.

$$c = k\int_0^s F_r\,ds = \overline{F}_r S \qquad (5)$$

Where:

c=charge weight (grams)
k=a constant (based on the propellant used)
F_r=resistive force (pounds)
S=stroke (inches)

$$\overline{F}_r = \frac{1}{S}\int_0^s F_r\,ds$$

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† Refer to footnote on page 24.

‡ Chosen on the basis of installed dimensions and dimensions) of standard tubing.

§ Different constants are used for catapults and removers since the characteristic propellant composition and energy losses for these two types of devices are different.

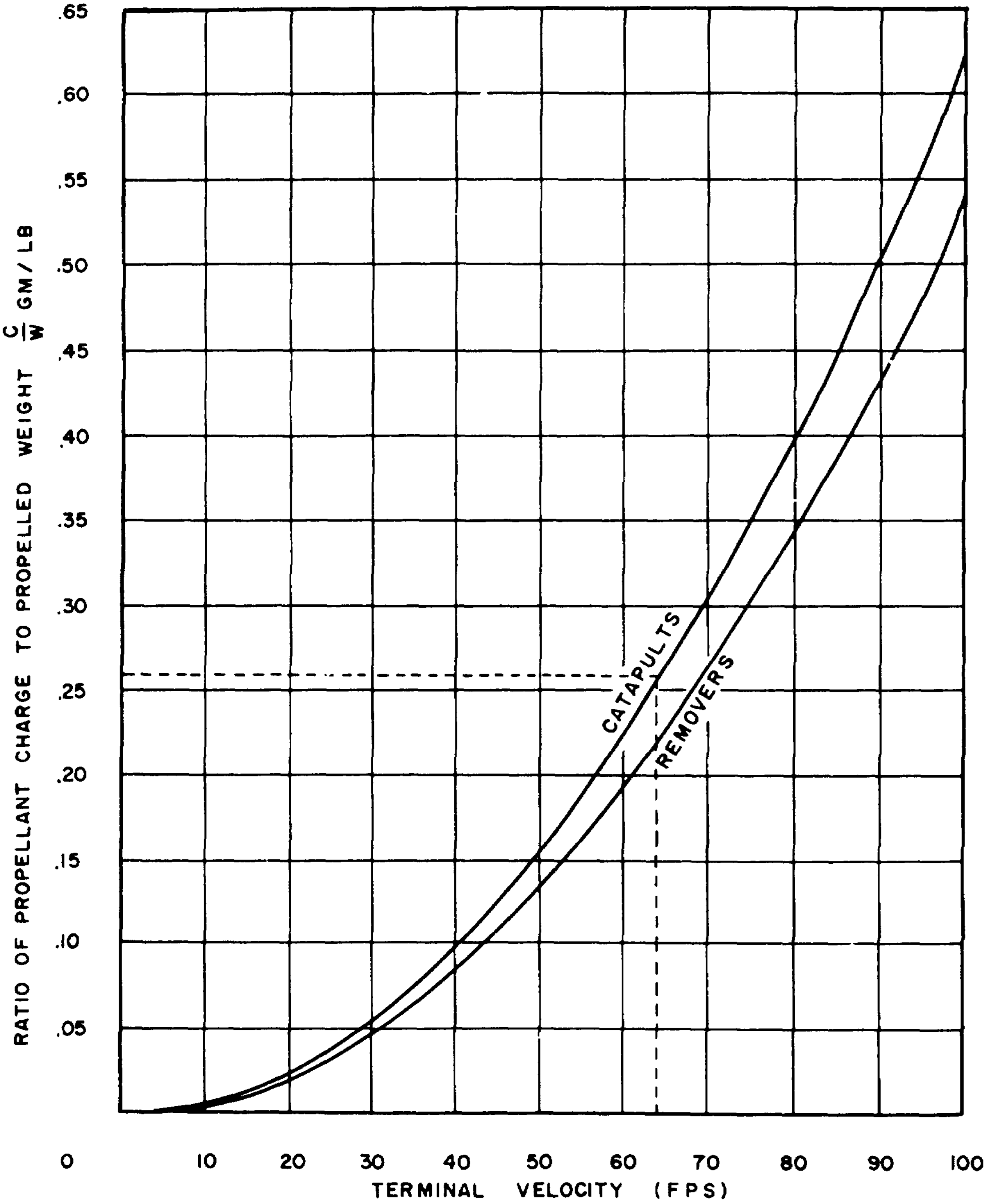

Figure 21. Curve for approximating propellant charge for catapults and removers.

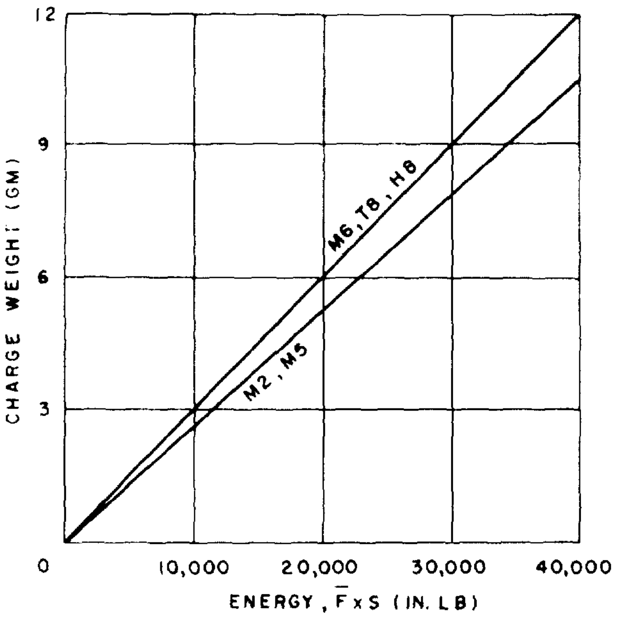

Figure 22. Curve for approximating propellant charge for thrusters.

(2) To determine the charge weight for a thruster, calculate the energy expended in doing the required work (in inch pounds). Then find the intersection of that particular abscissa with the curve representing the propellant to be used, and the ordinate of that intersection represents the approximate charge (in grams).

24. Propellant Web. The web is the minimum thickness of the grain between any two adjacent surfaces of the propellant and the initial propellant web in inches, w, may be estimated from equation (6):

$$w = 1.4\, C'Pt_m \qquad (6)$$

where C'=pressure coefficient of linear burning rate of the propellant (of the order of 2×10^{-4} in./sec/psi). As before, P is peak pressure (1,800 psi) and t_m is stroke time (0.210 sec), for the M5 catapult.

Therefore:

$$W = 1.4 \times 2 \times 10^{-4} \times 1{,}800 \times 0.210$$

$$W = 0.11 \text{ inch}$$

The actual web is 0.110 inch.

This equation may be applied to catapults, removers, and thrusters, remembering that it is only a first order approximation.

25. Cartridge Case Volume. *a*. The cartridge case volume is usually estimated in one of two ways, depending upon the size of the individual propellant grains. If the grains are "small" and will be oriented randomly when loaded into the cartridge case, the loading density is taken to be about 30 in.^{3}/lb of propellant. For an example, suppose it is estimated that 8 grams of propellant in the configuration of a cylinder 0.25 inch long by 0.10 inch outside diameter are required for a thruster application. The case volume required would then be estimated as:

$$30 \text{ in.}^3/\text{lb} \times 8 \text{ gm} \times \text{lb}/454 \text{ gm} = 0.53 \text{ in.}^3$$

Additional volume also must be provided for the 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.

b. If "large'" grains are to be used, they may be loaded iii some definite geometrical armament. The grains are then stacked in the cartridge with their centerlines parallel to the centerline of the case. The case volume is then estimated by the size and number of the grains and their geometrical arrangement. This is discussed in section **II**, chapter 6, in the design example on the M3 Catapult.

26. Igniter Charge. The igniter used in most propellant actuated devices developed up to the present time has been black powder. A rule of thumb that has evolved to estimate igniter charge weight is the use of about 40 grams of black powder per pound of propellant. This estimated igniter charge may have to be increased or decreased depending upon results of firings between -65° F. and 200° F.

Section III. DESIGN STRENGTH CALCULATIONS

27. General. *a*. In most propellant actuated device applications, minimizing the weight of assemblies is a primary consideration. For this reason, materials which possess a high strength-to-weight ratio, such as heat-treated alloy steels and high-strength aluminum, commonly are used. Critically stressed port ions of components of propellant actuated devices are designed so that material is used efficiently.

b. Resulphurized steels are never used, since they contain iron sulphide "stringers" or microstructural sulphide inclusions, oriented in the direction of working, and normal to the most critical stress, and thus are inadequate in devices with high internal pressures.

28. Safety Factors. *a.* Safety factors used in the design of propellant actuated devices may appear low, but they are adequate because they are subjected only to controlled loads.

b. Safety factor of a part is established as a ratio of the limiting stress to the design stress. All conditions having an effect on the stress is included in the determination.

c. Limiting stresses of pressure containing structures is based on the minimum yield strength of the material, and the design stress is based on the Distortion Energy Theory in accordance with the von Mises-Hencky Concept. Utilizing this theory, the minimum factor of safety of the cylindrical section or wall of the pressure chamber is 1.15.

d. The limiting stress of all other components also corresponds to the minimum yield strength, but a minimum factor of safety of 1.5 is applied. In the cases where shock or impact loads are applied, the minimum factor of safety is 2.0.

29. Temperature Effects. Temperature has a marked effect on the mechanical properties of metals at high temperatures. The burning of propellant in the device is for so short a time that the metal parts are unable to absorb much heat; consequently, a negligible temperature increase is experienced. In addition, propellant actuated devices are not exposed to ambient temperatures exceeding 200° F., and the change in strength at 200° F. is small and may be neglected.

30. Stresses. When calculating the sizes of metal parts to withstand the internal pressures of 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 device produces a direct radial compressive stress which is greatest on the inside wall, and induces a tangential stress (hoop stress) which is greatest also 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.

31. Distortion-Energy Theory. *a.* 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 given in equation (7),

$$2\sigma_e^2=(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2 \qquad (7)$$

Where:

σ_e=**equivalent yield stress**
σ_1=**radial stress**
σ_2=**tangential stress**
σ_3=**axial stress**

is shown in more useful forms in equations (8) and (9). The conversion of equation (7) to the forms of (8) and (9) is shown in appendix I.

$$\frac{P}{Y}=\frac{1}{\sqrt{3}}\frac{(W^2-1)}{W^2} \qquad (8)$$

Where:

P=maximum pressure
Y=yield strength of material
W=wall ratio

$$W=\sqrt{\frac{1.}{1-\sqrt{3}\left(\frac{P}{Y}\right)}} \qquad (9)$$

When a device is designed to withstand only biaxial stresses, equation (10) may be used.

$$\frac{P}{Y}=\frac{W^2-1}{\sqrt{(3W^4+1)}} \qquad (10)$$

b. The convenience of these forms of the distortion-energy equation is apparent when it is realized that the internal pressure, P, can be estimated and the strength of the material, *Y*, may be found in most engineering handbooks. The wall ratio (ratio of *OD* to *ID*) and a tube size can then be calculated. Appendix II contains a table of wall ratios for values of *P/Y* from 0.010 to 0.200. This table was calculated from the formulas presented in this section. Figure 23 presents curves of *P/Y* as a function of *W* for biaxial and triaxial stresses, based on the tables of appendix II.

c. 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 which is stronger than required (higher *W*) to avoid the expense of using special size tubing. Tubing sizes are presented in military standards.

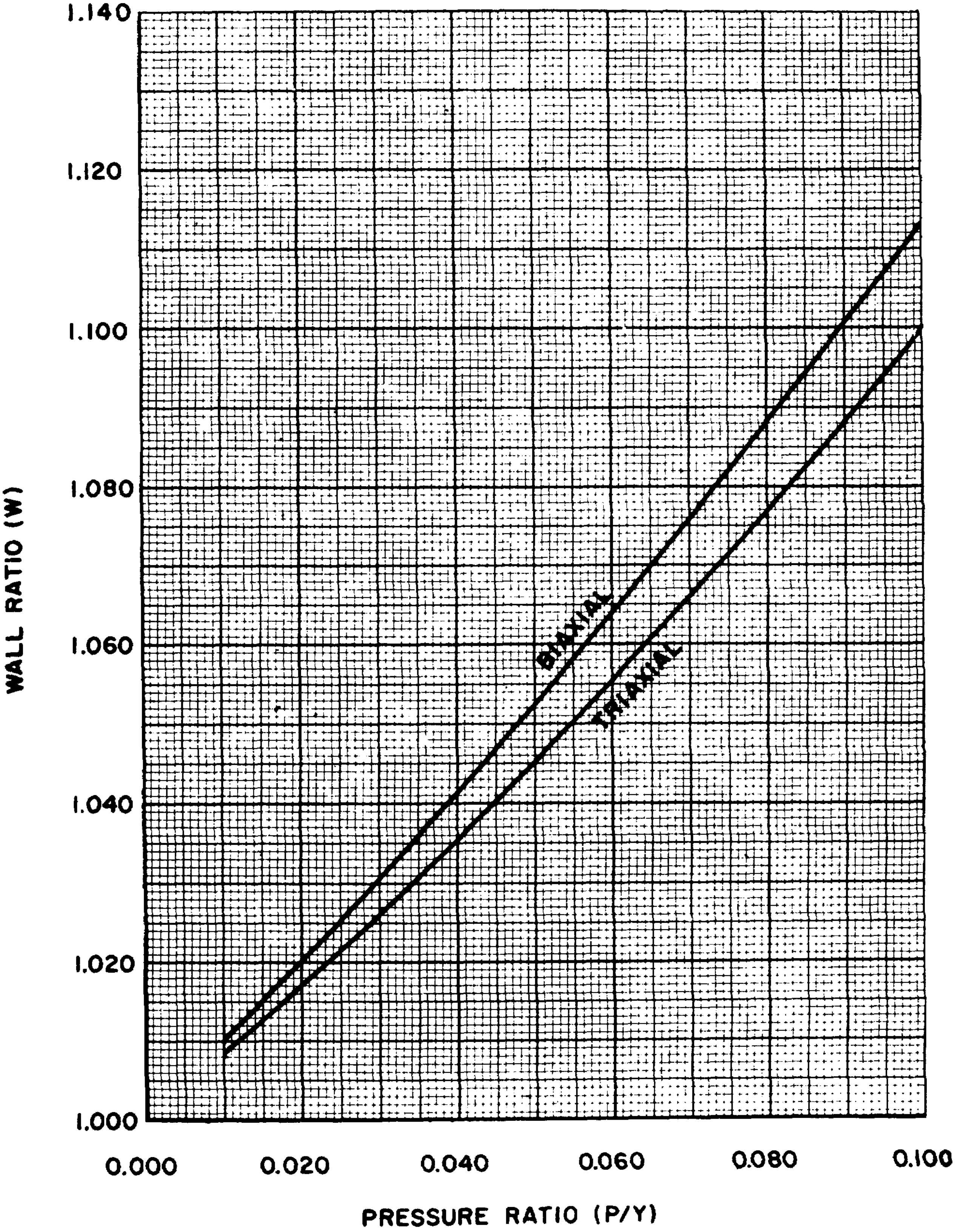

Figure 23. Biaxial and triaxial strength curves (sheet 1 of 2).

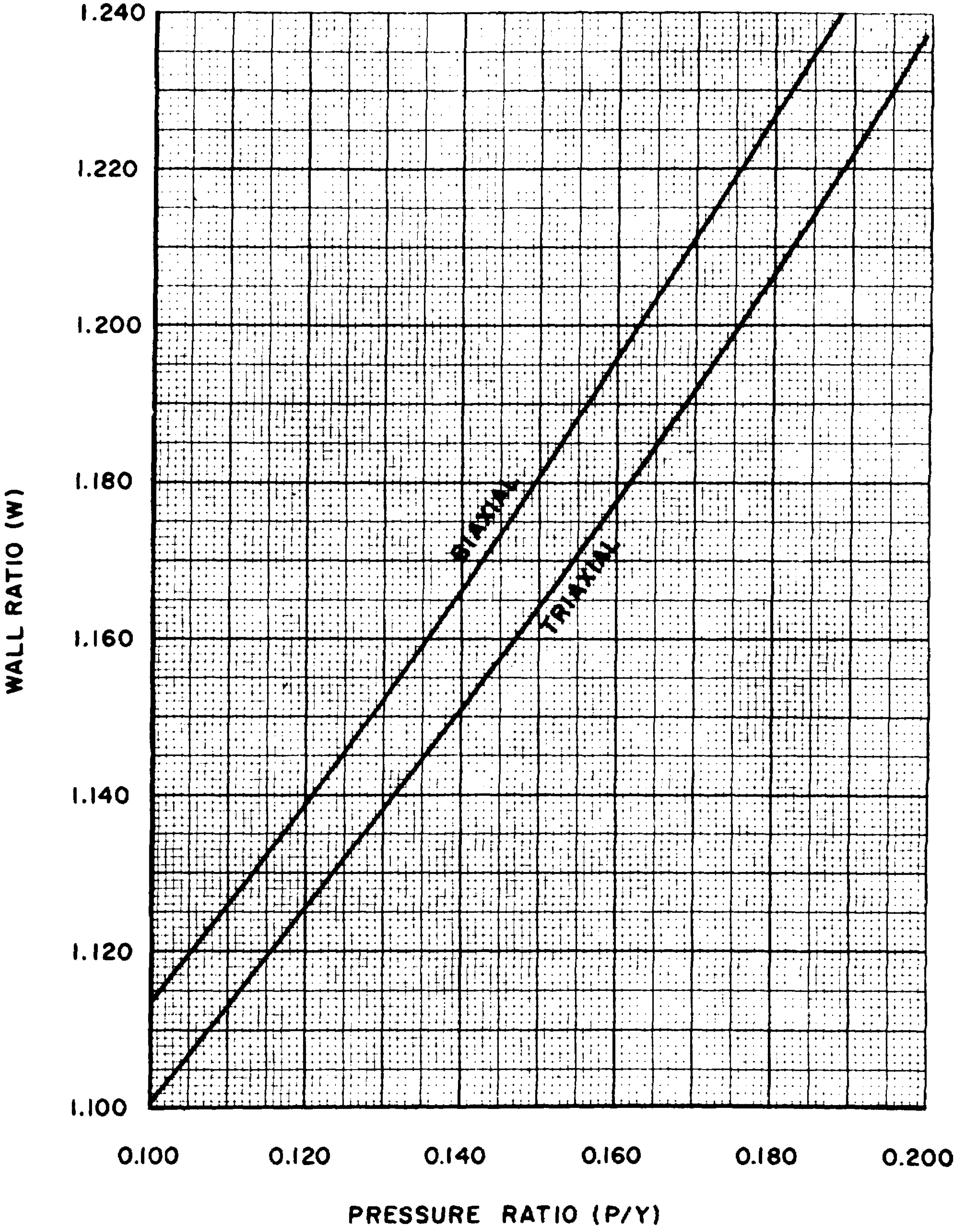

Figure 23. Biaxial and triaxial strength curves (sheet 2 of 2).

d. The tables of appendix II or figure 23 also may be used to determine the maximum permissible pressure when the tube size is specified. For example, the maximum pressure permissible with a tube whose dimensions are 1.500 outside diameter and 1.248 inside diameter may be found as follows:

$$W=\frac{OD^{\dagger}}{ID^{\dagger}}=\frac{1.500-0.016}{1.240+0.008}=1.191$$

Assuming that there are triaxial stresses, P/Y=0.170 is obtained from the tables in appendix II. If the material is steel with a value of Y=125,000 psi, then P=0.1770 X 125,000 =21,250 psi.

e. Conversely, the maximum pressure could have been estimated and the wall ratio taken from the table of figure 23. From the estimated *OD* or that specified by the envelope drawing, the necessary *ID* can be calculated. The tubing size specified in the military standards most closely approximating these dimensions would be used.

32. Length of Thread Engagement. After calculating the tubing size necessary to withstand the stresses involved, the second most important calculations are those for determining the length of engagement of threads. Threads are designed in accordance with Bureau of Standards specifications. The length of these threads may be calculated by using equation (11). (The derivation of equation (11) is given in appendix III.)

$$L=\frac{3\,PR^2}{S_s d} \qquad (11)$$

Where:

L=length of engagement of threads
P=maximum internal pressure
S_3=shear strength
R=major radius of female (max)
d=minor diameter of male (min)

This equation includes a 1.5 safety factor to allow for tolerances and the distribution of stresses within the engagement.

Section IV. DESIGN PROCEDURES

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

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

34. Gas-Generating Devices. *a.* The design requirements for gas-generating devices specify the pressure that is to be generated and where it is to be measured. For example, an initiator may be required to produce a pressure of 500 psi in an 0.062-cubic-inch chamber at the end of a 15-foot tube. 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. 24).

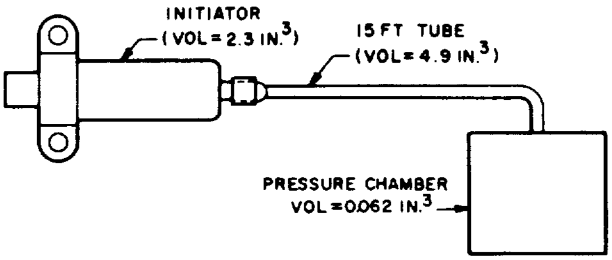

Figure 24. Simple PAD system using an initiator.

b. The ballistician uses these three values to estimate the propellant charge necessary to produce the required pressure. The method of estimating this pressure is described in the ballistics design discussion (chap. 5). The designer then calculates the maximum pressure which may be developed in the initiator when the device is fired "locked shut." (The chamber is closed so that the internal volume of the chamber must contain all of the gas generated by the burning propellant.) The strength of the walls is calculated from the "locked shut" pressure, using the curves or tables described previously.

c. To estimate the locked-shut pressure, the "gas law" is approximated as shown below:

---

† The smallest possible OD and largest possible ID are used. The numbers 0.016 and 0.008 are tolerances.

$$PV \approx 12CF \qquad (12)$$

Where:

P=maximum gas pressure (psi)
V=volume (in.^{3})
C=charge weight (lb)
F=the impetus of the propellant (ft-lb/lb)

The factor 12 is used to permit the use of inch units in the gas law. Rewriting equation (12) using the equivalents indicated, and introducing a factor (454) to permit the charge to be given in grams, yields

$$P \approx \frac{12cF}{454V} = 0.0264\,\frac{cF}{V} \qquad (13)$$

d. To illustrate the use of this equation, assume an initiator is to be designed with an internal volume of 2.3 cubic inches. The ballistician determines that 3 grams of propellant of F=360,000 ft-lb/lb is required. Applying equation (13),

$$P \approx 0.0264\,\frac{cF}{V}$$

$$P \approx \frac{0.0264 \times 3 \times 360{,}000}{2.3}$$

$$P \approx 12{,}400 \text{ psi} \qquad (13)$$

Since the maximum pressure which 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. 23) to determine the wall ratio and, therefore, the thickness of the wall.

e. It is common practice to fabricate the first model of a device (workhorse model) out of steel and to make it considerably stronger than necessary so that the operation of the device and the actual pressures which 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 of propellant actuated devices. These portions can be removed and modified without necessitating redesign of the complete device.

35. Stroking Devices. *a.* The design procedure for stroking devices is more complex than that for gas generators. 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 system and whether or not to use a damper to control the stroke. (A closed system is sometimes a military requirement: e.g., thrusters.) The decision on the damper is based on the estimated stroke time and required velocity or acceleration. Damper design is discussed in paragraph 45.

b. The next consideration is the envelope of the stroking device. The envelope dimensions may be specified with a complete drawing or only a few maximum 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 using trunnions for mounting is to permit self alignment; and thus avoid bending loads in stroking devices.) With all of the above completed, it is then determined whether the envelope will permit the necessary stroke. Thrusters have been developed with as many as 3 moving tubes (fig. 25) to reconcile the necessary stroke with the specified envelope.

c. It is now possible to compute the initial volume (available to the powder gases) and the final volume (the volume at end of stroke or where the tubes separate) and determine the expansion ratio. The expansion ratio of a device is the ratio of the final volume to the original volume. It is customary in propellant actuated devices to limit the expansion ratio to 3 to 1, although several devices have had ratios greater than 4 to 1.

d. In an effort to enlarge the initial volume of a device (and therefore reduce the expansion ratio), many devices are designed with holes in the walls of the inside tubes to permit gas to flow around the tubes as well as within the tubes. Figure 25 shows a thruster with this design feature. Gas flowing outside as well as within the tubes also eliminates large pressure differentials and permits the inside tube walls to be made thinner and lighter.

e. 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 is also determined. If the device is to bypass pressure at the end of stroke, it must be insured that sufficient energy remains in the device after completing its stroke to permit the proper energy bypass.

f. The next step is to fit a firing mechanism to the device and design the individual components. Any changes in design that are necessary are made, and a

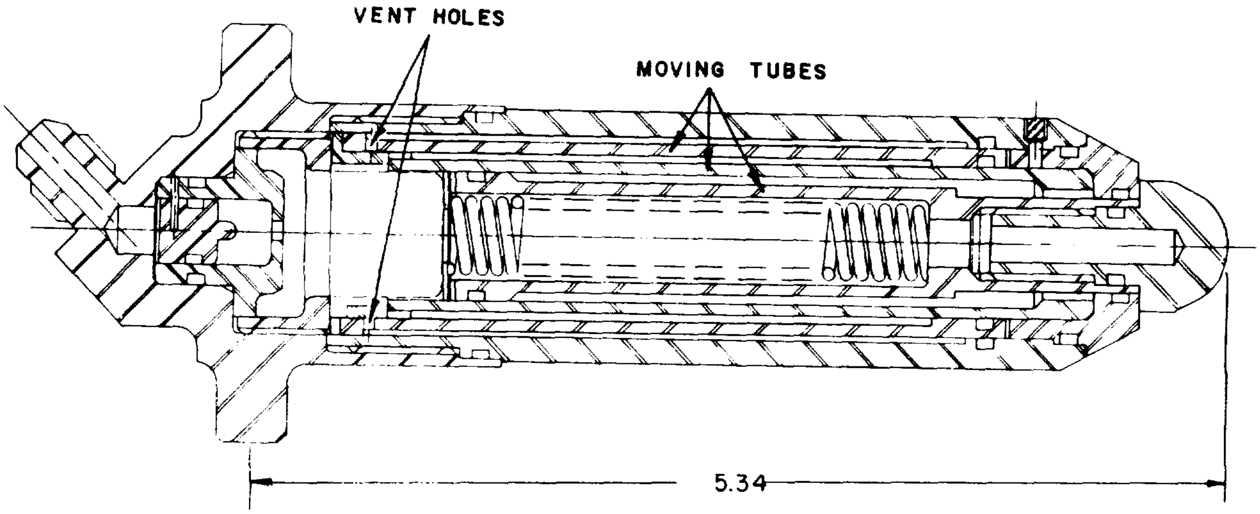

Figure 25. T28 Thruster.

workhorse model is fabricated and tested. The procedure then becomes one of modification and retest until the design specifications are satisfied with the most efficient arrangement of components.

g. A portion of the design and testing phases may be eliminated by using computers. An analog computer has been used for analyzing a catapult's performance theoretically under various acceleration loads and friction forces.

36. Systems. *a*. Multi-component PAD systems generally are designed by the air-frame or missile manufacturer under the direction of the cognizant agency. However, in the design of propellant actuated devices, systems can be improved by eliminating devices or combining several operations into one device to improve reliability and guarantee proper operating sequence of the system.

b. The sequencing of operations is determined by experience with previous systems, but the testing phase is the major determinant. Systems are tested on breadboard mockups and on rocket sleds at various speeds to determine the overall operation of each device in conjunction with every other device.

c. The operation of devices in a system may be sequenced by mechanical means such as gear trains or static lines; however, the most common method is through pyrotechnic delays and bypass fittings on the ends of propellant actuated devices. Many pyrotechnic delays have been standardized, but their metal parts often are modified to insure the proper fit in the various cartridge cases. The tubing, hose, and gas fittings used in these systems are also standardized. Various fittings and types of hose or tubing 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.

Section V. COMPONENT DESIGN

37. Cartridge. *a. General.*

(1) The cartridge (fig. 26) is a metal can which contains the propellant, igniter, and primer. It is designed to burst open from the pressure of the propellant gases. The can (case) is hermetically sealed to keep out moisture (moisture interferes seriously with performance). 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.

(2) Most cartridges contain percussion primers, although electric ignition elements have been used in place of percussion primers in cartridges for missile applications. An electrically initiated cartridge is similar except for the primer. The percussion primer is fired by

the impact of a firing pin. The primer, in turn, ignites the igniter which ignites the propellant.

(3) Small cartridges with easily ignited propellants, such as the cartridge shown in figure 27, do not ordinarily contain separate igniter chambers. Instead, the (black powder) igniter is mixed with the propellant. In figure 26, the black powder charge is located in the cone-shaped opening on the inner face of the cartridge head.

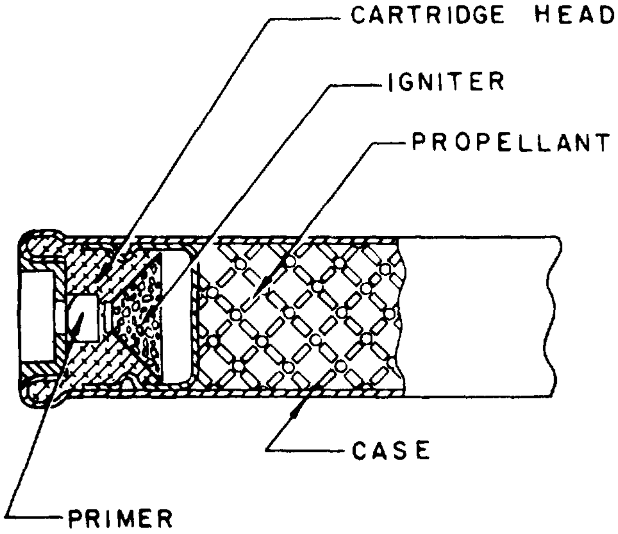

Figure 26. Typical large cartridge.

b. Cartridge Case.

(1) Design and development time is reduced whenever possible by using existing cartridge cases. Table VIII presents data on cases already developed. The letters in the column headings refer to the lettered dimensions in figure 27.

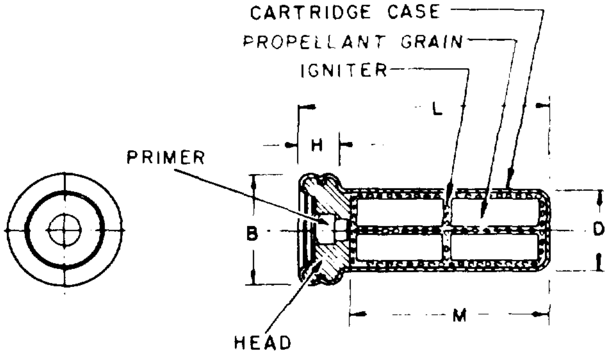

Figure 27. Typical small cartridge.

Table VIII. Sizes of Existing Cartridge Cases

Body diameter D (in.)	Head diameter B (in.)	Length L (in.)	Shoulder H (in.)	Propellant chamber † M (in.)	Approximate volume (in.^{3})	Cartridge ‡
0.550	0.710	7/8	0.26	1/2	0.1	M67
0.550	0.710	1 3/8	0.26	1	0.2	M38
0.550	0.710	1 5/8	0.26	1 1/4	0.2	M42
0.687	0.875	1.075	0.26	1/2	0.2	T292
0.687	0.875	2	0.26	1 1/2	0.5	M46
0.687	0.875	2 5/16	0.26	1 13/16	0.6	M70
0.710	0.880	1 3/32	0.26	1/2	0.2	T297
1.085	1.245	2 7/8	0.26	2 3/16	1.8	M31A1
1.245	1.390	755	0.26	1/8	0.1	T298E1
1.245	1.390	1 7/16	0.26	3/4	0.8	M69
1.245	1.390	1 11/16	0.27	15/16	0.9	M29A2
1.245	1.390	2.02	0.26	1 1/8	1.3	T299
1.245	1.390	2 3/8	0.26	1 9/16	1.7	T254
1.245	1.410	6 1/8	0.26	5 7/16	6.1	M37
1.495	1.660	4 7/16	0.30	3 5/8	6.0	M30A1
1.495	1.660	4 3/4	0.28	4	6.6	M28A1
1.495	1.660	8 7/8	0.24	8 3/16	13.5	M36
1.745	1.910	6 7/8	0.26	6 3/16	13.9	T125

† Assuming a standard cartridge head (no delay element).

‡ One of the cartridges in which the case is used.

(2) If no difficulty is anticipated in staying within the envelope specified, it may be advantageous at the start of mechanical design, to tentatively select a cartridge case and build the chamber and body around it. The selection of a case is based on the volume of the propellant which it must contain and 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 pound per cubic inch may be used with most compositions and large grain configurations.

e. Cartridge Head.

(1) 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.

(2) The base of the cartridge head, under the primer recess, is machined to a thickness between 0.006 and 0.010 inch to insure that it will "blow through" when the primer fires. Prior to cartridge actuation, this thin web separates the primer from the propellant or igniter, since the volatile chemicals of these may desensitize the primer mixture if permitted to come in contact with it.

d. Primers.

(1) Figure 28 shows a typical percussion primer. The dimensions and compositions of the four primers in common use in propellant actuated devices are presented in table IX.

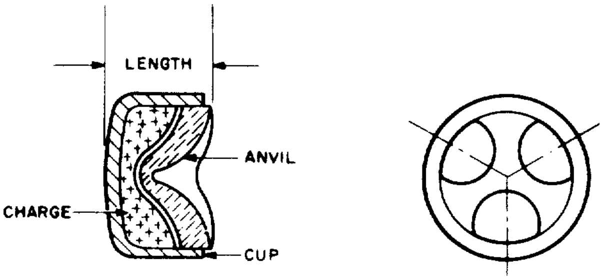

Figure 28. Percussion primer.

(2) The sensitivity of primers, as measured by all fire height, which varies from one model 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 is discussed in paragraph 40, firing mechanism.

e. Cartridge Seals.

(1) The cartridge must be hermetically sealed to permit storage for as long as .3 years without affecting ballistic performance. As previously described, the primer is separated from the propellant by a thin web at the base of the cartridge head. An O-ring between the head and the 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.

(2) The feasibility of a new design (fig. 29) which uses extrusion cold-weld seals and eliminates all nonmetallic parts of the cartridge is being studied. This design promises to provide a seal far superior to any now used. Other designs eliminating nonmetallic parts but relying on lap welds are illustrated in figure 30. This continued research indicates the importance of sealing problems in cartridges.

Table IX. Percussion Primers Used in Propellant Actuated Devices

Designation	OD (in.)	Length (in.)	Charge weight (grains)	Composition	All fire energy (in. oz)
M29A1	0.205	0.115	0.42	5061 Rem	18
M42...	0.170	0.115	0.33	WC #793	26
72M...	0.212	0.125	0.55	5061 Rem	60
50M...	0.317	0.225	2.20	5061 Rem	120

38. Body and Chamber. *a. Gas-Generating Devices.*

(1) The body of a propellant actuated device is the enveloping member or housing, and the chamber houses the cartridge. In simple propellant actuated devices, such as initiators, the body serves as a chamber as well as the housing.

(2) One type of initiator is shown in figure 31. The cylindrical shape is chosen because it is easy to fabricate. The physical dimensions are either specified or are functions of the necessary internal volume. Wall thickness is a function of internal pressure and is calculated as shown earlier in paragraph 31. It usually is possible to reduce the bending stresses which occur at the junction of the cylinder and each closed end by using a thick end section and suitable fillets. This is discussed in detail in chapter 6. The stresses occurring in gas-generating devices are triaxial because a longitudinal stress is introduced by the partially or fully closed ends.

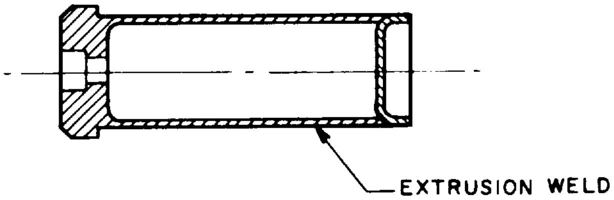

Figure 29. Cold welded cartridge

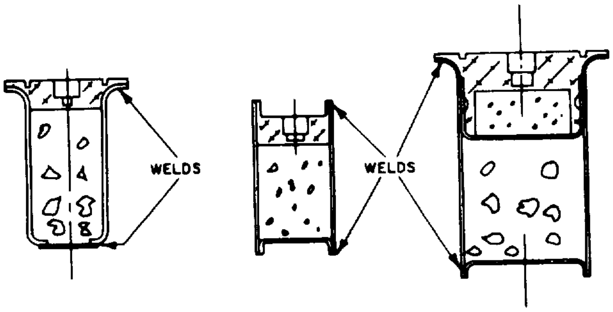

Figure 30. Feasible configuration of cartridges with lap welds (cold weld type).

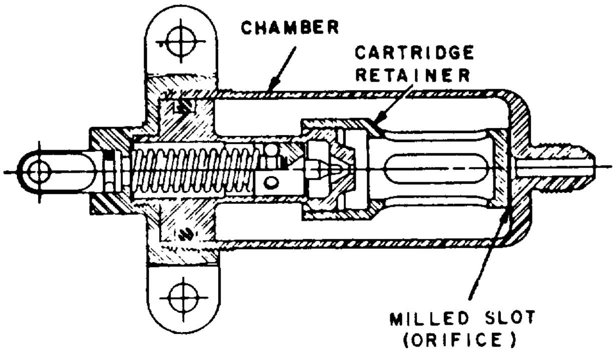

Figure 31. Initiator with cartridge retainer.

(3) 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. Tie cartridge retainer fits over the cartridge. It is cylindrical in shape and has a series of slots machined in its walls to permit the cartridge walls 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 hose or tubing. 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 the slots under the cartridge retainer should have areas which exceed the area of the exit port to prevent their functioning as flow-restricting orifices.

b. Stroking Devices.

(1) 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 must not only contain the internal pressure, but act as a structural member.

(2) 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.

(3) 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.

(4) 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.

39. Piston. *a.* 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).

b. 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.

c. For pistons loaded in compression, Eulers' column formulas may be used. The formulas are not presented in this text since they are dependent on end conditions which must be established for each application. For example, a thruster's 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.

40. Firing Mechanism. *a. General.* The firing mechanism initiates the primer which 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 pill 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 it special primer directly.

(1) *Firing pins.*

(a) Firing pins (fig. 32) are contained oil both gas and mechanically operated firing mechanisms, and their design is critical. 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 leave 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 is possible. Table X shows the length-to-diameter ratios and the clearances used in some existing devices.

Table X. Firing-Pin Ratios and Clearances

Device	Length/ diameter ratio	Firing pin and guide clearances
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.

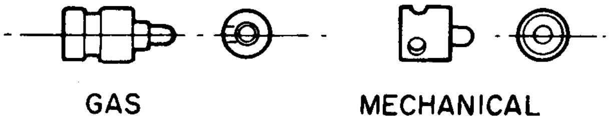

Figure 32. Firing pins.

(b) 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 inch off center of the primer cup.

(2) *Firing Plugs.*

(a) Artillery-type primers may be used. in cartridges using firing plugs seated in the cartridge head over the primer cup.

This plug (fig. 33) 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.

(b) At present, firing plugs are not used as much to compensate for off-center strikes as to prevent "primer blowback", 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").

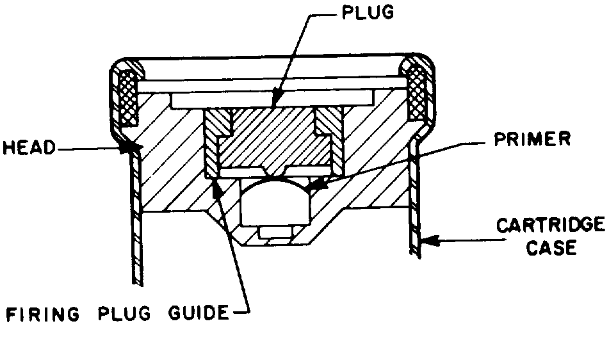

Figure 33. Firing plug.

(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" (fig. 34). 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 XI presents the desired protrusions and diameters for the four primers currently used in propellant actuated devices.

Table XI. Firing Pin Protrusions and Diameters

Primer	Firing pin protrusion (in.)	Firing pin tip diameter (in.)
M29A1	0.025+0.005	0.075
M42..........................	0.025+0.005	0.040
72M..........................	0.030+0.007	0.075
50M..........................	0.058+0.010	0.093

b. Gas-Operated Firing Mechanisms.

(1) 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.

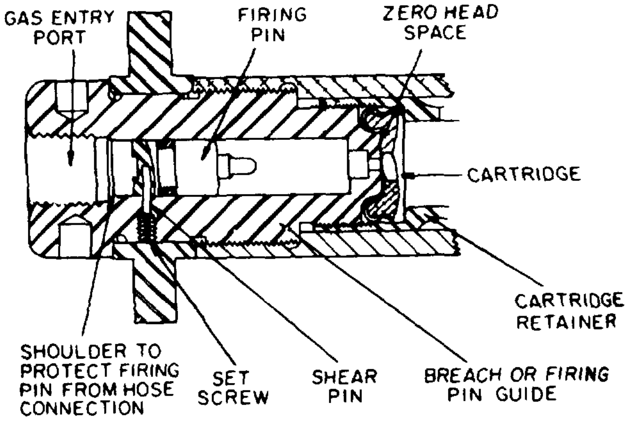

Figure 34. Gas-operated firing head.

(2) The gas-operated firing mechanism (fig. 34) 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 pill is sufficient to shear the firing pill 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 was, therefore, considered advisable to include (in table XII) 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 X are used.

Table XII. Firing Pins and Shear Pins Used in Propellant Actuated Devices

Firing pin diameter (in.)	Shear pint diameter (in.)	Primer to be struck	Units in which used
0.500	0.046	72M	Thrusters, M1, M2, M5, T16.
0.500	0.040	50M	Thrusters, T7, T8.
0.343	0.040	M42	Initiators, M6, M10.
0.343	0.040	M29A1	Initiators, T26, T31.

†Force required to shear copper pins: 0.046 dia = 48 ± 4 lb, 0.040 dia = 41 ± 5 lb.

(3) The shear pins indicated in table XII 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.

(4) 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, 1/2-inch diameter firing pins may have to be assembled from the cartridge end since the gas entry port is sometimes as small as 5/16 inch.‡: The smaller firing pills may be inserted through the gas entry port.

(5) 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 the 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.

c. Mechanically Operated Firing Mechanisms.

(1) 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.

(2) The mechanically operated tiring mechanism (fig. 35) 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

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†Propellant actuated devices must be dropped 6 feet 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 Bring pin to limit the entry of the hose fitting, preventing its contact with the firing pin.

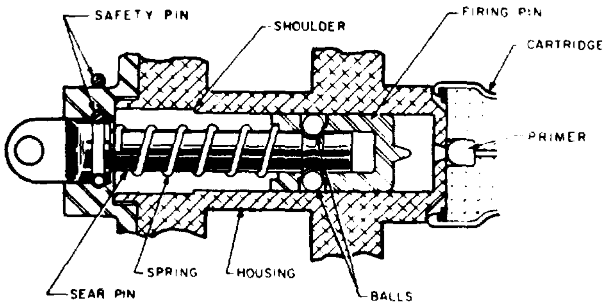

Figure 35. Mechanically operated firing mechanism.

(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.

(3) The energy required to fire the primer (table IX) must be provided by the spring 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.

(4) 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.

(5) 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 are never designed with firing pins in the cocked position. However, the cocking and firing of the device is initiated by a single operation.

(6) The actual procedure followed in designing a mechanical firing mechanism may best be seen by referring to paragraph 85 where the design of a mechanically operated initiator is illustrated.

41. Locking Mechanisms. *a.* 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 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 locks also prevent unintentional separation of the device due to tampering, vibration or dropping.

b. 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 which locks into a groove or other depression in the piston.

c. 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 this chapter under "Special Problems," para. 44) generally eliminate this type of arrangement from consideration. A method used in several thrusters is shown in Figure 36. 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. Figure 37 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.

d. 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.

42. Seals. *a.* 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

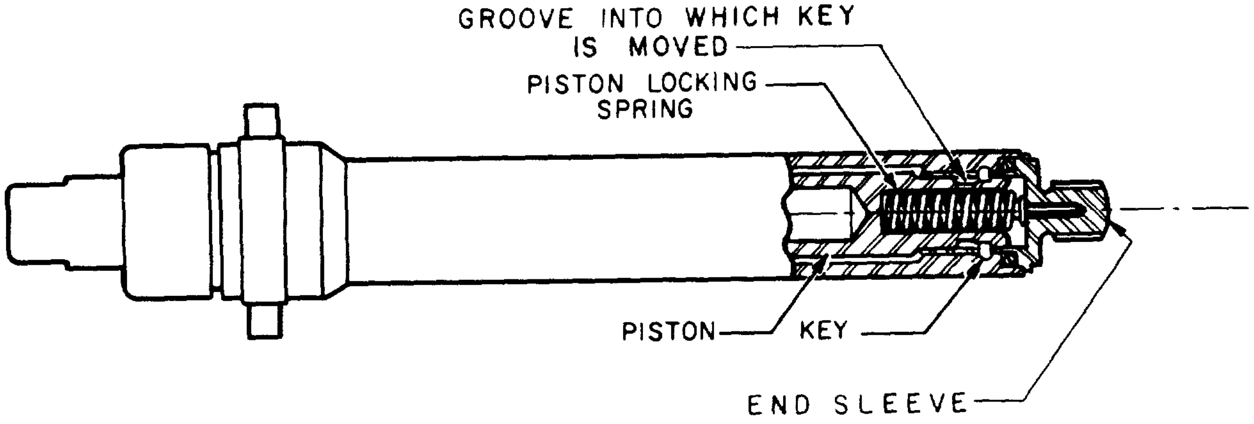

Figure 36. Thruster looking mechanism.

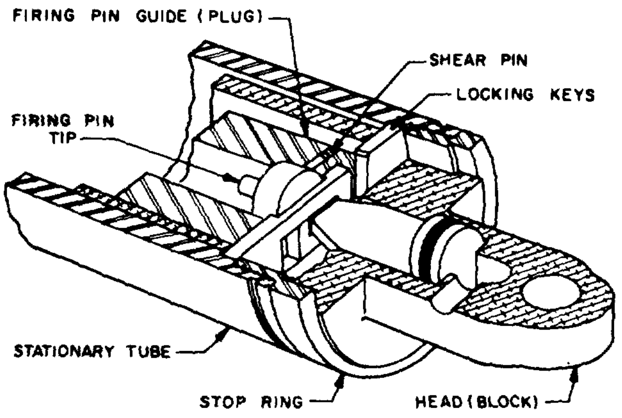

Figure 37. Locking keys and firing pin.

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.

b. The majority of propellant actuated devices rely on threaded connections and O-rings for sealing. For example, in the initiator shown in figure 31, 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.

c. The recommended diametral squeeze dimensions for O-rings which vary according to size and type of seal, generally decrease the cross-section 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.

d. 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.

e. Where a seal must retain the buffer fluid under static conditions and seal the gas under dynamic conditions, tolerances, clearances, and surface finishes must be carefully selected. Tests, evaluations, and modifications are continued until a satisfactory combination of conditions is obtained. Some catapults employ a tortuous-path-type seal which has proved effective. This type of seal is, essentially, a close-fitting coil of wire which fits in a helical groove. The end of the seal wire is provided with a tang which 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.

Section VI. SPECIAL PROBLEMS

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

44. Shear Pins. *a.* 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.

b. Spring pins (fig. 38) 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.

c. 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.

45. Damping Systems. *a.* When gas pressure is developed in the chamber of a stroking device, operating against 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 para. 46) are used, the initial volumes of devices are increased, and slower-burning or more progressive-burning propellants are used. (The selection of propellants and the determination of burning rates are discussed in chapter 5.)

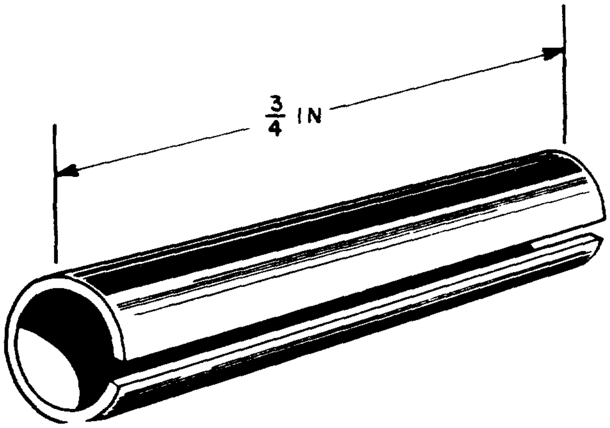

Figure 38. Spring pin.

b. 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.

c. 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. 39). 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.

d. 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.

e. One other damping system which warrants attention is the "hydraulic multiplier" (shown schematically in fig. 40). This device contains a gas piston and a load piston which is connected to the load. An orifice in the load piston permits liquid to pass from the liquid chamber into the

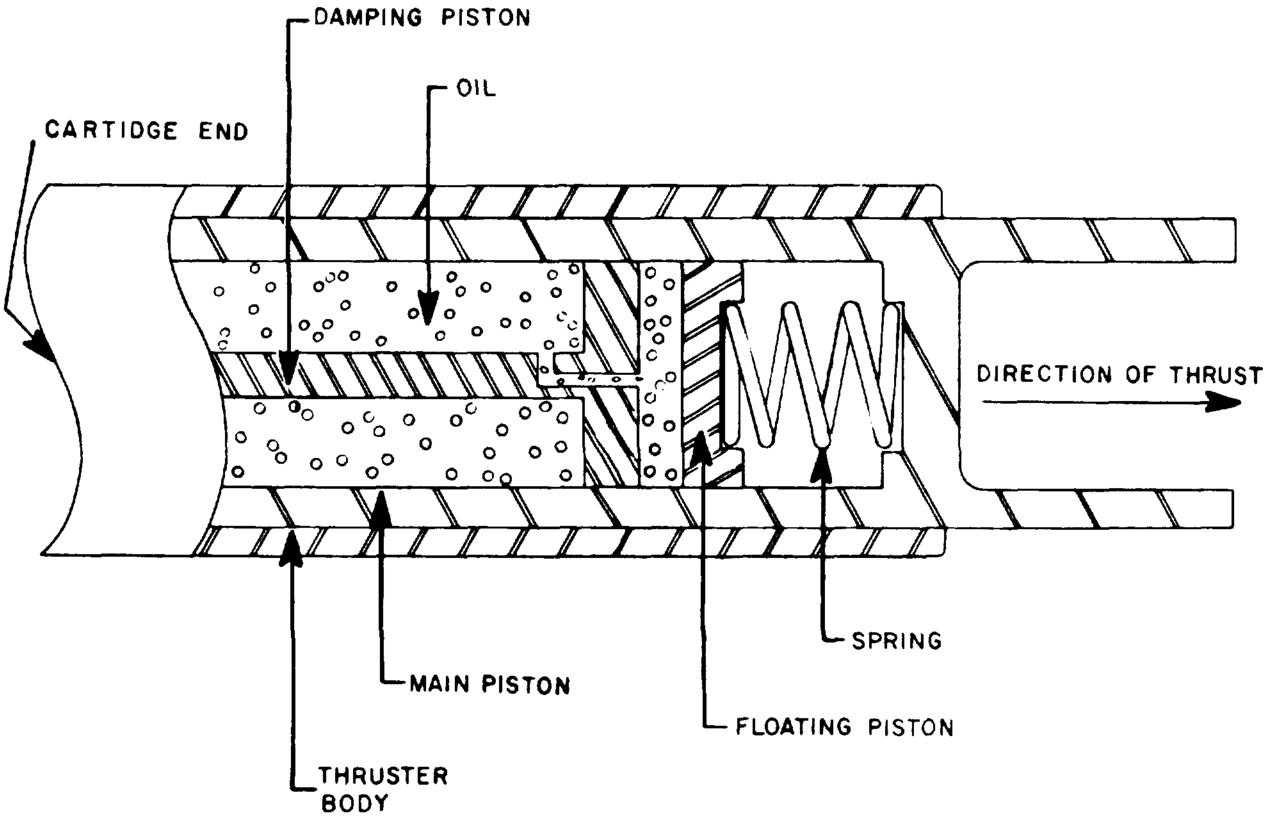

Figure 39. Floating piston and thermal expansion chamber.

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.

f. 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 figure 40 may be calculated as described earlier in paragraph 30, 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 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.

g. 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.

46. High-Low Systems. *a.* In propellant actuated devices using high-low systems, propellant

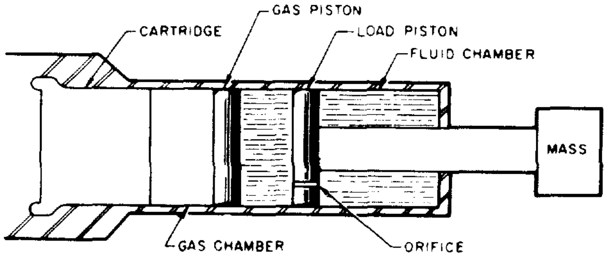

Figure 40. Thruster with fluid damping.

gases are generated in a high-pressure chamber and then are bled off through a nozzle or orifice into a low-pressure chamber, where the pressure energy is converted into work.

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

c. 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 which are produced for repeated applications, and the feasibility of using high-low pressure systems must be weighed carefully.

47. Protective Coatings. *a.* Protective coating 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.

b. 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 readily detached by bending or any other process used in ordinary fabricating.

c. 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.

48. Dissimilar Metals. *a.* 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.

b. 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.

c. 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.

d. 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.

e. Although contacting similar metals are not

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†The envelope dimensions dictate whether a uniaxial assembly with high- and low-pressure chambers on a single axis or a pair of concentric chambers with the high-pressure chamber within the low-pressure chamber is used.

subject to galvanic corrosion, when an aluminum surface passes over another aluminum surface, there is it tendency for the surfaces to gill. Galling also occurs when a cadmium surface rubs against another cadmium surface, as a cadmium plated piston sliding (stroking) through a cadmium-plated bushing. 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.

CHAPTER 5

BALLISTIC DESIGN AND ANALYSIS

Section I. BALLISTIC DESIGN

49. General. *a.* The interior ballistics of propellant actuated devices can be described by the following equations:

(1) *Equation of motion.*

$$m\frac{dv}{dt}=PA-\alpha mg \qquad (14)$$

(2) *Burning rate equation.*

$$\frac{w}{2}=\int_{o}^{t} BP^{n}dt \qquad (15)$$

(3) *Equation of state.*

$$PV=nRT \qquad (16)$$

(4) *Conservation of energy.*

$$\frac{FN}{(\gamma-1)}=\frac{PV}{(\gamma-1)}-\frac{P_oV_o}{(\gamma-1)}+\frac{mv^2}{2}+\alpha mgs+H(t) \qquad (17)$$

Where:

m = propelled mass
v = instantaneous velocity of mass
t = time
P = instantaneous pressure
A = piston (or tube) area
a = launch angle gravitational field factor
g = acceleration of gravity
w = propellant web
B = burning rate constant
n = burning rate exponent (Burning Rate Equation), or number of moles of propellant gas (Equation of State)
V = internal volume of device
F = propellant impetus
N = weight of gas produced
g = ratio of specific heats
s = travel
$H(t)$ = dissipated energy including heat loss and gas leakage
R = universal gas constant
T = instantaneous gas temperature

The use of these basic equations and equations derived from them in the design and analysis of propellant actuated devices is discussed in this section.

b. Because it has been impossible to define the energy losses in propellant actuated devices theoretically, their design and development have been empirical in nature. Since most devices have been developed to meet a specific requirement and no two are exactly alike, each new device must be designed and developed with heavy reliance on past experience. The basic aim of this chapter is to (1) refine the first order approximations of Section II, chapter 4, and show how they were derived, (2) provide some basic ideas which will allow development of the propellant charge design to meet any set. requirements, and (3) provide some "rules of thumb" or experience factors to aid in some areas where problems are commonly encountered.

50. Propellant Parameters. *a.* The propellant parameters necessary for a ballistic analysis of propellant actuated devices are as follows:

γ = ratio of specific heats
T_o = isochoric adiabatic flame temperature
F = propellant impetus
p = solid propellant density
r = burning rate of solid propellant

b. The ratio of specific heats, γ, of propellant gases varies from about 1.23 to 1.26 for most propellants used in propellant actuated devices. The isochoric flame temperatures of common propellants used in propellant actuated devices range from 2,000° K to 3,300° K. The values of propellant impetus, which is a measure of the available propellant energy, are on the order of $3X10^5$ to $4X\ 10^5$ ft-lb/lb. The densities of common double-base propellants range from 0.055 to 0.062 lb/in.^{3}. Propellant parameters can be computed from the propellant's chemical composition. The important parameters are given in table XIII for several typical propellants used in propellant actuated devices.

Table XII. Thermochemical Properties of Some Propellant Used in Propellant Actuated Devices

Type	Flame temp, T_O (^OK)	Impetus, F (10^3 ft-lb/lb)	Ratio of specific beats	Density, p (lb/in.^{3})	Burning rate coefficient, C' † (10^{-4} in./sec/psi)
M2	3319	360	1.224	0.060	4.5
M5	3245	353	1.226	0.060	
M6	2570	317	1.254	0.057	2.3
M10..	3000	339	1.234	0 060	3.3
T8, H8	2306	310	1.262	0.057	1.8

† These are(approximate values which satisfy the equivalence. $C'P\text{-}BP^{n.}$

c. The linear rate of burning of a solid propellant depends oil the rate at which the surface receives heat from the surrounding combustion products. All exposed surfaces should receive heat at the same rate and, therefore, should burn at the same rate. This conclusion is known as Piobert's Law and was first stated for black powder. It has been verified for solid propellants in rocket, gun, and propellant actuated device applications by examination and measurement of partially burned grains.

d. The rate of regression of a burning propellant surface, measured normal to the surface, is known as the linear burning rate, *r*. It is expressed usually in terms of inches per second. Several factors affect the burning rate, including the pressure at which the burning takes place, initial temperature of the propellant, gas velocity over the burning surface, and composition of the propellant.

e. Of the several relationships that have been developed to describe the burning rate vs pressure dependency of propellants, the following relationship applies, in general, to most propellants:

$$r = BP^n \tag{18}$$

Where:

r = linear burning rate
B = burning rate constant
P = maximum pressure
n = pressure exponent of burning rate

This form of the burning rate-pressure relationship will be found in other portions of this bulletin.

51. Refinements to First Order Approximations. *a. Stroke Length.*

(1) *General.*

(a) The problem considered will be to determine the minimum travel for a three-tube catapult when given a required terminal velocity, v, and when limitations are set on the rate of change of acceleration, å, and on the maximum acceleration a_m.

(b) The "ideal" acceleration-time curve for a catapult (shown in fig. 41) is constructed from the human tolerance limits of acceleration, a_m,, and rate of change of acceleration, å, in any specified ejection direction. The physiological limitations are presented in Table 1, and in military specifications. The initial slope of the acceleration-time curve is å and the level portion is a_m. If a three-tube catapult is assumed, the corresponding pressure-time curve would be as shown in figure 42. The point marked t_2, where an instantaneous rise in pressure is shown, corresponds to the initial movement of the inner tube of the catapult when the telescoping tube stops. If the acceleration is to remain constant, the applied force must also remain constant. Since the inner tube presents a smaller area to the gas pressure than the telescoping tube (see fig. 2), the pressure must increase correspondingly to provide a constant force.

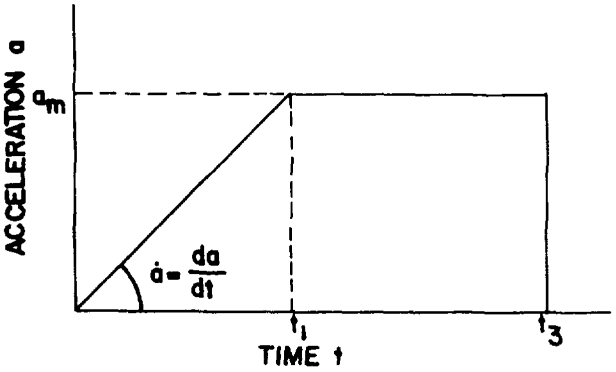

Figure 41. "Ideal" acceleration vs time curve.

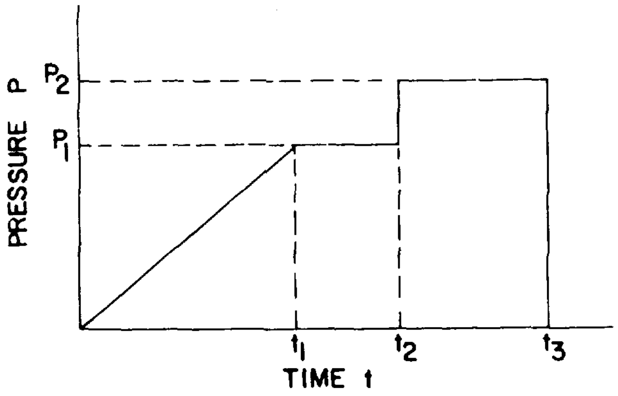

Figure 42. "Ideal" Pressure vs time curve.

(c) As it would be difficult, if not impossible, to attain it constant acceleration system, catapult designs usually are based on a pressure time curve (fig. 43) from which all acceleration-time curve (fig. 44) can be derived. The solid lines ill both figures show the desired operating conditions.

(*d*) Inasmuch as acceleration is proportional to the pressure acting on the catapult piston and the velocity and travel are, at least ideally, tile first and second integrals of this acceleration, it is possible to discuss the performance of a catapult in terms of its pressure characteristics. Curve 0-1-2 of figure 45 illustrates the ideal pressure characteristics determined from limits of acceleration and rate of change of acceleration currently used for human ejection in an upward direction. Conventional catapults are designed to approach this ideal characteristic through the selection of interior ballistic parameters and propellants. Catapults usually are designed so that the maximum design limitations are met only at the high-temperature operating condition (curve A of fig. 45) performance is appreciably lower when operating at 70° F. and -65° F. (curves

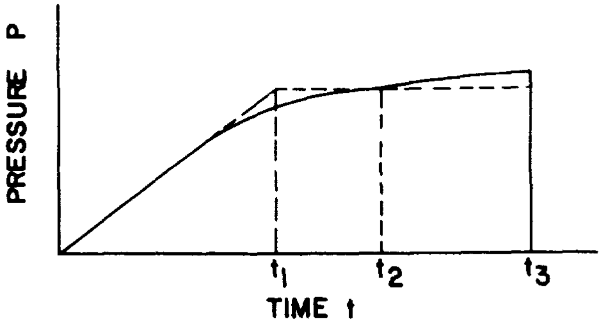

Figure 43. Desired pressure vs time curve.

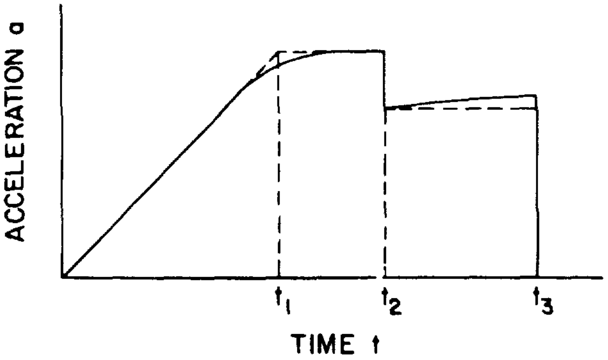

Figure 44. Acceleration vs time curve corresponding to desired pressure vs time curve.

B and C). Since the final velocity imparted by the catapult is proportional to the area enclosed by the pressure-time curve, it is evident (from fig. 45) that the catapult must be designed so that acceptable performance results at both extremes of allowable temperature.

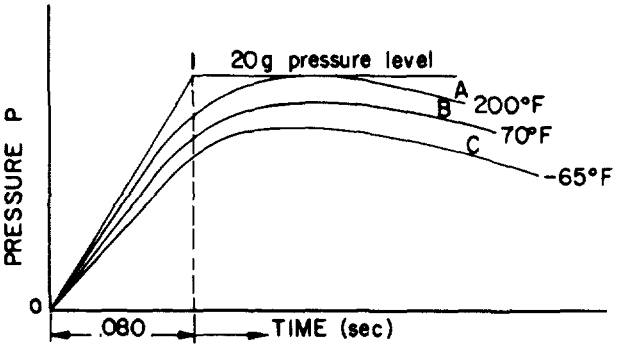

Figure 45. "Ideal" pressure characteristic curve compared with typical empirical curves.

(2) *Use of "Ideal" acceleration vs. time curves to estimate stroke length.*

(a) Based upon the discussion of the preceding paragraph, the following derivation illustrates a method for determining the approximate acceleration, velocity, and travel vs. time curves for a three-tube catapult system.

(b) Several assumptions are made in the derivation:

1. The strokes of the telescoping and inner tubes of the catapult are equal and the inner tube moves only upon completion of the stroke of the telescoping tube.

2. The ratio of the inner tube to the area of the telescoping tube (hereinafter called the tube area ratio) is equal to 0.82. This figure is representative of the catapults developed for pilot ejection.

3. A constant pressure system is assumed after reaching maximum acceleration (a_m) as shown by the dashed lines of figure 43 and as described in the preceding paragraphs. The basis for this derivation is the acceleration-time curve for a three-tube catapult shown by the dotted line approximation of figure 44. The subscripts 1, 2, and 3 refer to increments of acceleration, velocity, or travel over the times t_{0-1}, t_{1-2}, and t_{2-3}, respectively.

$$a_m = \dot{a} t_{0-1}$$

or

$$t_{0-1} = a_m / \dot{a} \qquad (19)$$

$$v_1=\frac{\mathring{a}(t_{0-1})^2}{2}=\frac{\mathring{a}}{2}\left(\frac{a_m}{\mathring{a}}\right)^2=\frac{{a_m}^2}{2\mathring{a}} \tag{20}$$

$$s_1=\frac{\mathring{a}(t_{0-1})^3}{6}=\frac{\mathring{a}}{6}\left(\frac{a_m}{\mathring{a}}\right)^3=\frac{{a_m}^3}{6\mathring{a}^2} \tag{21}$$

The equation for terminal velocity, v_m, is:

$$v_m=v_1+v_2+v_3$$

Referring to the acceleration-time curve,

$$v_2=a_m t_{1-2}$$

and

$$v_3=0.82a_m t_{2-3}$$

therefore,

$$v_m=\frac{{a_m}^2}{2\mathring{a}}+a_m t_{1-2}+0.82a_m t_{2-3} \tag{22}$$

For any constant acceleration system, the distance traveled, *s*, in time, *t*, is related to the initial velocity, v_0, and the acceleration, *a*, by:

$$s=v_0t+1/2at^2$$

therefore,

$$s_2=v_1t_{1-2}+\frac{a_m}{2}(t_{1-2})^2$$

$$s_2=\frac{{a_m}^2}{2\mathring{a}}t_{1-2}+\frac{a_m}{2}(t_{1-2})^2$$

Similarly,

$$s_3=(v_1+v_2)t_{2-3}+(0.82)\frac{a_m}{2}(t_{2-3})^2$$

$$s_3=\frac{{a_m}^2}{2\mathring{a}}t_{2-3}+a_m t_{1-2}t_{2-3}+0.41a_m(t_{2-3})^2$$

As the telescoping length is equal to s_1 + s_2 and the inner tube is equal to S_3, and they are assumed to be of equal length

$$s_1+s_2=s_3$$

$$\frac{{a_m}^3}{6\mathring{a}^2}+\frac{{a_m}^2}{2\mathring{a}}t_{1-2}+\frac{a_m}{2}(t_{1-2})^2=\frac{{a_m}^2}{2\mathring{a}}t_{2-3}+a_m t_{1-2}t_{2-3}+0.41a_m(t_{2-3})^2 \tag{23}$$

Simultaneous solution of equations (22) and (23), with simplification, results in:

$$\frac{{a_m}^3}{18\mathring{a}^2}+\frac{{v_m}^2}{2\mathring{a}}-1.82v_m t_{2-3}+0.82a_m(t_{2-3})^2=0 \tag{24}$$

which can be solved for t_{2-3} given the requirements of maximum acceleration, a_m, maximum rate of change of acceleration, å, and terminal velocity, v_m. The time, t_{1-2}, can be found from the revision of equation (22).

$$t_{1-2}=\frac{v_m}{a_m}-\frac{a_m}{2\mathring{a}}-0.82t_{2-3} \tag{25}$$

Finally, the stroke length equation is:

$$S=s_1+s_2+s_3$$

$$S=\frac{a_m^3}{6\mathring{a}^2}+\frac{a_m^2}{2\mathring{a}}t_{1-2}+\frac{a_m}{2}(t_{1-2})^2+\frac{a_m^2}{2\mathring{a}}t_{2-3}+a_m t_{1-2}t_{2-3}+0.41a_m(t_{2-3})^2 \tag{26}$$

As an example, assume the desired performance of a catapult is:

terminal velocity (v_m)=80 ft/sec
maximum acceleration (a_m)=18 g
maximum rate of change of acceleration (å)=150 g/sec

From equations (19), (20), and (21)

$$t_{0-1}=\frac{18\,g}{150\,g/\text{sec}}=0.120\text{ sec}$$

$$v_1=\frac{(18\,g)^2}{2(150\,g/\text{sec})}=\frac{18^2(32.2)^2}{300(32.2)}$$

$$=34.8\text{ ft/sec}$$

$$s_1=\frac{(18\,g)^3}{6(150\,g/\text{sec})^2}=\frac{18^3(32.2)^3}{6(150)^2(32.2)^2}$$

$$=1.39\text{ ft}$$

Solving equation (24) for t_{2-3} gives
$t_{2-3}=0.0489$ sec
Then from equation (25)
$t_{1-2}=0.0379$ sec

The approximate stroke length then is determined from equation (26)

S=6.47 ft or 77.6 in.

(c) These quantities (t_{0-1}, t_{1-2}, and t_{2-3}) are used to define the acceleration-time curve of figure 46. If the velocity-time and travel-time curves are desired, they can be determined by first and second integrals of the acceleration-time curve.

(d) These curves, then, define the approximate stroke length and stroke time for a three tube catapult operating with a constant internal pressure after t_1 and designed in accordance with assumptions in *(b) 1* and *2* above. This method may be modified if the tube lengths are known or are related in some manner, or if the tube areas are known or related in some manner, by minor changes in equations (22) through (26).

(e) Since it is not possible to match the acceleration-time curve of figure 46 exactly, the value of the stroke length should be increased by approximately 10 percent. To reach the desired separation velocity of 80 fps, the stroke should be approximately 86 inches.

(f) The equation for approximate stroke length as used in chapter 4,

$$S=0.6\,\frac{v^2}{a_m} \tag{1}$$

was based on equal tube areas for the inner and telescoping tubes (essentially a two-tube catapult). The reduction and simplification of equation (26) using a tube area ratio of 1 result in the following equation:

$$S=\frac{v^2}{2a_m}+\frac{{}^{a}m^3}{24\mathring{a}^2} \tag{27}$$

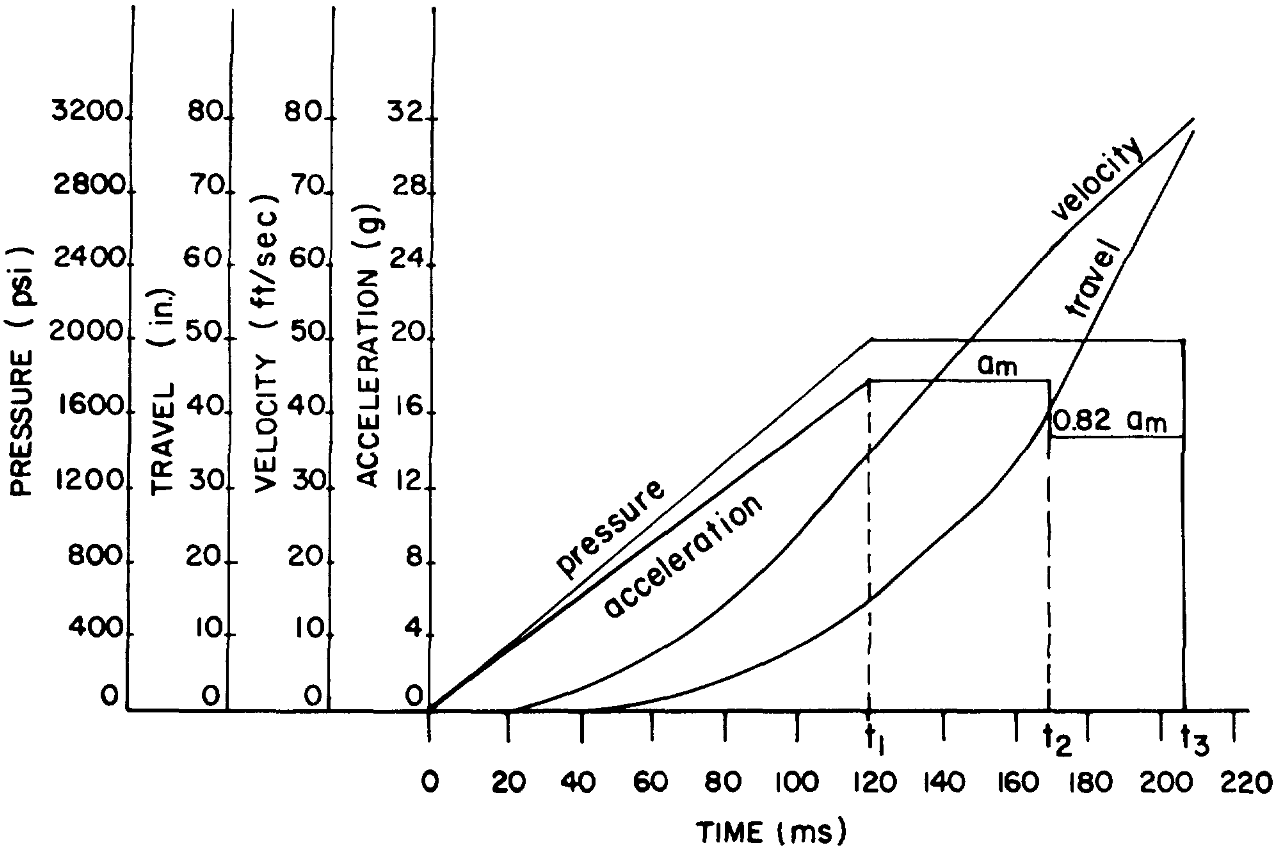

Figure 46. "Ideal" pressure, acceleration, velocity, and travel vs time curves for a three-tube catapult.

The second term may be eliminated, since the value of $24\mathring{a}^2$ is so large that it makes the term a_m^3 insignificant. Firing tests have indicated that for a closer approximation of stroke length, equation (27), with the elimination of the second term, should be modified by increasing the values by 20 percent. The equation then becomes

$$S=0.6\,\frac{v^2}{a_m} \tag{1}$$

which is plotted in chapter 4 (fig. 20) showing stroke length as a function of terminal velocity for several values of maximum acceleration.

(g) It should be noted that these parameters (acceleration, velocity, and travel) are independent of the mass to be accelerated. The mass fixes only the required pressure and tube areas as will be shown in b below.

b. Pressure and Tube Area Relationships.

(1) The pressure and tube area relationship is based upon the equation of motion

$$m\,\frac{dv}{dt}=PA-\alpha mg$$

or (14)

$$ma=PA-\alpha mg$$

Substituting a_m for a and eliminating αmg (since $\alpha amg \ll PA$), the equation relating piston area to peak pressure becomes:

$$PA=ma_m \tag{3}$$

(2) the required pressure-time curve, which will provide the desired acceleration-time relationship, can be determined by continuing the example of the preceding paragraphs. Assume the catapult must accelerate a 360-lb load vertically upward. From a mechanical design standpoint and based on space envelope limitations, optimum tube areas are established at 3.10 in.^{2} and 2.56 in.^{2} for the telescoping and inner tubes, respectively. The maximum pressure needed corresponding to am and a telescoping tube area of 3.10 in.^{2} is:

$$P=\frac{ma_m}{A}=\frac{360/g\times 18g}{3.10}=2090 \text{ psi}$$

Where P = maximum pressure, psi

a_m = maximum acceleration, ft/sec^2

m = propelled mass, lb-sec^2/ft

A = tube area, in.^{2}

The pressure-time curve can then be constructed as shown in figure 46.

c. *Use of Estimated Acceleration vs Time Curve to Determine Approximate Propellant Web.*

(1) The propellant web may be estimated if either the burning rate vs. pressure curve for the propellant or the constants B and n in the burning rate law ($r=BP^n$) are known.

(2) The burning rate curve of the propellant may be used by selecting small intervals of time Δt, on the pressure-time curve of a propellant actuated device, and taking an average pressure over Δt. Then find a burning rate to match this average pressure and find the product of $r\Delta t$. The propellant web, *w*, can then be defined as:

$$w=2\sum r\Delta t \tag{28}$$

The propellant web may also be defined as:

$$w=2\int_0^t r\,dt=2\int_0^t BP^n dt \tag{29}$$

Returning to the example and the acceleration-time curve of figure 46, equation (29) may be integrated to:

$$w=2B\left(\frac{m}{A}\right)^n\left\{\frac{\dot{a}^n(t_1-t_0)^{n+1}}{n+1}+a_m{}^n(t_2-t_1)+(0.82\,a_m)^n(t_3-t_2)\right\} \tag{30}$$

9

where A = average area of telescoping and inner tubes.

(See appendix IV for the derivation of this equation.) Application of this equation to the example, assuming a propellant (M2) with constants, B= 1.525 X 10^{-3} in./ sec/psi and n=0.855, results in a web of 0.33 inch.

(3) This calculated web is slightly larger than should be used for initial testing purposes. This can be ascribed to the following:

(a) The actual pressure-time curve of a catapult deviates from the theoretically optimum pressure-time curve as shown in figure 46.

(b) In most actual catapults, the propellant web burns out some time before tube separation.

(c) The theoretical web was based upon the burning rate curve of the propellant (M2) at +160° F. Operation of the catapult at -65° F. will result in a longer burning time because of the lower burning rate and reduced pressures. The web may then have to be reduced to allow generation of all of the propellant gas during the ballistic cycle. For these reasons, testing should begin with propellants having a web of approximately 85 to 90 percent of that calculated by the above methods.

d. Estimation of Propellant Charge Weight.

(1) *Catapults and removers.*

(a) The propellant charge weight in pounds, C, required for a catapult or remover may be estimated using equation (31).

$$C=\frac{m'v^2(\gamma-1)}{2F\epsilon} \qquad (31)$$

Where:

m' is calculated from

$$m'=1.03m\left(1+\frac{2Sg}{v^2}\sin\alpha\right) \qquad (32)$$

and where

F = propellant impetus
e = overall efficiency (use 0.10 as a representative figure for catapults and removers)
y = ratio of specific heats
g = acceleration due to gravity
m = propelled mass
m' = modified propelled mass
a = angle between direction of thrust and-horizontal
V = velocity at separation
S = stroke to separation

(b) In the equation for modified propelled mass, the factor 1.03 is used to account for the affects of friction and the quantity $\frac{2Sg}{v^2}$ sin a corrects for the angle of thrust with the horizontal. For downward ejection, the plus sign in equation (32) would be replaced by a minus sign.

(c) Figure 21 for determining charge weight is based upon the following equation:

$$C=kWv^2 \qquad (4)$$

This equation is a modification of equation (31). The constant, *k,* was determined by letting $\gamma=1.25$, *e* = 0.10, F = $3.1\text{X}10^5$ for catapults and $3.6\text{X}10^5$ ft lb/lb for removers, and m' = 1.1m. In addition, k includes a term to permit propelled weight to be substituted for mass and another term to give the answer (charge weight) in grams. The constant was found to be: k =$6.25\text{ x}10^{-5}$ gm sec^2/lb ft^2 for catapults, and $5.38\text{X}10^{-1}$ gm sec^2/lb ft^2 for removers.

(2) *Thrusters.*

(a) The charge weight for a thruster may be estimated using equation (33).

$$\frac{CF\epsilon}{(\gamma-1)}=\int_0^s F_r\,ds \qquad (33)$$

Where:

F = total resistive force
S = piston stroke
e = overall efficiency (0.10 is a representative value)
g = ratio of specific heats

(b) Figure 22 is based on the following equation:

$$c=k\overline{F}_rS \qquad (5)$$

Where:

$$\bar{F}_r = \frac{1}{S_0}\int_0^s F_r ds$$

The constant, *k,* was determined by letting $\gamma = 1.25$, $e = 0.10$, and $F = 3.14 \times 10^5$ ft lb/lb for M6, H8, and T8 propellants and 3.56×10^5 ft lb/lb for M6 and M2 propellants. *k* also includes a term to convert the answer to grams. The constants were found to be $k = 2.66 \times 10^{-4}$ gm sec^2/ft^2 lb and 3.01×10^{-4} gm sec^2/ft^2 lb for M6 and M2 propellants respectively.

(c) As an example of how this equation may be refined, assume that a thruster must move a hatch under an aerodynamic load, F_a, which is a linear function of stroke, as shown in figure 47. The hatch weighs 100 lbs and has a mass moment of inertia, I_y, about its hinge of 90 in.-lb-sec^2. In addition, the maximum allowable angular acceleration, α, is set at 5 rad/sec^2.

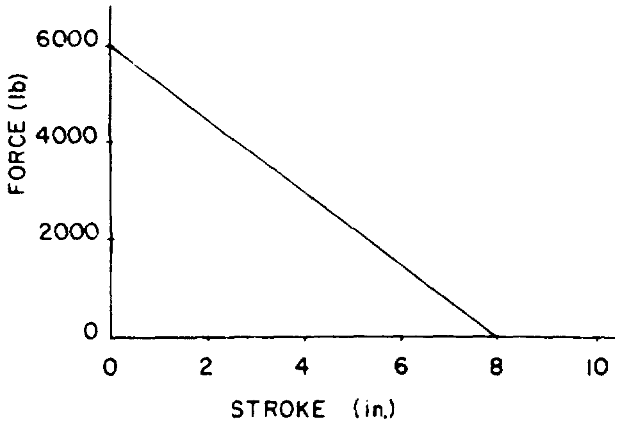

Figure 47. Load vs stroke relationship for a thruster.

(d) If a thruster is mounted at an angle of 15° from the vertical, the equation of motion may be set up as

$$m\frac{dv}{dt} = F_r \cos 15° - W - F_a$$

Where:

m = mass of hatch, lb-sec^2/ft
W = weight of hatch, lb
F_r = force exerted by thruster, lb

but

$$m\frac{dv}{dt} = \frac{I_y \alpha}{k}$$

Where:

k = radius of gyration

Therefore,

$$F_r \cos 15° = W + F_a + \frac{I_y \alpha}{k}$$

Integration over the stroke, S, gives

$$\cos 15° \int_0^s F_r ds = W\int_0^s ds + \frac{I_y \alpha}{r}\int_0^s ds + \int_0^s F_a ds$$

which, with simplification, gives the total energy output of the thruster *(F_TS)*.

$$\overline{F}_r S = Ws/\cos 15° + I_y\alpha\ \theta/\cos 15° + \int_0^s F_a ds/\cos 15°$$

Where:

θ = angle in radians through which the hatch moves.

The angle through which the hatch moves is 15° or 0.26 radian. Substituting the applicable figure gives

F_TS = 100(8)(1/cos 15°)+90(5)(.26)(1/cos 15°)+(1/2)(6,000)(8)(1/cos 15°)

F_TS = 830+120+24,800=25,750 in.-lb

(e) Devices of this type usually operate at about 10 percent ballistic efficiency; therefore, the required propellant weight may be estimated as follows:

Assume

$$F = 3.6 \times 10^5 \text{ ft-lb/lb}$$
$$\gamma = 1.25$$

then

$$\frac{12CF\epsilon}{\gamma - 1} = \overline{F}_r S$$

$$C = \frac{\overline{F}_r S(\gamma - 1)}{12F\epsilon} = \frac{25{,}750(1.25 - 1)}{(12)(3.6 \times 10^5)(0.10)}$$

$$= .0149 \text{ lb or } 6.75 \text{ gm}$$

(f) The thruster must overcome a high initial force which decreases as the stroke progresses; hence, plateau propellant composition with regressive geometry (i.e., cord grains (uninhibited rod)) probably are best for this application.

(g) If the angle (θ) through which the hatch moves is known, an approximate stroke time and propellant burning time can be estimated.

$$\theta = \frac{a}{2} t_m^2$$

$$t_m = \sqrt{\frac{2\theta}{a}} = \sqrt{\frac{2(0.26)}{5}} = 0.32 \text{ sec}$$

This stroke time is conservative because it is based on an average acceleration of 5 rad/sec which is actually the peak acceleration. The average would be somewhat lower.

52. Development of Propellant Charge Design. *a. Grain Design.*

(1) The basic problem in the selection of a propellant grain design for most stroking propellant actuated devices is the requirement that gases must be supplied at an increasing rate during the functioning time of the device. As noted earlier in this chapter, for most catapult applications a constant or even slightly increasing pressure is desired after maximum acceleration has been reached. Due to (1) the increase in internal volume as the stroke lengths, (2) the high heat transfer rate which causes a large loss of energy, (3) gas leakage, and (4) energy transferred to the accelerated mass, an increasing rate of gas evolution must be provided. Limiting this rate of gas production, however, is the maximum rate of change of acceleration and the maximum acceleration allowable which

are direct functions of the rate of change of pressure and maximum pressure within the system. The problem then is to obtain the desired pressure-time curve in the devices by proper selection of propellant and propeller grain design.

(2) Ballistically there are several limiting factors in the selection of an "optimum" propellant charge design. The mechanical design and ignition characteristics of catapults and removers limit the degree-to which grain geometry and propellant formulations can be varied to obtain the desired pressure-time curves. When the igniter burns, the propellant cartridge ruptures and grains travel down the inner tube and strike the head cap where some are randomly fractured. Also, ignition of the grains is not instantaneous nor as uniform as desired. In addition, the selection is limited by the charge geometries that are available in the desired size. Because of the small required webs and the very low charge weight, and therefore small overall grain dimensions, only certain configurations are commonly extruded and available for development and production purposes.

(3) Two basic grain designs have been used for the most part in propellant actuated devices.

These are uninhibited, single-perforated grains and uninhibited, seven-perforated grains.† Propellants with high burning rate exponents can be supplied as single perforated grains. As the surface-time history of an uninhibited, single-perforated grain is approximately constant, the increasing rate of gas production is caused by an increase in the burning rate of the propellant as the pressure in the propellant actuated device builds up. Plateau propellants with low burning rate exponents can be supplied as uninhibited, seven-perforated grains. The pressure rise in the propellant actuated device does not cause as large an increase in the burning rate of seven-perforated propellant as does the increasing surface area of the grain (made available as the web decreases). This increasing surface area provides the increase in the rate of gas evolution.

(4) Other grain designs may be usable in propellant actuated devices, but may not be feasible from production and cost standpoints. These designs could include externally inhibited single or multiperforated grains or a grain in the shape of a right triangular prism externally inhibited except for a small surface along the three edges of the sides. It is also possible to combine several propellants and grain designs within one charge.

(5) The development of the desired surface-time history for a given application is discussed later in this chapter.

b. Use of Experimental Pressure vs Time Curve to Refine Propellant Charge Design. Four aspects of the pressure-time curve are of prime importance in any experimental pressure-time curves obtained from any propellant actuated device. They are ignition delay, rate of pressure rise, peak pressure, and the integral of the pressure-time *(P-t)* curve. These four aspects are not independent of each other, and any modification of one to improve its ballistic characteristics may result in modification of one or all of the remaining aspects.

(1) *Ignition delay.*

(a) The aim in design of most devices is to make the ignition delay as short as possible. (This may not be true in some devices when a delay of a few seconds is necessary for proper sequencing of operations, but in this case, a delay train is incorporated into the device.) The ignition delay time is a function of the conditioning temperature, i.e., as the conditioning temperature is lowered, the ignition delay increases. For this reason, any modifications to the ignition system to minimize ignition delay usually are tested fit the low temperature operating conditions.

(b) The following are factors which may affect ignition delay time:

Primer: total energy or rate of energy release.
Igniter: weight, composition, and granulation.
Propellant: weight, composition, and grain geometry.
Cartridge case: rupture strength and geometry of the case; arrangement of primer, igniter, and propellant in the case; size of the orifice between the primer and igniter.

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† A single-perforated grain is a cylindrical grain with a single perforation along its axis. A seven-perforated grain has one perforation on the axis and six additional perforations equally spaced on the common radius around the center hole.

Chamber of device: possible source of large energy losses and leakage. If a long ignition delay is observed in initial testing, it may be minimized by using one or a combination of the following remedies:

Use a "stronger" primer, i.e., one which will supply more energy in the form of hot gases or one which will supply the hot gases at a faster rate.

Increase the energy released by the igniter by using a heavier charge or by changing to a material with a higher impetus.

Use a coarser igniter granulation. (A coarse granulation provides more passageways for gas flow and decreases the time required to ignite the ignition material.) Arrange the propellant so as not to restrict the hot gas flow from the igniter.

Increase the strength of the cartridge case so that a higher pressure may be built up before the case ruptures.

(c) The development of the correct combination of primer, igniter, and propellant charge to minimize ignition delay while meeting the other ballistic characteristics requires careful consideration of the factors which affect the delay and application of the proper remedies. The use of standard cartridges and primers listed in chapter 4 will minimize ignition problems and these should be used whenever possible.

(2) *Rate of pressure rise.*

(a) The rate of pressure rise is important in catapult applications because it determines the rate of change of acceleration, which must be held within certain specified limits. The rate of pressure rise will probably be highest at the high-temperature operating limit.

As the rate of change of acceleration has little effect on the terminal velocity, the objective is to stay under the upper limit and not to necessarily match this limit.

(b) The following are factors which will affect the rate of pressure rise:

Ignition system: primer and igniter combination.
Propellant: composition, grain geometry.
Chamber: initial free volume of device.
Mass to be accelerated.

(c) The following are techniques which may be used to lower an excessive rate of change of acceleration:

Reduce the initial surface of the propellant by changing the grain geometry or by inhibiting some of the surface of the grains.

Change to a plateau-type propellant or to a propellant composition which has a lower burning rate exponent (n) over the pressure range obtained in the device.

Use a combination of different propellants or different webs.

Increase the initial free volume of the device.

Lower the peak pressure by increasing the piston area of the device.

For a given charge, a decrease in the mass to be accelerated will result in a lower rate of change of acceleration.

(d) Usually as a last resort, some type of mechanical damper may be incorporated into the device to control the rate of change of acceleration. The use of damped thrusters is quite common in some applications requiring comparatively slow positioning of objects.

The mechanical design of these damped devices is discussed in paragraph 45.

(e) Operation at the low temperature extreme may also cause an excessive rate of pressure rise if the grains are not restrained; they may be fractured upon striking the head cap of the devices, thereby exposing excess surface area. A grain trap may be used to restrain the propellant, but care must be taken in its design to prevent unwanted nozzling of the gasses. On the other hand, nozzling may be used (a high-low device) to obtain the desired ballistic characteristics.

(3) *Peak pressure.* The peak pressure is important because it determines the maximum acceleration (which in catapult applications is fixed by human tolerance limits) and the strength and, therefore, the weight of the device. The object in this area is to match the

acceleration limit and, therefore, the peak pressure at the high temperature extreme. Operation at a lower temperature will result in a lower peak pressure. The peak pressure in a propellant actuated device may be varied by changing the propellant web, the propellant composition, or the web and composition simultaneously. A reduction in web or use of a higher burning rate propellant will increase the peak pressure; conversely, an increase in web thickness or use of a lower burning rate propellant will decrease the peak pressure. Use of a plateau propellant may also lower the peak pressure if a propellant is chosen which has a plateau at the desired operating pressure. If a change in metal parts is permitted, the internal volume and piston area may be increased to lower the peak pressure. A change in peak pressure may affect the rate of change of acceleration. Generally, a higher peak pressure will cause a higher rate of change of acceleration, while a reduction in the peak pressure will cause a lower rate of change of acceleration.

(4) *Integral of the pressure vs time curve.*

(a) The integral of the pressure-time curve is proportional to the terminal velocity. If the terminal velocity is too low, the propellant charge weight must be increased. It is desirable for the *P-t* curve to be flat (a slight increase in pressure toward the end of the cycle is desirable in catapult applications if telescoping tubes are used with a reduction in tube area) so that for a given stroke length the terminal velocity will be higher. A drop (negative slope) in the pressure-time *(P-t)* curve may be lessened or eliminated by use of a more progressive grain design in which the surface-time relationship increases faster as the grains burn. Several grain designs mentioned in the preceding paragraph will provide a progressive surface-time history.

(b) The propellant web should also be sized so that burnout occurs at or slightly after tube separation.

(c) With a given pressure-time curve and the equations describing the burning process, the time at which propellant burning has ceased can be calculated. The time at which the web has burned out can be found by replotting the pressure-time curve as BP^n, vs time. Integrations of the curve of BP^n vs time over the interval $t = 0$ to $t = t_b$ should be made to satisfy the equation

$$\int_0^{t_b} BP^n dt = \frac{w}{2} \qquad (29)$$

The upper limit of the integral, to, represents the time of all burnt.

(d) In an experiment in which propellant combustion is completed during the burning cycle, the end of burning can be determined by preparing a graph such as shown in figure 48. After gas production has ceased, the pressure and volume are related functionally by the polytropic law (Pv^a = constant). On logarithmic scales, this function is a straight line. The point of tangency of the straight line with the curve corresponds to burnout of the propellant.

Section II. MATHEMATICAL ANALYSIS OF INTERIOR BALLISTICS

53. Catapults and Removers. *a.* A mathematical description of ballistic performance consists of a group of simultaneous equations with time as the independent variable. These equations, which describe the conservation of energy, the motion of the propelled mass, and the production of propellant gas, form the basis of any theory of interior ballistics.

b. The following assumptions usually are made in an analysis of the interior ballistics of propellant actuated devices:

(1) Ignition is isochronic; that is, stable combustion is established over the entire propellant surface at the beginning of the ballistic cycle.

(2) The rate of production of propellant gas is determined by the geometry of the grain and the burning rate. It is assumed that all dimensions of the propellant grain recede in a direction normal to all uninhibited surfaces at the same rate.

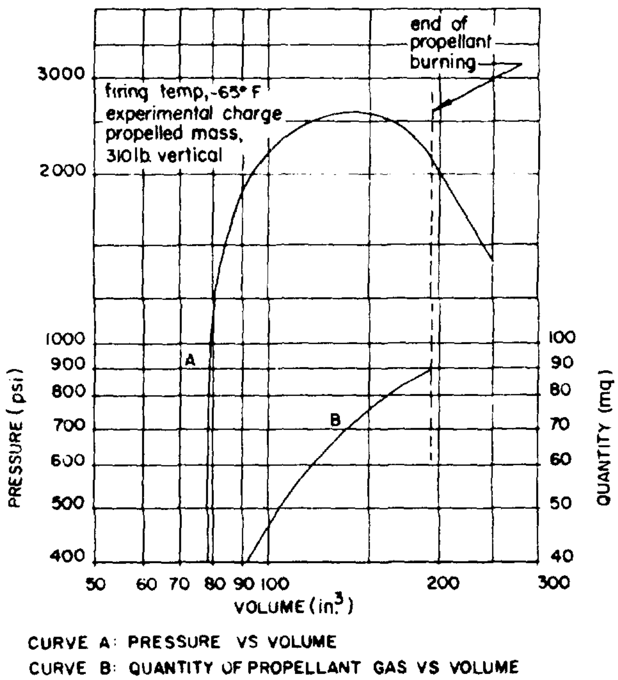

Figure 48. Pressure and quantity of propellant gas vs volume on logarithmic scales.

(3) The rate of recession, r, of each dimension of the propellant grain is dependent on the pressure, *P*, according to the law: $r=BP^n$, where *B* and *n* are constants for a particular propellant composition and initial temperature.

(4) Propellant gases are perfect gases with constant specific heats and molecular weights.

(5) The total energy made available by the combustion of the propellant is equal to the product of the mass of propellant consumed and the specific energy of isochoric explosion (a constant dependent upon propellant composition).

(6) Gas leakage is negligible.

(7) Work done against friction is negligible. (This assumption is applicable, in general, only to catapult systems.) (8) The cartridge case ruptures when propellant combustion begins.

(9) Pressure, temperature, and composition of gases are assumed to be uniform throughout the chamber.

c. Although it is possible that none of these assumptions are completely valid in an actual ballistic system, they simplify the problem of computation so greatly that they are used widely in interior ballistic calculations.

d. The assumptions discussed in b above, are embodied in the following equations which describe the interior ballistic performance of catapults and removers, and, with slight modifications; thrusters. The modifications of these equations to adapt them for an analysis of the interior ballistics of thrusters are discussed in paragraph 54.

(1) *Conservation of energy.*

$$\frac{FN}{(\gamma-1)}=\frac{PV}{(\gamma-1)}-\frac{P_0V_0}{(\gamma-1)}+\frac{mv^2}{2}+\alpha mgS+H(t) \qquad (17)$$

Where:

F = impetus of propellant
N = gas produced
y = ratio of specific heats

P_0 = pressure at time zero produced by combustion of igniter and small fraction of propellant
V_0 = initial free volume
m = propelled mass
v = velocity of propelled mass
a = gravitational field factor (equal to the sine of the angle between thrust vector and horizontal)
g = acceleration of gravity
S = length of stroke
$H(t)$ = energy term including heat loss required to balance equation.

The term $\frac{P_o V_o}{(\gamma-1)}$ approximates the gaseous energy produced by the igniter up to time zero. The time function *H(t)* is added to make the equation balance. This quantity usually is identified with the energy lost to the walls of the device and leakage during the ballistic cycle. However, in addition to the dissipated energy, this term also includes errors inherent in the other terms of the equation.

(2) *Equations of motion.*

$$m\frac{dv}{dt}=PA-\alpha mg$$

$$v=\int_0^t\left(\frac{PA}{m}-\alpha g\right)dt \tag{14}$$

Where:

P=pressure
A=piston area

$$S=\int_0^t vdt \tag{34}$$

(3) ***Equations of gas production.***

$$\frac{w}{2}\frac{df}{dt}=BP^n \tag{35}$$

$$f=1-\int_0^t\frac{2B}{w}(P^n)dt \tag{36}$$

$$N=C(K_0+K_1f+K_2f^2) \tag{37}$$

defined for $1\geq f\geq 0$

$$N=C(K_{0'}+K_{1'}f+K_{2'}f^2) \tag{38}$$

defined for $0\geq f\geq -0.5$ (splinter burning).

Where:

w=propellant web
f=fraction of web remaining unburned
B=burning rate coefficient
n=burning rate exponent
C=propellant charge weight
N=quantity of propellant gas
K_0, K_1, K_2, $K_{0'}$, $K_{1'}$, and $K_{2'}$=constants for geometrical form function†

---

† The form function is a property of the charge which describes the amount of gas produced with the burning of a given fraction of the propellant web.

e. Equation (37) governs the production of propellant gas in a multiperforated propellant before the web has burned through; equation (38) governs the production of the gas after the web has burned through. With propellant grains in which there is no perforation or only one perforation, equation (38) is not needed because a zero web fraction corresponds to the complete consumption of the propellant. These equations are close approximations of the true geometrical form functions, and the coefficients are defined in terms of propellant dimensions.

f. The coefficients for the geometric form functions of single-perforated grains are:

$$K_e = 1 \qquad K_{0'} = K_e$$

$$K_1 = 1 - \frac{w}{L} \qquad K_{1'} = \frac{3K_e - 4}{3}$$

$$K_2 = -\frac{w}{L} \qquad K_{2'} = \frac{4 - 6K_e}{3}$$

Where:

w = propellant web
D = diameter of grain
d = diameter of perforation
L = propellant grain length

g. Coefficients for form functions of seven-perforated grains are presented in table XIV.

Table XIV. Coefficients for Form Function (Sewn-Perforated Propellant)

D/d	Coef	L/d				
		1.5	2.0	2.5	3.0	3.5
	K_e.................	0.8490	0.8362	0.8335	0.8316	0.8303
8	K_1.................	0.9111	0.9300	0.9414	0.9490	0.9544
	K_2.................	0.0702	0.0938	0.1079	0.1174	0.1241
	K_e.................	0.8563	0.8516	0.8487	0.8468	0.8455
10	K_1.................	0.9447	0.9673	0.9808	0.9898	0.9963
	K_2.................	0.0884	0.1157	0.1321	0.1430	0.1508
	K_e.................	0.8652	0.8603	0.8574	0.8554	0.8541
12	K_1.................	0.9673	0.9923	1.0073	1.0173	1.0245
	K_2.................	0.1021	0.1320	0.1499	0.1619	0.1785

(1) *Equations of definition of volume.*

$$V_1 = V_0 + A_1 s \tag{39}$$

before telescoping tube stop

$$V_2 = V_0 + (A_1 - A_2)\, S_1 + A_2 S \tag{40}$$

after telescoping tube stop

Where:

V_1 = volume during telescoping tube stroke
V_0 = initial free volume
A_1 = piston area during telescoping tube stroke
V_2 = volume during inner tube stroke
A_2 = piston area during inner tube stroke
S_1 = telescoping tube stroke
s = length of stroke at time t

(2) *Equation of state.*

$$PV = (Nn + k)RT \qquad (41)$$

Where:

n = the number of moles of propellant gas per unit of propellant burned
N = weight of propellant burned
k = total number of moles of gas produced by igniter charge
R = universal gas constant
T = space mean temperature

h. An analytical simultaneous solution of these equations is not possible because of the interrelationship of the many dependent variables, and the fractional pressure exponent in the burning law, although they can be evaluated by an analog computer. Attempts have been made to simplify their relationships by assuming that the heat loss is some definite fraction of the kinetic energy of the moving mass, by modifying y (ratio of specific heats) to account for heat losses, or by various other assumptions. Such simplifications are successful in describing the interior ballistics of guns where the time cycle is much shorter and the heat losses are much smaller fractions (approximately 10 percent) of the total energy produced by the propellant. The longer functioning time of a propellant actuated device (approximately four or five times that of a gun) permits energy losses (mostly heat losses) of from 40 to 60 percent of the total available energy and prevents the use of such simplifying assumptions without experimental measurement of energy losses.

i. These usually are determined by analysis of pressure-time data. The results of figure 49 were obtained from a computer analysis of the pressure-time and acceleration-time curves (fig. 50) for the M5 catapult. Use of analog or digital computers makes detailed analyses of this type possible.

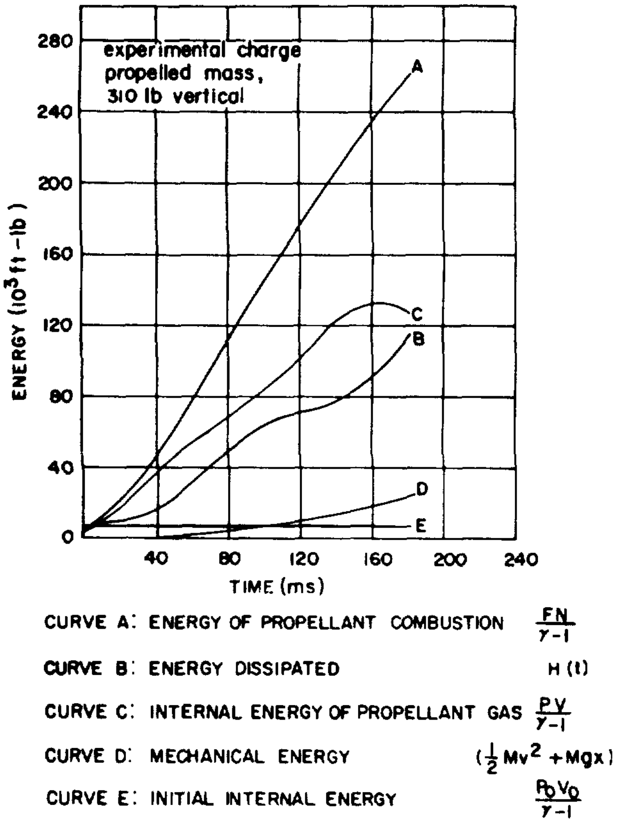

Figure 49. Energy balance of M5 Catapult (firing temperature, 70° F.)

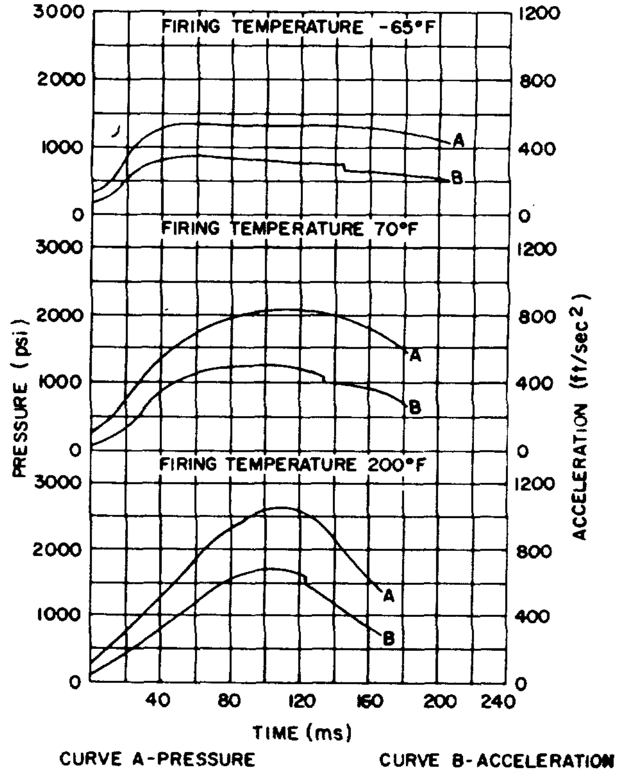

Figure 50. Pressure and acceleration vs time data used in analysis of energy balance of M5 Catapult.

j. The various terms of which the energy balance is composed are plotted against time in figure 49. Notice that only a small fraction of the chemical energy made available by the combustion of propellant - (curve A) is transformed into useful work (curve D). Most of the available energy is either lost through dissipation (curve B) or maintained in a potential form as gaseous internal energy (curve C) of which a sizable portion is completely lost to the atmosphere at the end of stroke. The values of the various terms of the energy balance at the end of the stroke and the thermal efficiency for firings of the M5 catapult with an experimental charge are tabulated in table XV. The thermal efficiency is defined as the ratio of the mechanical energy of the accelerated mass to the energy of propellant combustion.

Table XV. Values of Energy Balance Terms Upon Completion of Stroke

Propellant:		Propellant-Continued	
Composition	T18	Length	1.95 in.
Lot	PAE 12951	Impetus	777.5ft-lb/gm
Web	0.17in.	Ratio of specific heats	1.24
Number of perforations	-1	Igniter	65 gm A1BP
Outer diameter	0.447 in.		

Propelled weight † (lb)	Propellant charge (gm)	Firing temp. (°F.)	Cycle time (sec)	Thermal efficiency (%)	Energy of propellant combustion $\frac{FN}{n-1}$ (ft-lb)	Initial Internal energy $\frac{P_0V_0}{n-1}$ (ft-lb)	Gaseous internal energy $\frac{PV}{n-1}$ (ft-lb)	Mechanical energy (1/2 mv^3+mgs) (ft-lb)	Energy loss *H(t)* (ft-lb)
310	89.0	70	0.193	8.6	264,410	8420	129,580	22,690	120,560
310	89.0	70	0.193	8.1	278,790	9780	131,560	22,590	123,040
310	89.0	70	0.182	9.0	258,420	6770	129,700	23,360	112,130
310	89.5	-65	0.195	8.2	214,460	9990	105,220	17,550	102,420
310	89.2	-65	0.198	8.3	208,150	6230	99,570	17,220	97,590
310	90.0	-65	0.203	7.2	214,690	8340	92,430	15,500	116,000
310	89.4	160	0.168	10.0	289,620	7120	126,750	28,930	14,300

† Weight propelled vertically upward.

k. All of these energy-time functions, with the exception of the dissipation function (curve *B*), were derived directly by feeding experimentally obtained data into the theoretical equations given previously. The energy remaining after all the other energy forms have been accounted for is the dissipation function.

l. Figure 49 indicates the following approximate energy balance at tube separation in terms of the percentage of the energy produced by combustion of the propellant charge:

Energy dissipated $H(t)$	**41%**
Internal energy of propellant $\frac{PV}{\gamma-1}$	**47.5%**
Initial internal energy $\frac{P_0V_0}{\gamma-1}$	**2%**
Mechanical energy $(1/2mv^2+mgs)$	**9.5%**

This indicates an overall thermal efficiency of approximately 10 percent for a catapult. This efficiency is also representative of removers and thrusters.

54. Thrusters. From an interior ballistic standpoint, the major difference between thrusters and other stroking propellant actuated devices (catapults and removers) is in the term of importance, i.e., for a thruster which is a closed system, the main function is the overcoming of a resistive force and the kinetic energy imparted to the mass is incidental.

$$\text{Thruster: } \int F_r ds >>> \int mv\, dv$$

For a catapult, the terminal velocity and, therefore, the kinetic energy is important and the resistive forces are very small.

$$\textbf{Catapult:} \int F_r ds >>> \int mv\, dv$$

Thus, the energy balance equation must contain a term describing the work done by a thruster in exerting a force through a distance. In general terms, the work is equal to $\int_0^s F_r ds.$. The equation of motion must also be altered to include the resistive force against which the thruster acts. In general, this resistive force is constant or a function of stroke (para. 51*d* (2)).

a. *Damping Requirement.* In some thruster applications, the velocity of the piston must be held below certain values. To limit the piston velocity, either internal or external buffer systems are used. The interior ballistics of a buffered thruster can be described by the following equations. The general energy equation defines the heat loss in terms of a heat transfer coefficient, the surface area of the device exposed to hot gases, and a temperature difference.

(1) *Equations of motion.*

$$PA(1-A^*/A')-KA^*v^2 \pm \sin \alpha mg - ma = 0 \tag{42}$$

$$v = \int_0^t a\,dt \tag{43}$$

$$s = s_0 + \int_0^t v\,dt \tag{44}$$

(2) *Bernoulli's theorem.*

$$P^* = P(A/A') + Kv^2 \tag{45}$$

$$K = \frac{\rho_{af}}{2gC_d^2}\left(\frac{A^*}{A_t}\right) \tag{46}$$

(3) *General energy equation.*

$$NC_vT_0 = NC_vT + 1/2mv^2 + K'\int_0^t A_s(T-T_0)dt + KA^*\int_0^t v^3dt + \sin \alpha mg(s-s_0) \tag{47}$$

(4) *Equation of state.*

$$PA[s_0 + S(1-A^*/A') + (C-N)/\rho_{s,p}] = NRT \tag{48}$$

(5) *Equations of gas production.*

$$BP^n = -\frac{w}{2}\frac{df}{dt} \tag{35}$$

$$f = 1 - \int_0^t \frac{2B}{w} P^n dt \tag{36}$$

$$N = C(K_0 + K_1f + K_2f^2) \tag{37}$$

defined for $1 \geq f \geq 0$

$$N = C(K_{0'} + K_{1'}f + K_{2'}f^2)$$

defined for $0 \geq f \geq 0.5$

(6) *Symbols used in equations.*

a = acceleration of propelled mass
A = propellant chamber cross-sectional area
A' = return oil chamber cross-sectional area
A^* = oil damper cross-sectional area
A_t = oil damper orifice area
A_s = surface area available for heat transfer

B = burning rate coefficient
C = weight of unburned propellant
C_d = orifice discharge coefficient of oil damper
C_v = specific heat of gas at constant volume
g = acceleration due to gravity
f = fraction of web remaining unburned
K = oil damper velocity coefficient
K_1 = heat transfer coefficient
K_0, K_1, K_2, K_{01}, $K_{1'}$, K_2, = constants for geometrical form function
m = propelled mass
N = weight of burned propellant equal to weight of gas produced at time t
n = burning rate exponent
P = propellant gas pressure
P^* = oil damper oil pressure
R = gas constant
T_0 = propellant adiabatic flame temperature
T = space mean temperature of propellant gas
v = velocity of propelled mass
w = propellant web
s = travel
s_0 = initial displacement
a = maneuver load factor
r_{sp} = density of solid propellant
r_{df} = density of damping fluid

(7) The value of the heat transfer coefficient, K', in thrusters is of the order of 100 to 200 ft-lb/sec-ft^2 = °F.

(8) Because of the interdependence of the many variables in the equations describing the interior ballistics of a damped thruster, an electronic analog usually is set up to solve the equations as a function of time. The coefficients and other factors in the equations are then varied on the analog computer to match as best as possible an experimental pressure time curve from a workhorse (heavy-weight) developmental thruster. One or more of the coefficients (*B, n*, form function coefficients, etc.) which define the rate of gas production can be varied until an "ideal" pressure-time curve is defined. The propellant charge design can then be refined to meet the "ideal" coefficients. The refined charge would then be tested in an actual device for verification of the computer study.

b. Bypass Requirements.

(1) Bypass conditions are specified for some thrusters at the end of stroke in order to obtain a required pressure at the end of a fixed length of high pressure hose. Assume that a minimum bypass pressure, P_t, is required at the end of a fixed hose length, L_t, and is to be supplied at the end of function of the thruster. It is necessary to know the pressure in the thruster when the bypass port is uncovered, P_f; it is also necessary to know the volume of the thruster, V_d.† For a hose with volume, $V_{,t}$, and surface area, S., an estimate of the hose pressure is given by:

$$P_t = P_f \left[\frac{V_d}{V_d + V_t}\right]\left[1 - \frac{h_t S_t}{P_f V_d}(\gamma - 1)\right](1 - \beta) \qquad \textbf{(49)‡}$$

Where:

h_t = heat loss per unit surface area of hose as a result of wall friction.
β = fraction heat loss due to flow through the orifice and additional heat loss in the thruster after ports are uncovered.

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†V_t includes volume of the end block or any other volume attached to hose, in addition to the hose volume.
‡ See app. V for derivation of equation (49).

(2) The value of h_t is of the order of 25 to 30 ft-lb/in.^{2} for aircraft hose. The value of β is approximately 0.2 to 0.3.

(3) For example, the M3A1 thruster is designed to bypass gas into a 3/16-inch (inside diameter) A hose at the end of its stroke. The parameters from chapter 6 are:

Thruster: $P_f = 5{,}700$ psi
$V_d = 1.30$ in.^{3}
$g = 1.25$
Hose: $V_t = (0.1\,\dagger + 0.0276L_t)$ in.^{3}
L_t = tube length, in.
$S_t = 0.59L_t$

(4) These values are substituted in equation (49) using $h_t = 26$ ft-lb/in.^{2} and $\beta = 0.3$. The curve which results is given in figure 51 as hose pressure, P_t, versus hose length, L_t, and it follows the experimental curve closely enough to confirm the choice of the various parameters.

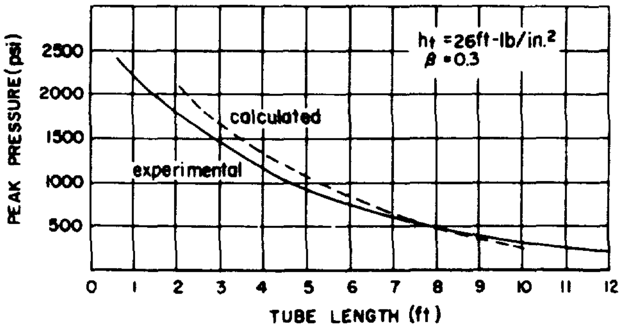

Figure 51. Experimental and calculated bypass pressure for MSA1 Thruster.

c. *Locked-Shut Requirements.*

(1) An estimate of the locked-shut pressure in a thruster can be obtained from the equation of state by making a few assumptions:

$$PV=nRT \qquad (16)$$

In terms of charge weight, *C,* and propellant impetus, *F,*

$$P=\frac{CF+C_tF_t}{V_c}\,(0.54) \qquad (50)$$

Where:

C_t = weight of igniter
F_t = impetus of igniter material
V_t = initial thruster volume

(2) The factor 0.54 is estimated as follows:

(a) The peak pressure is assumed to occur when only 90 percent of the propellant has been consumed.

(b) In systems that use propellants with "large" webs (w>0.3), it is safe to assume that the pressure is reduced by about 40 percent due to dissipation of heat to the walls of the device.

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† The additional 0.1 in.^{3} is for end block and gas volume, etc.

(*c*) Therefore, the peak pressure is approximately 0.9 times 0.6, or 0.54 times the pressure calculated from the perfect gas law.

55. Initiators. *a.* The hose-end pressure from an initiator can be estimated from the equation of state, modified to account for heat losses in the initiator body, at the initiator orifice, and in the aircraft hose.

$$P_t=\frac{CF}{V_c+V_t}\left[1-\beta-\frac{h_tS_t(\gamma-1)}{CF}\right] \qquad (51)$$

Where:

P_t = pressure at end of hose
C = charge weight
F = propellant impetus
V_c = initiator volume
V_t = hose volume
b = fraction heat loss in initiator and at initiator orifice
h_t = Wheat loss per unit area in hose
S_t = hose surface area
g = ratio of specific heats

b. The value of β is generally 0.25 to 0.35, and h_t for aircraft hose is on the order of one-tenth to one-fifteenth the heat loss encountered in guns and propellant actuated devices where the energy transfer is to metal, or about 25 to 30 ft-lb/in.^{2}. Equation (51) 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 are shown in figure 52 as functions of hose length and are in satisfactory agreement.

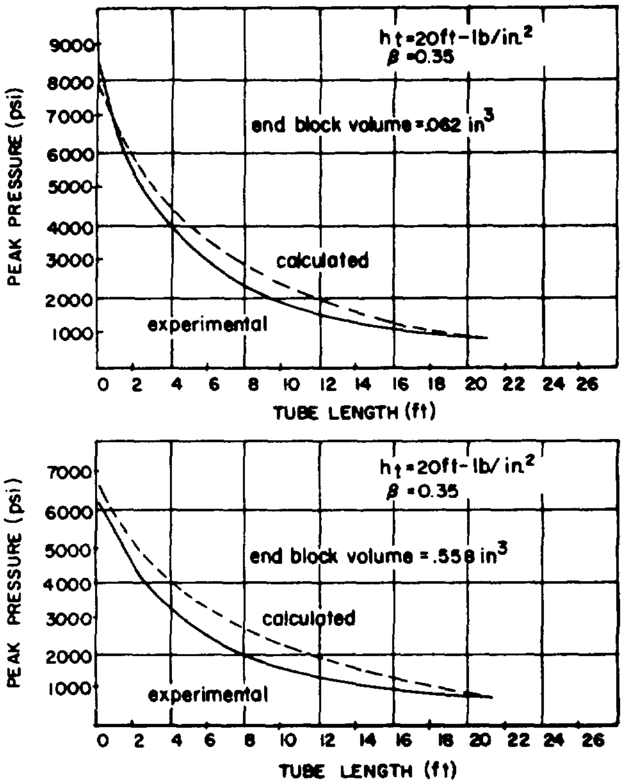

Figure 52. Relationship of hose pressure and hose length for M3 Initiator.

CHAPTER 6

DESIGN EXAMPLES

Section I. GENERAL

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

57. Scope. The devices chosen to illustrate these principles are the M3 catapult, the M3A1 thruster, and the M4 initiator. The M3 catapult was one of the first gas-actuated catapults to be standardized, and it is still used in operational aircraft. The M3A1 thruster is a typical thruster with a bypass port at the end of its stroke. The M4 initiator is a delay initiator.

Section II. M3 CATAPULT

58. General. The M3 catapult is a three-tube telescoping device, designed for upward ejection of a 350-pound seat-man combination from an aircraft in the event of an emergency.

59. Design Requirements. The original requirements for the M3 catapult specified the following performance and physical characteristics:

a. Performance Characteristics.

Operating temperature range	-65 to 160°F†
Velocity	80 fps min
Acceleration	20 g max
Acceleration change rate	250 g/sec
Weight propelled vertically	350 lb

b. Physical Characteristics.

Overall length	501/2 in. max
Structural loads:	
Tension	2,000 lb
Compression	6,000 lb
Firing mechanism	Gas actuated
Pressure to actuate	1,200 psi
Mounting:	
Airframe	Trunnion at upper end
Seat	Male clevis at upper end

60. First Order Approximations. Stroke length, stroke time, peak pressure, charge weight, and grain geometry are calculated in the manner described in section II, chapter 4. The equation numbers appearing below refer to the equations presented in chapter 4.

a. Stroke Length.

(1) Using equation (1) or figure 20 and the values specified in the design requirements, the approximate stroke length necessary to meet the requirements may be found. The maximum stroke is often specified, since the airframe does have a limit to the maximum stroke which 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 arrived at in the following manner: The overall length of the catapult is 50 1/2 inches (specified), so the maximum stroke which may be obtained with a single stroking tube is less than 50 inches. Referring to figure 20, it is obvious that a 50-inch stroke would acquire an acceleration greater than 20 g (the maximum acceleration tolerable to the human body in upward ejection). The maximum stroke which may be fitted in the overall catapult length specified using two stroking tubes would be approximately 90 inches, assuming that each moving tube is 45 inches long (the remainder of the

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† At the time the M3 catapult was developed, the temperature range was -65° F. to 160° F. The upper limit of later devices has been raised to 200° F.

overall length accommodates the firing mechanism and mounting arrangement).

(2) Referring again to figure 20, it may be determined that a catapult with a separation velocity of 80 fps minimum and an acceleration of 20 g maximum would require a stroke of 72 inches. Since it is not practical to design to the minimum velocity nor the maximum acceleration, it is determined, using figure 20, that i terminal velocity of 85 fps can be obtained with a stroke of 90 inches with an acceleration of 18 g. With these approximate. values established. the design is continued.

b. Stroke Time. Using equation (2) from paragraph 21, the values of velocity and acceleration found in the previous approximation, and the rate of change of acceleration specified, the time is estimated as follows:

$$t_m=\frac{v}{a_m}+\frac{a_m}{2\dot{a}}$$

$$t_m=\frac{85\text{ ft/sec}}{18(32.2)\text{ ft/sec}^2}+\frac{18\text{ g}}{2\times 250\text{ g/sec}}=0.182\text{ sec} \qquad (2)$$

c. Peak Pressure.

(1) To use equation (3) from paragraph 22, either the peak pressure or the diameter of the catapult must be known. Since no diameters are specified in the design requirements, it is advantageous to choose a peak pressure which experience has shown will satisfy the design requirements without requiring unusually large diameter tubes. The selection of the preliminary peak pressure is also determined, in part., by the characteristics of available propellants. Such a peak pressure is 2,000 psi. Using this figure in equation (3), the effective area (a function of diameter) of the catapult is found as follows:

$$PA=m\,a_m$$

$$A=\frac{350/\text{g}\times 18\text{ g}}{2{,}000}=3.15\text{ in.}^2 \qquad (3)$$

This corresponds very closely to a diameter of 2 inches.

(2) Peak pressure and acceleration occur when the telescoping tube (intermediate tube) and the inner tube are traveling together. Therefore, the outside diameter of the telescoping tube determines the effective area, and from this calculation the diameter becomes 2.0 inches.

d. Propellant Charge Weight.

(1) The propellant charge weight is estimated by using figure 21. From this figure it may be seen that the approximate ratio of propellant charge to propelled weight for a catapult with a terminal velocity of 85 fps is 0.44 gm/lb. Since the propelled weight, W, is 350 pounds, the propellant charge, c, is:

$$\frac{c}{W}=0.44$$

$$c=0.44\times 350=154\text{ gm}$$

(2) It is possible to refine this approximation using equation (31) from the refinements to first order equations section (para. 51).

$$C=\frac{m'v^2(\gamma-1)}{2F\epsilon} \qquad (31)$$

(3) In this equation, m' is the modified propelled mass, modified to correct for friction effects and direction of ejection. It may be calculated from equation (32):

$$m'=1.03\,m\left(1+\frac{2Sg}{v^2}\sin\right) \qquad (32)$$

(4) The following values are assumed for use in equation (32):

m = propelled mass 350/g slugs
S = stroke to separation 90 in.
g = acceleration due to gravity 32.2 ft/sec2
v = velocity at separation 85 fps
a = angle between direction of thrust and horizontal + 90° (vertical-upward ejection)

$$\therefore m'=1.03\times\frac{350}{32.2}\times\left(1+\frac{2\times\frac{90}{12}\times 32.2\times 1}{85^2}\right)$$

$$m'=12.0\text{ slugs}$$

(5) The charge weight may then be calculated using equation (31), assuming an

efficiency of 10 percent and also assuming that H8 propellant will be used. The value of propellant impetus, *F*, for H8 propellant is 3.1×10^5 ft lb/lb and γ is approximately 1.25 for propellants used in propellant actuated devices.

$$C = \frac{12.0 \times 85^2 \times 0.25}{2 \times 3.1 \times 10^5 \times 0.10}$$

$$C = 0.37 \text{ lb} = 170 \text{ gm}$$

e. Grain Geometry.

(1) The grain used in this catapult should be cylindrical with a single perforation. †. The thickness of the web is estimated by using equation (6). Peak pressure and stroke time have already been estimated, and the pressure coefficient of linear burning rate (*C*′) for H8 propellant, is given in table XIII.

$$w = 1.4 C' P t_m$$

$$w = 1.4(0.18 \times 10^{-4})(2{,}000)(0.182)$$

$$w = 0.09 \text{ in.} \qquad (6)$$

(2) The web estimated above can be used in the initial charge, but it may have to be modified during the charge establishment firings, since it is based on two other approximations: peak pressure and stroke time.

61. Component Layout. *a.* The component layout 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. Ballistically, this requires the volumes at the beginning and end of stroke in order to complete the calculations.

b. The initial layout starts with the specified overall length (50 1/2 in.) and assumes the 2-inch outside diameter for the telescoping tube previously estimated. The necessary components, such as the cartridge, firing mechanism, and stroking members, are then fitted to the layout. As previously determined, two moving tubes are required. (The envelope tube is generally referred to as the outside tube; the innermost tube is called the inside tube; and the intermediate tube between these two is called the telescoping tube.) As a first approximation, assume that the telescoping and inside tubes are each 45 inches long, thus providing the necessary stroke.

c. After the tubes are placed in the envelope (based on approximated lengths and diameters) and space is provided for the firing mechanism, the initial and final volumes are calculated. It is desired to make the ratio of final volume to initial volume (expansion ratio) approximately 2. Assume, as in figure 53, that each stroking tube is 45 inches long, that the inside diameter of the inside tube is 1 1/2 inches (which may be obtained by making the walls of the telescoping and inside tubes 1/s inch thick), and that the telescoping and outside tubes fit over the inside tube without airspace. The expansion ratio calculated for the assumed device shown in figure 53 is slightly greater than 4, which is twice as large as that desired. To reduce the expansion ratio and still maintain the required stroke, it is necessary to increase the initial volume. Since the device cannot be lengthened (overall length is specified as 50 1/2 inches), the diameter of the device must be increased.

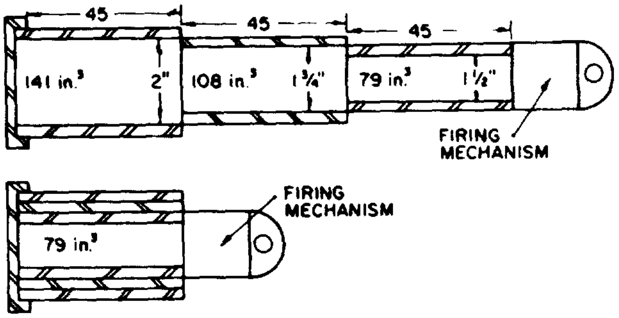

Figure 53. Expansion ratio approximations.

d. The diameters of the inside and telescoping tubes are kept constant, but the outside tube diameter is increased to 3 inches and vented spacers are provided to permit propellant gas to flow into the annular volume between the outside tube and the telescoping tube (fig. 54). These changes increase the initial volume to approximately 200 cubic inches and the final volume to approximately 450 cubic inches. The expansion ratio is now approximately 2, and the design may be continued, using the general layout of components shown in figure 55.

e. The layout of the catapult includes the following components: a cap; outside, telescoping, and inside tubes; seals; trunnion; locking mechanism; firing mechanism; shock washer; expander;

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† The selection of propellant and propellant grain geometry are discussed In chapter 5.

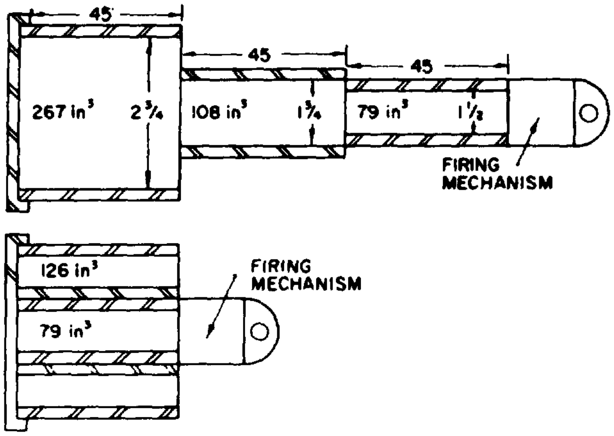

Figure 54. Expansion ratio with annular volume.

spacer; block; and cartridge. The design of these components is described later in this chapter.

f. The catapult (fig. 55) is fired by propellant gas from an initiator. Pressure behind the firing pin increases until it provides sufficient force to shear the shear pin and drive the firing pin toward the primer. As the firing pin moves, the safety lock recesses in the latches are cleared and the tapered sides of the firing pin center section cause the catapult latches to be drawn toward the center, unlocking the catapult. The firing pin strikes the cartridge firing plug which, in turn, strikes the primer and fires the cartridge.

g. Propellant gas, generated by the catapult cartridge, causes the cartridge case to rupture, permitting the propellant gas to flow into the inside tube and through the spacer into the annular volume between the outside and telescoping tubes. Pressure in the catapult causes the inside and telescoping tubes to move outward as a unit until the telescoping tube and trunnion stopping shoulders come into contact. The inside tube continues to move and finally separates from the telescoping tube. The inside tube remains attached to the seat, and the rest of the catapult remains in the aircraft.

62. Cartridge. *a.* The cartridge is designed to fit in the inside 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 under consideration, it has been determined that the case, will be 1 1/2 inches in diameter and that approximately 200 grams of single perforated H8 propellant will be used. (Approximately 20 percent has been added to the computed charge to slow for experimental charge development.).

b. For convenience, it w-as decided to use single perforated H8 propellant grains of 0.318 inch diameter. These grains are 2.73 inches long and 0.2 cubic inch in volume, and 13 or 14 will fit in the cartridge. Since the density of H8 propellant is 0.057 lb/in.^{3} (table XIII), approximately 7.6 cubic inches or 35 propellant grains are required. A standard cartridge case (M36A1) is of the required diameter and about 9 inches long, and can be used for the preliminary design.

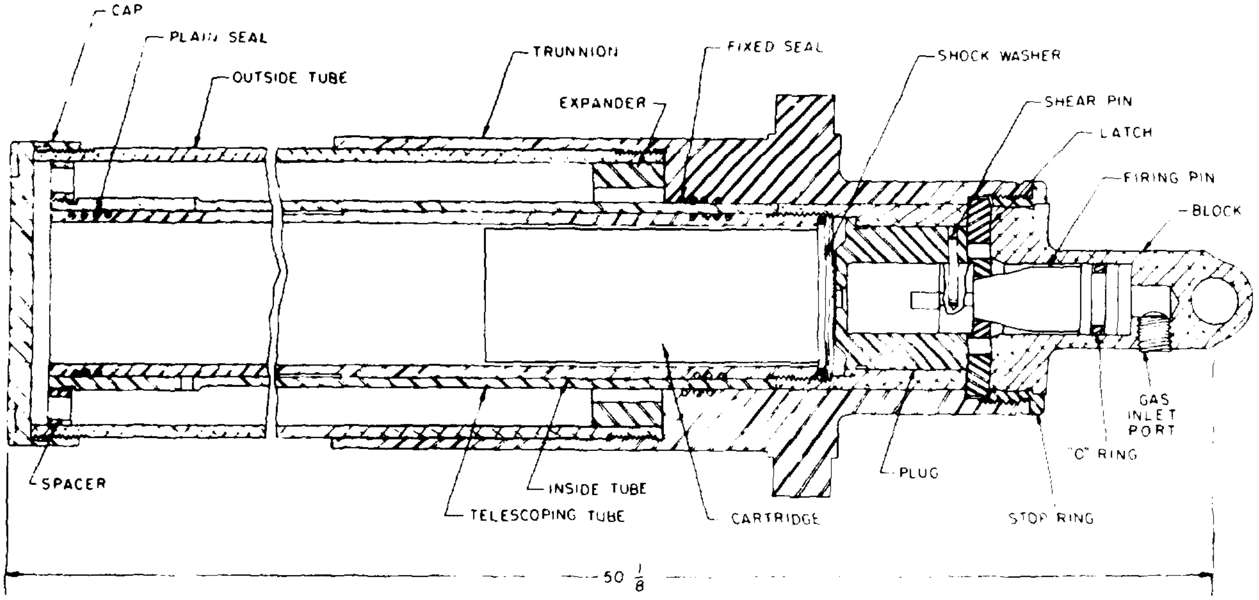

Figure 55. Catapult component layout.

c. A standard head is selected for the cartridge. The top of the cartridge head has a shallow, lard diameter recess which is used to position the retaining ring, which retains the firing plug and M61 primer. The primer cavity is located in the bottom of the cartridge head and has sufficient depth to hold the primer and firing plug. The igniter is retained in an annular cavity having a semicircular cross section. The approximate igniter charge may be found using the method described in chapter 4. Black powder is commonly used as an igniter in propellant actuated devices Assuming that 40 grams of black powder are required for each pound of propellant, the igniter charge for the M3 catapult cartridge is:

$$0.408\ \text{lb}_p \times 40\ \text{gm/lb}_p = 16\ \text{gm}$$

This charge, as well as the propellant charge, is subject to modification during the evaluation program. For example, the M36A1 cartridge uses 65 grains of igniter.

d. A disc and retaining spring are provided at the base of the head to separate the igniter from the propellant. The igniter is retained in the igniter chamber by a thin magnesium wafer (igniting charge disc) which ignites when the igniter burns. Four flash holes connect the primer and the igniter chambers. Figure 56 shows the cartridge has been standardized as the M36.

63. Tubes. *a.* The tubes of the catapult act as both the pressure chamber and the stroking members. The inside tube is a long cylinder with grooves on the outside of the tube at each end to accommodate wire (tortuous path) seals. The cartridge end has external threads to which the block is attached. The outside surface of the inside tube is machined, except at the ends (fig. 57) to a slightly smaller diameter to reduce friction as it strokes. Four slots are machined in the cartridge end of the inside tube to provide a means of locking the block to the tube. Three holes in the block provide a locking position (the position where a slot in the tube and a hole in the block are aligned) every 30°.

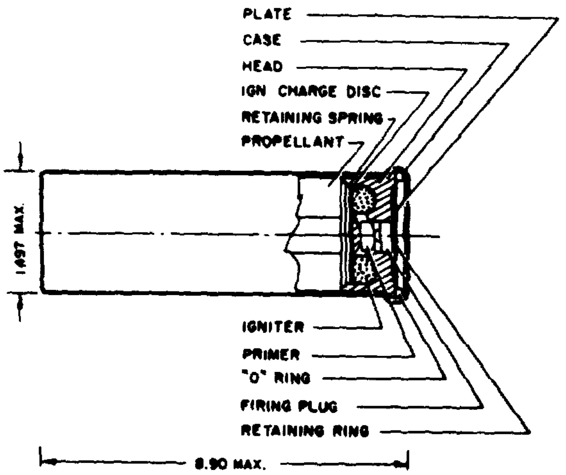

Figure 56. Catapult Cartridge, M36

b. The telescoping tube is a long cylinder, the base of which has a larger outside diameter than the cartridge end. The base is threaded to accommodate the internal threads of the spacer. (The functions of the spacer are described later in para. 69.) The outside diameter of the telescoping tube is enlarged for the last 1 inch (at the spacer end) to act as a stopping shoulder in arresting the motion of the telescoping tube as it approaches the stopping shoulder of the trunnion. Eight holes are located around the circumference of the telescoping tube (fig. 58) to permit propellant gas to enter the space between the telescoping and inside tubes and equalize the pressures within all three tubes.

c. The outside tube is a long cylinder with external threads at each end. The cap is used to close the bottom end and the trunnion is attached to the top (the cartridge end of the device).

d. The sizes of the tubes are calculated using the equation of von Mises-Hencky, which is plotted in figure 23. Catapults generally are not designed to withstand locked-shut pressures; therefore, the peak pressure assumed in the first order approximations (2,000 psi) may be used in the calculations.

e. It was assumed previously that the inside tube had a 1l/2-inch inside diameter and 1/8-inch walls (a standard wall thickness in tubing of this size), while the telescoping tube had a 13/4-inch inside diameter and 1/8-inch walls. These nominal sizes are used in the following calculations. The outside diameter of the inside tube must be large enough to permit grooves to be machined in each end for insertion of the wire seal. Assuming that aluminum will be used for the inside tube to minimize weight, the pressure ratio *(P/Y)* is:

$$\frac{P}{Y}=\frac{2{,}000\times 1.15^{\dagger}}{42{,}000}=0.0547$$

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† A 1.15 safety factor to used, since this it a cylindrical part which must withstand Internal pressure without rupturing (see Design Strength considerations, section III, chapter 4).

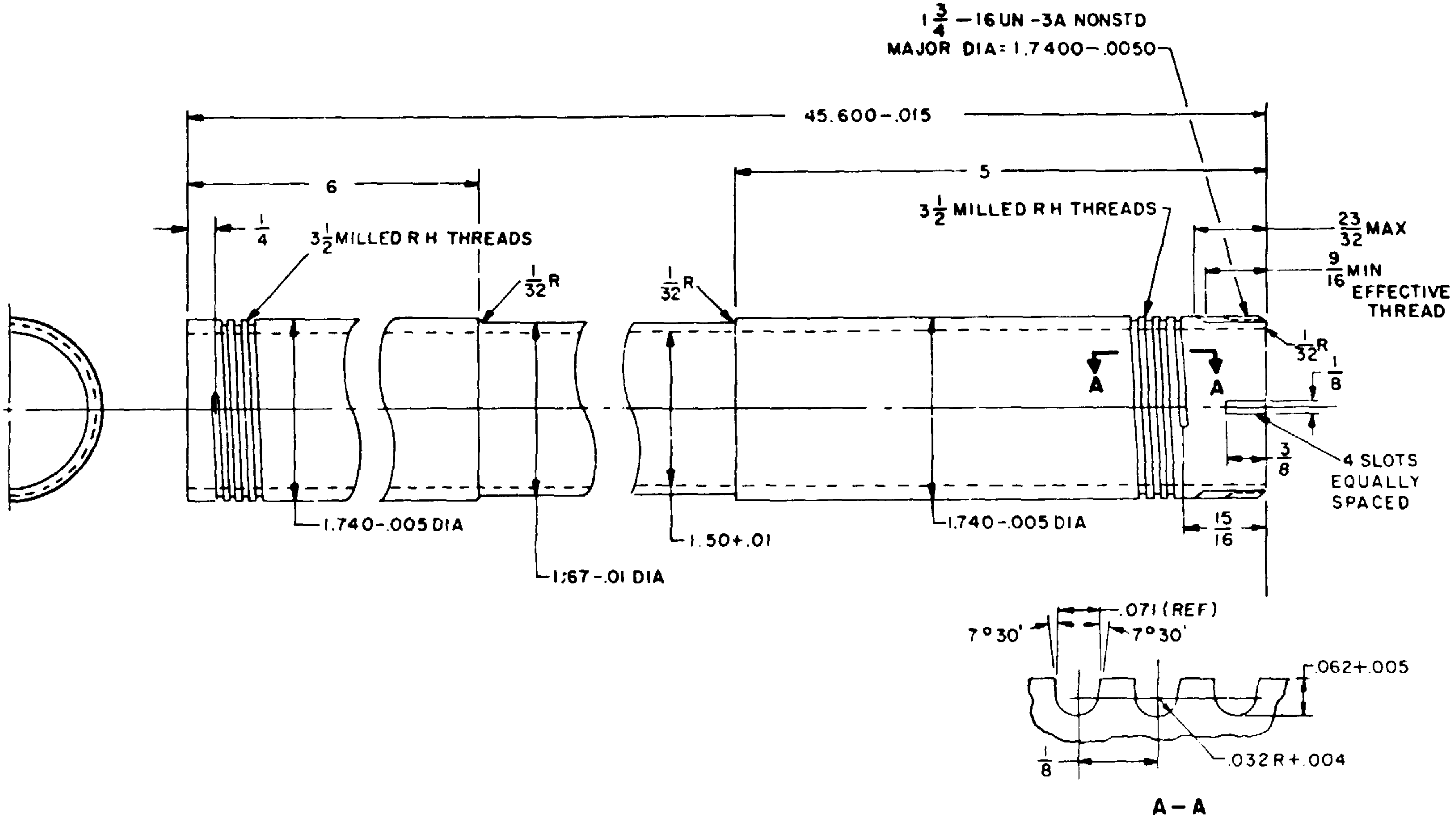

Figure 57. Inside tube for catapult.

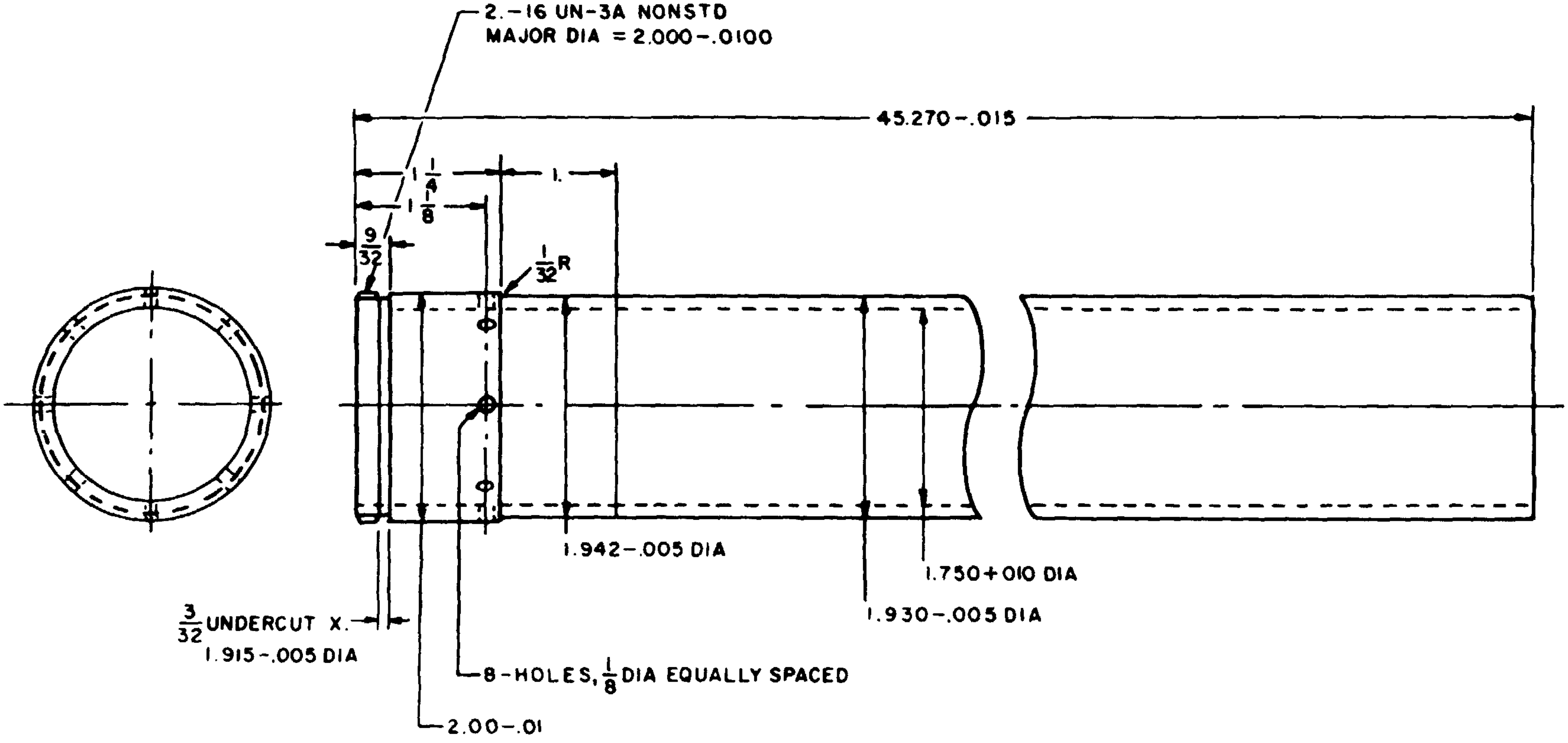

Figure 58. Telescoping tube for catapult.

Using figure 23 and the ordinate of the intersection of pressure ratio 0.055 and the biaxial stress curve (catapults are subjected to radical and tangential stresses but not to longitudinal stresses), the wall ratio is found to be 1.059. Since wall ratio is the ratio of outside diameter to inside diameter, the outside diameter is calculated as follows:

$$W=\frac{OD}{ID}=1.059$$

therefore,

OD = W X ID = 1.059 X 1.50=1.59 inches

This is the diameter of the base of the machined groove and the relieved section, not the outside diameter of the inside tube. Since the groove must be at least 1/16 inch deep, the diameter of the inside tube must be 1/8 inch larger than 1.59, or 1.72 inches (fig. 57). Referring to tubing standards, it is found that 1.740-.005 is a standard size tube.

f. It is assumed that the telescoping tube will also be made of aluminum. The tube size is determined in a manner similar to that used for the inside tube. The inside diameter of the telescoping tube is 1.75 inches and the outside diameter is 2.00 inches. Again, the large outside diameter is not calculated from the wall ratio, but rather the diameter of the undercut at the end of the tube is found. Using the wall ratio already found (1.059), the minimum diameter of the -undercut is found to be 1.86 inches. The telescoping tube of the final design is illustrated in figure 58. From the figure it can be seen that although the standard 2-inch tube is machined down over most of its length, the last 3 inches (near the shoulder) are tapered and the final 1 1/4 inches of the tube are 2.00 inches in diameter. This increase in diameter of the telescoping tube is designed to create an interference fit (0.000 to 0.007 inch) between the telescoping tube and the trunnion bore, and thus absorb some of the energy of the moving members before the telescoping tube and its attached spacer strike the stopping shoulder of the trunnion.

g. In the estimate, the outside tube was calculated to have a 3-inch outside diameter and a 2 3/4-inch inside diameter. A commercially available tube made of 2024-T3 aluminum (WW-T-785) has an outside diameter of 3.0 inches and an inside diameter of 2.8 inches. The wall ratio of this tube is:

$$W=\frac{OD}{ID}=\frac{3.0}{2.8}=1.071$$

Referring to sheet 1 of figure 23, the pressure ratio (P/Y) is found to be 0.066 and the minimum strength of the material is calculated as follows:
From figure 23:

$$\frac{P}{Y}=0.066$$

therefore,

$$Y=\frac{2{,}000\times 1.15^{\dagger}}{0.066}=34{,}800 \text{ psi}$$

Since the yield strength of 2024-T3 aluminum is 42,000 psi, the material provides more than the required safety factor of 1.15 and can be used for the outside tube.

64. Trunnion.

a. The trunnion (fig. 59) is a cylindrical alloy-steel body which has two pivots, 180° apart, perpendicular to the longitudinal axis of the catapult. The trunnion has internal threads to accommodate the stop ring which serves as one bearing surface for the latches. The recess in the trunnion below these threads serves as the other bearing surface for the latches. The stop ring-trunnion combination, for positioning the latches, is used in most catapults and removers because of its ease of assembly. The upper portion of the trunnion's large bore is threaded to accommodate the outside tube. The small bore of the trunnion acts as a bearing surface for the telescoping tube. A spring (tortuous path) seal is provided in the trunnion to seal the telescoping tube.

b. The trunnion pivots are an integral part of the trunnion. 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 6,000 pounds. The maximum kinetic load applied to the pivots, resulting from operation of the catapults, is computed by using Newton's law:

$$F=ma=\frac{350}{g}=18\ g=6{,}300 \text{ pounds}$$

Since the kinetic load is greater than the static load specified (6,000 pounds) in the design requirements, the kinetic load is used in calculating the size of the trunnion

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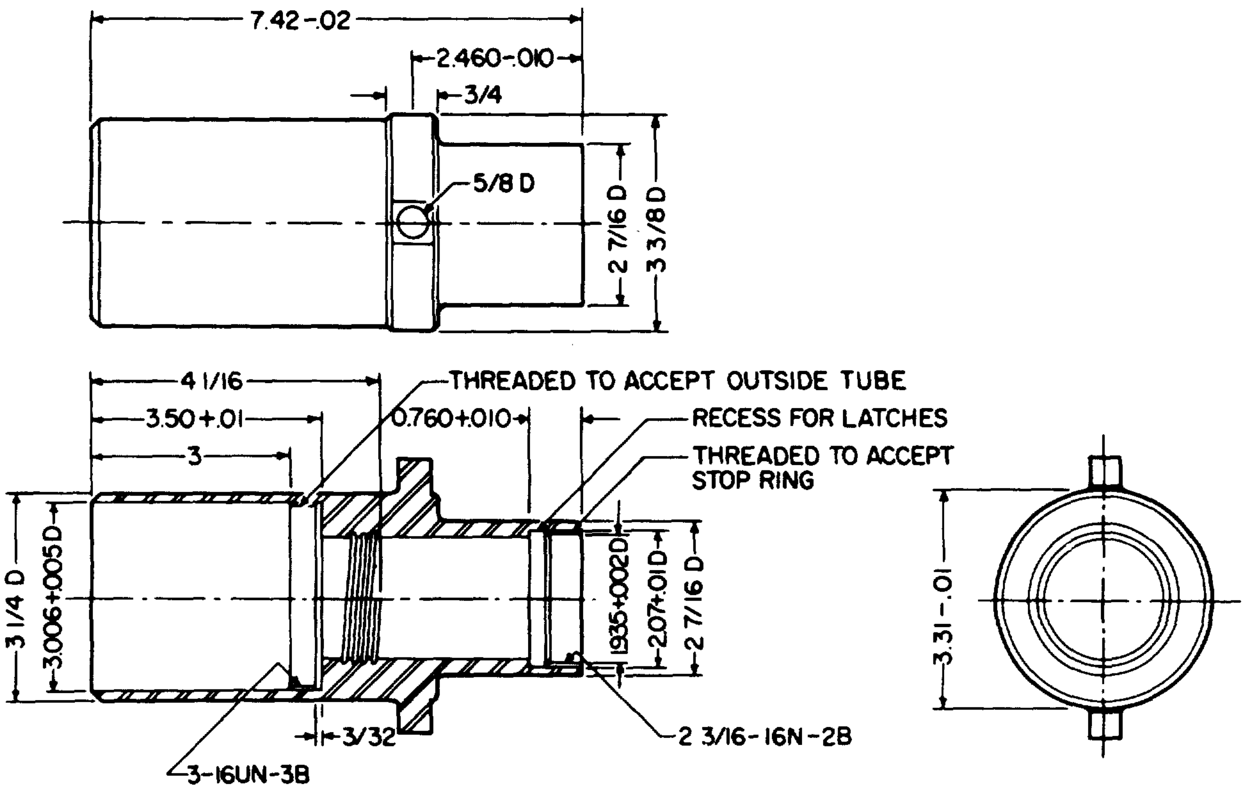
† Safety factor.



pivots. The trunnion is to be made of 4140 steel having a tensile strength of 125,000 psi. Assuming that the shearing stress is 60 percent of the tensile strength or 75,000 psi, the Divot size is calculated as follows:

$$A=\frac{F}{S_s}=\frac{6,300\times 2^{\dagger}}{75,000}=0.169 \text{ in.}^2$$

Where:

S_3 = shearing stress
F = load
A = area in shear

If it is assumed that the full load may be carried by a single pivot under certain loading conditions, a trunnion pivot 5/8 inch in diameter will be safe.

c. Good 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 trunnion bearing loads must be taken close in to the trunnion body so as to eliminate excessive bending loads. However, a fillet is required to minimize stress concentrations in the corner.

d. The outside diameter of the trunnion where the pivot is located must be designed to fit the mounting piece in the aircraft without free play; otherwise, a bending moment may be set up in the pivot. A fillet should be provided where the pivot joins the trunnion to avoid unnecessary stress concentrations.

e. Figure 55 shows that the outside tube screws into the trunnion, but the skirt of the trunnion extends an additional 3 inches along the outside tube. This design feature is incorporated because the bending moment caused by the eccentric loading of the seat ‡ acts on the trunnion. If the trunnion stopped at the end of the threaded section of the outside tube, the bending moment would be transmitted from the trunnion to the outside tube at the undercut of the threads, causing excessive stress concentrations at this point. Since the trunnion extends along the outside tube,

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† 2 is the safety factor for structural members.

‡ The catapult is attached to the back of the pilot's seat, and, therefore, cannot direct its thrust through the center of gravity of the seat. An additional moment is created by the aerodynamic force on the pilot and seat. This moment opposes the Initial moment, therefore, bending may occur In either direction.

the bending moment is applied to the outside tube well below the threaded section, thus avoiding excessive stress concentration.

65. Block.

a. The block (fig. 60) is the component which houses the firing mechanism and the latches. The block is cylindrical at one end and rectangular at the other. The cylindrical section of the block has internal threads to accommodate the inside tube. The inside tube houses the cartridge. A polyethylene shock washer is installed between the end of the inside tube and the cartridge shoulder, and the inside tube is then screwed into the block assembly. Three equally spaced holes are provided around the lower portion of the block. When the inside tube (with cartridge inserted) is screwed into the block, one of the four slots in the tube is aligned with one of the three holes in the block with every 30° of rotation. When the joint is tightened to the required torque, a ball is inserted in the hole and slot which are aligned, and the hole is staked (distorted) to lock the block to the inside tube. Near the top of the cylindrical section of the block, two slots, diametrically opposite to one another, are provided for the latches. A shear-pin hole, just below one of the latch slots, permits the firing pin to be locked in position. A gas inlet port is provided in the rectangular portion of the block, and a mounting hole permits the catapult separating parts (the block and inside tube) to be attached to the pilot's seat.

b. The block must be strong enough to contain the gas pressure supplied to the firing mechanism contained in the block. The area around the mounting hole (fig. 61) must be strong enough to withstand the 2,000-pound tensile load placed on the mounting.

c. The minimum thickness of material in the male clevis is (0.38-0.01) - (0.250+0.001) inch or 0.119 inch. (See fig. 6-9.) The area in tension is, therefore:

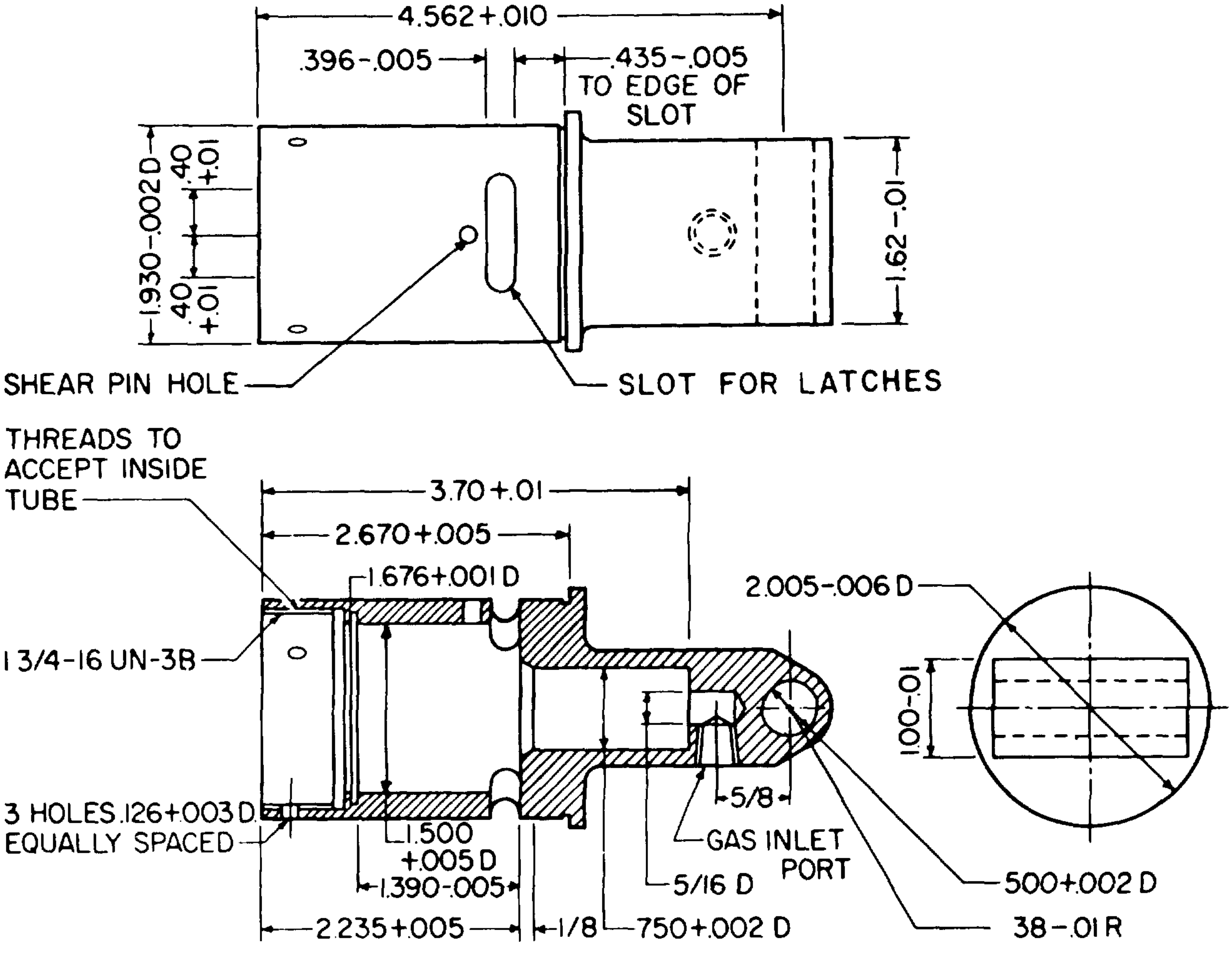

Figure 60. Block for catapult.

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

Assuming the block will be made of aluminum, the tension load required to tear the male clevis is:

$$F = SA$$

$$F = \frac{42{,}000 \times 0.192}{2^{\dagger}}$$

$$F = 3{,}900 \text{ pounds}$$

It is obvious from the above calculation that the design can easily withstand the 2,000-pound tension load required; therefore, the male clevis part of the block is designed more than adequately. Aircrewmen worry less about the apparent strength of the device when lightening procedures are not used in this section. The walls of the block in the area of the latch slots must be thick enough to provide sufficient bearing when the tension load is applied. Areas of stress concentration must. be avoided when designing the block.

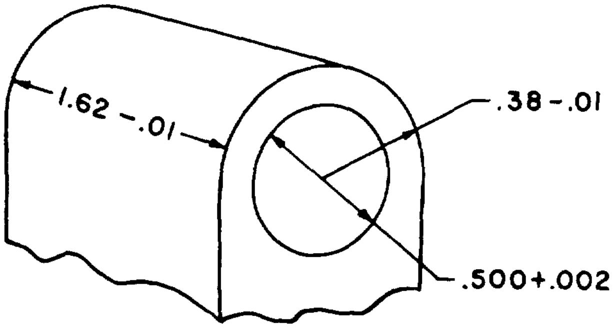

Figure 61. Enlarged view of block mounting hole (male clevis).

66. Firing Mechanism.

a. The firing mechanism consists of the firing pin and its guide (the plug). The firing pin has cylindrical ends and a flat, tapered, center section (fig. 62). The tapered surfaces are the camming surfaces which move the latch toward the center, unlocking the catapult as the firing pin is driven forward. Figure 37 illustrates the shape and action of the firing pin. One cylindrical section of the firing pin contains a groove into which an O-ring is fitted for sealing purposes. The other circular section has a shear pin hole (which is aligned with the shear pin hole in the block) and air bleed grooves. A copper shear pin is used to hold the firing pin in position prior to actuation.

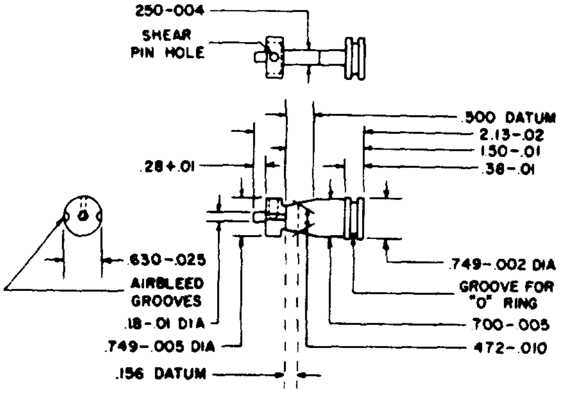

Figure 62. Firing pin for catapult.

b. The gas from the initiator must give the firing pin sufficient kinetic energy to unlock the latches and actuate the primer. Since the energy supplied to the primer is equal to the force exerted on the firing pin times the distance it travels (less losses), the firing pin is provided with sufficient area to exert the proper force and sufficient travel to develop the necessary energy to fire the primer. However, since this firing pin performs a dual function, the unlatching operation must be considered. The firing pin travel as -well as the firing pin itself must be sufficiently long that the camming angle is not too steep.

c. The plug acts as a firing pin guide. The closed end of the plug seats against the head of the cartridge to support the cartridge. A small hole is provided in the plug to allow the tip of the firing pin to pass through and to protrude so as to strike the cartridge. The plug not only supports the head of the cartridge but stops the forward motion of the firing pin to prevent piercing the cartridge primer. The dimensions of the base of the firing plug must insure the proper protrusion of the firing pin.

d. The size of the shear pin for the firing pin must be such that the pin will fail when the gas pressure develops a force on the firing pin of 220 pounds; however, it must not fail when the assembled device is dropped 6 feet onto a concrete slab in three different positions. The force behind the firing pin is 110 pounds when 250 psi is applied. In calculating the pin size it must be realized that there are many variables involved, and the only way of establishing the actual pin size is through performance and drop tests.

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†2 is the safety factor for structural members.

67. Locking Mechanism. *a.* The locking mechanism consists of two identical steel latches which are located in a plane perpendicular to the longitudinal axis. The outside face of the latch (fig. 63) has the same curvature as the inside of the trunnion, and the top edge of the face is beveled. When assembled, the latches pass through the slots in the block and extend into the space between the stop ring and the shoulder in the trunnion (fig. 55), locking the catapult in the closed position. The latches are held in a locked position by the firing pin, which is seated in a circular recess in the bottom face of the latches (figs. 37 and 63). The firing pin is held in place by the shear pin.

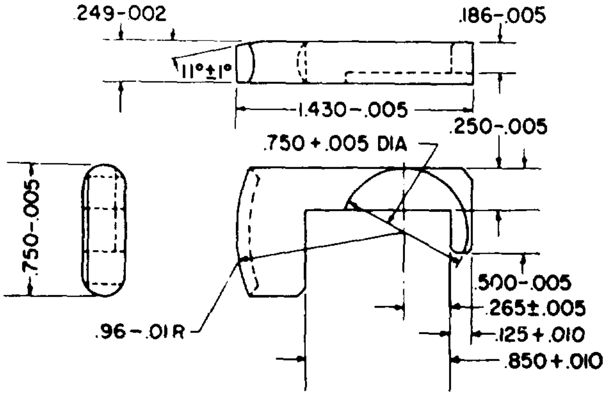

Figure 63. Locking key for catapult.

b. The latches are designed to hold the tubes in the closed position when the 2,000-pound tension load is applied. Since the latches fit into the trunnion and the stop ring without free play, the latches are in single shear. Applying a simple stress formula, the area required for the latches is calculated as follows:

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

Where:

A = area
F = load
S_s = shear stress

$$A=\frac{2{,}000\times 2\dagger}{75{,}000}$$

$$A=0.53\text{ in.}^2$$

Another important consideration is the bearing load of the latches upon the stop ring.

$$A_b=\frac{F_c}{S_c}$$

where F

F_c = compression load
S_c = yield strength in compression
A_b = bearing area

$$A_b=\frac{2{,}000\times 2^{\dagger}}{125{,}000}=0.032\text{ in.}^2$$

c. It is apparent from the calculations that the latches (fig. 6.3) will be overdesigned and no stress problem exists. The width must be made about 3/4 inch to permit the recess of the firing pin to be machined in the latch (for locking) and a thickness of 1/4 inch provides more than ample thickness for machining the locking recess in the side of the key.

d. It is important to note an 11° bevel at the latch end. This makes extraction of the latches easier and reduces the load on the small end (tang) of the latch.

e. Using a tang 1/8 by 3/16 inch (1/4-1/16 recess) provides a 0.0234 in.^{2} area for shear (each latch). The force, F, required to shear the tang is there-
fore:

$$\frac{0.0234\times 75{,}000}{2^{\dagger}}=880\text{ pounds}$$

Using a coefficient of friction μ of 0.2, the perpendicular load, *N*, which the latch tangs are capable of moving, neglecting bending, is:

$$N=\frac{F}{\mu}$$

$$N=\frac{880}{0.2}=4{,}400\text{ pounds}$$

68. Cap. *a.* The cap (fig. 64) is a short, cylindrical, alloy-steel cup-shaped section. The cap contains internal threads and is screwed on the outside tube, closing the tube at the base. Two shallow holes are drilled in the cap to permit tightening the cap on the outer tube.

b. The cap may fail in three ways: the end may blow out, the side may tear at the undercut of the threads, or the threads may shear out. The strength of the end of the cap is calculated by using the formula for stress in a circular plate with fixed edges subjected to a uniformly distributed load.

$$t^2=\frac{kr^2P}{S_s}$$

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† A safety factor of 2 is used because this is a structural member.

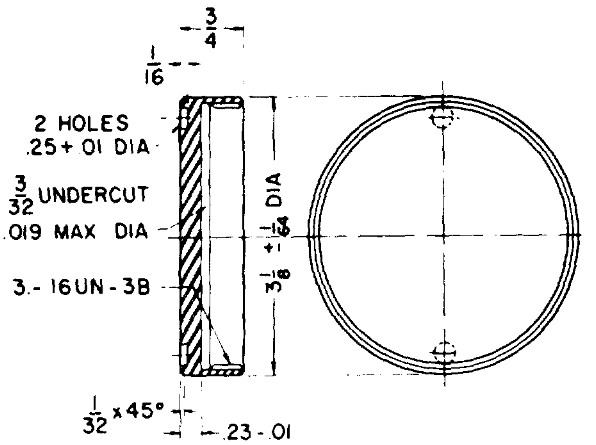


Figure 64. Cap for outside tube.

Where:

t = thickness
$k = 0.5$ for steel (fixed edge)
r = radius
P = internal pressure
S_s = shear stress (60 percent of yield strength)

$$t^2=\frac{0.5\times\left(\frac{3.019}{2}\right)^2\times 2{,}000\times 1.15^{\dagger}}{0.6\times 125{,}000}$$

$$t^2=0.035$$

$$t=0.19 \text{ inch}$$

The base of the cap is made 0.23 - 0.01 inch thick to provide sufficient thickness to prevent failure of the end piece.

c. The minimum thickness of the wall of the cap at the undercut of the threads, as designed, is 0.045 inch. One way this section could fail would be the result of tension. The tensile force is equal to the internal pressure times the area of the end disc, and the surface resisting this force is equal to the thickness of the wall at the undercut times the circumference of the cap.

$$F=SA$$

$$2{,}000\times\frac{\pi}{4}\times 3.109^2=S\times 0.045\times\pi\times 3.109$$

$$S=34{,}500$$

$$34{,}500\times 1.15^{\dagger}=39{,}600 \text{ psi}$$

Since the yield strength of steel is well above 39,600 psi, the cap is sufficiently strong as designed.

d. To determine the minimum length of threads required, equation (11) from paragraph 32 is used:

$$L=\frac{3PR^2}{S_s d} \tag{11}$$

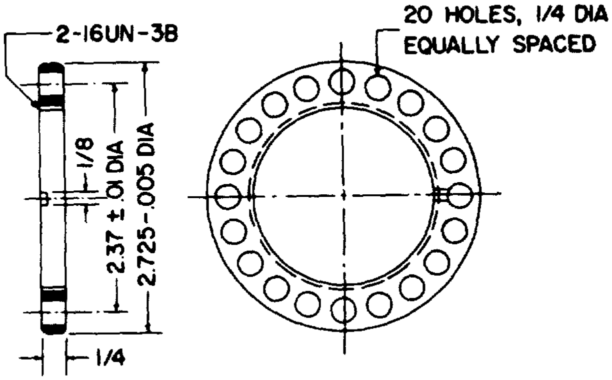
$$L=\frac{3\times 2{,}000\left(\frac{3.014}{2}\right)^2}{0.6\times 125{,}000\times 2.914}=0.062 \text{ inch}$$

e. These calculations show that one full thread in engagement would hold the design pressure of 2,000 psi with a 50-percent margin of safety (built into the formula). Therefore, there is no thread problem. The thread is made long enough to provide room for sealing.

69. Minor Parts. *a.* The spacer, expander, stop ring, and seals are considered minor parts. The spacer (fig. 65) is a ring located between the outside tube and the telescoping tube. This part has 20 holes in it to permit propellant gas to flow into the void between the outside and telescoping tubes. It is provided with internal threads to attach it to the telescoping tube.

b. The expander is an alloy-steel ring, and it is located at the top of the outside tube in order to lock the outside tube to the trunnion. The outside diameter of the expander increases slightly at the top to provide a wedge surface. When the outside h tube is threaded to the trunnion, the expander wedges the outside tube tightly against the trunnion, locking them together. The expander also provides better sealing action in the threads.

c. The stop ring (fig. 66) is a short, circular steel section with external threads to accommodate the trunnion, and a shoulder to prevent tightening the ring too far into the trunnion. When it



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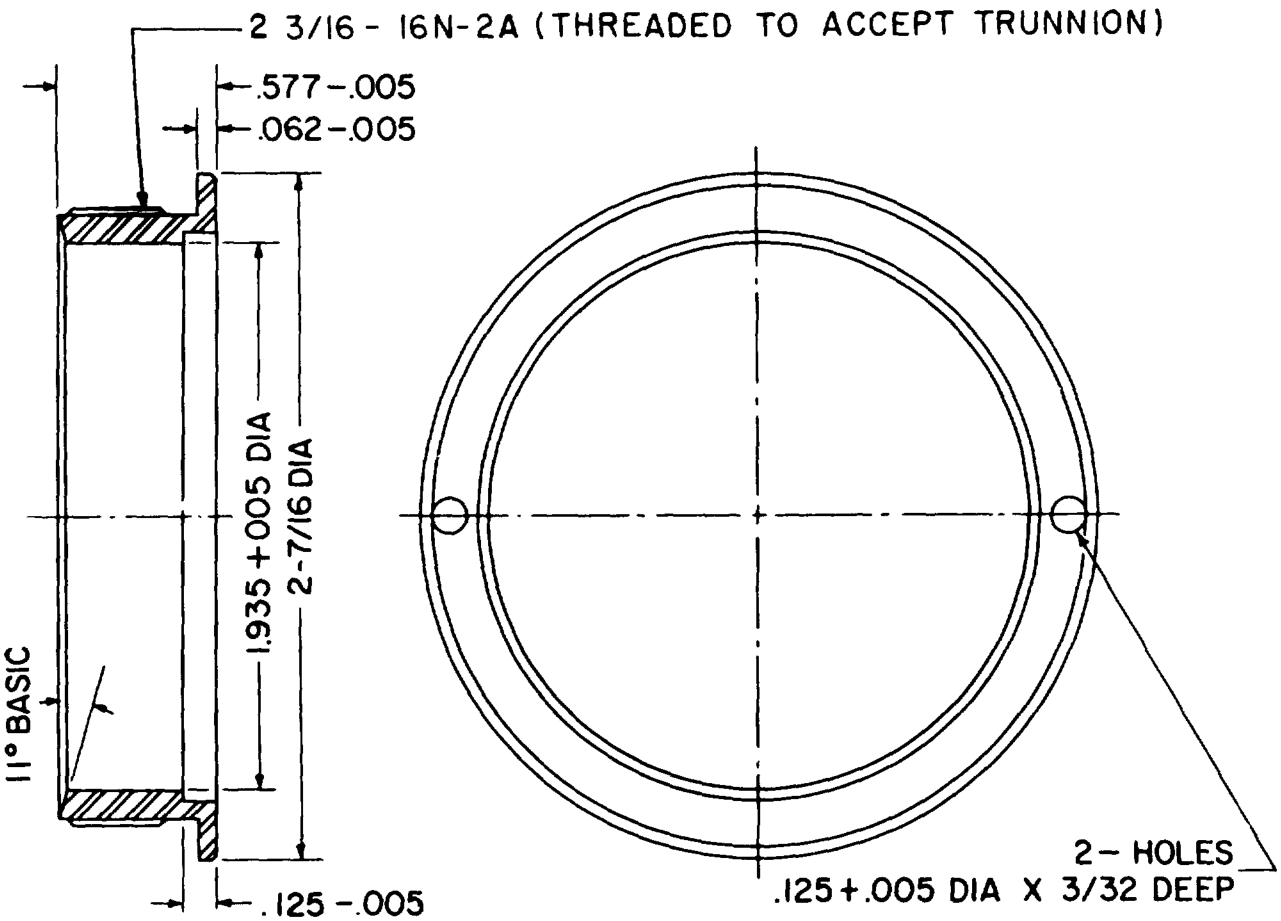
† Safety factor.



is assembled to the trunnion, the bottom face of the ring becomes the upper bearing surface for the latches. A pair of shallow holes are provided to aid in assembling the ring to the trunnion.

d. The seals used on the ends of the inside tube and inside the trunnion are spiral, wound-wire seals. (Wire seals are used because they must pass over holes in the telescoping tube when the inside tube moves inside the telescoping tube.) If O-ring seals were used, they might tear as they passed the holes. The seals fit in grooves machined in the trunnion and inside tube. A small tab on the spring seal fits into a small hole drilled in the grooves. The arrangement keeps the seals from rotating in the grooves and threading out of the grooves, thereby preventing undesirable friction.

Section III. M3A1 THRUSTER

70. General. The M3A1 thruster was developed to release the control column stowage spring and to operate the seat-actuator disconnect in the B52 aircraft escape system.

71. Design Requirements The design requirements for the M3A1 thruster are presented below:

Operating temperature range.	-65° to 160° F.[†]
Stroke	1.5 inches
Firing mechanism	Gas operated by a 500 psi min [‡]

[†] At the time of development, devices were not required to function at 200° F.

[‡] When a device is designed to furnish 500 psi to function the firing mechanism of another propellant actuated device, it is customary to design it to supply 1,000 psi to insure functioning.

Bypass requirements.	Bypass at end of stroke, 500 psi at end of 4-ft. hose
Lock requirements	Initial lock required
Thrust	Propel 550-pound weight upward through 1.5-inch stroke
Structural loads	800 pounds in tension
Envelope	Envelope and mounting are to remain the same as those of an earlier thruster, the T3
Locked-shut	The thruster shall withstand locked-shut firings without mechanical failure
No-load	The piston shall not separate from the body when the thruster is fired without load

72. Component Layout. *a.* 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.

b. All components of the thruster may be mounted on a single longitudinal axis. A typical gas firing mechanism 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 is then fitted in the remaining space in the envelope. A locking mechanism similar to the one described in paragraph 41 (fig. 36) is fitted in the piston. Figure 67 shows the layout of components. 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 pill 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 cam 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.

73. First Order Approximations. *a.* Before workhorse models of the thruster can be fabricated, using the tentative layout 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.

b. The thruster is designed to supply gas at a pressure of 1,000 psi to a 0.062 cubic-inch chamber at the end of 4 feet of hose after moving a 550-pound weight vertically upward for 1 1/2 inches.

c. The tentative diameter of the piston is 0.50 inch, with a corresponding area of 0.20 square inch. To raise the 550-pound load, the minimum pressure required is 2,750 psi.

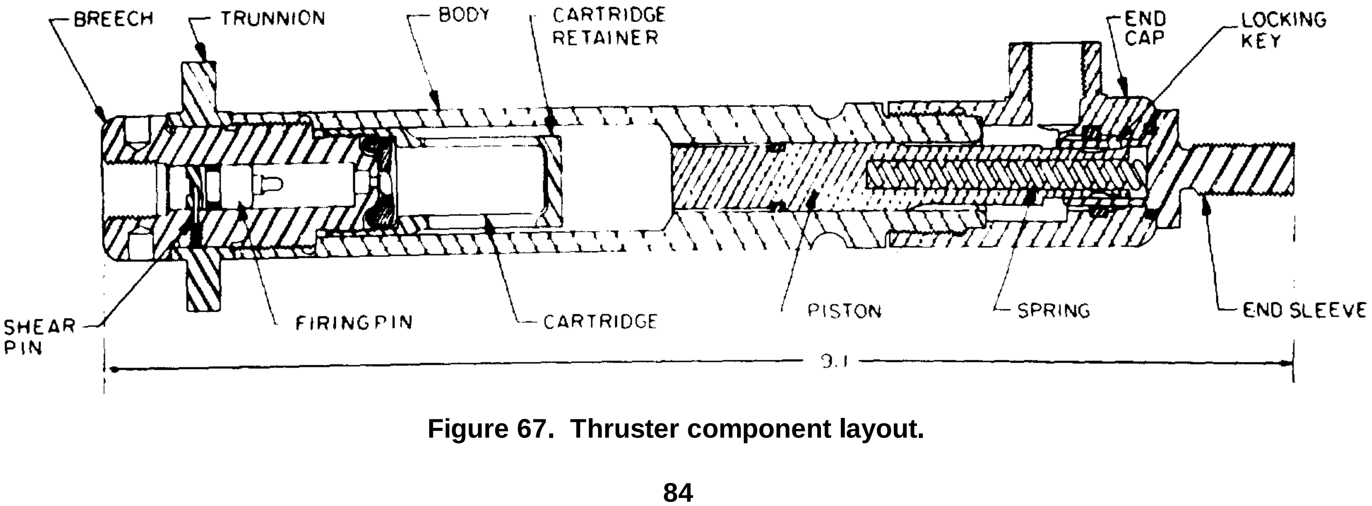


Figure 67. Thruster component layout.

(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 cubic inch. The initial free volume of the cylinder, taking into account the cartridge retainer, etc., is 0.98 cubic inch. The total final interior volume of the thruster is then 1.28 cubic inches.

d. Since the thruster must also supply bypass gas, the charge weight is calculated in two parts. The minimum charge for thrust is found from figure 22 to be 0.25 gram (550-pound load, lifted 1.5 inches). The charge required for bypass can be calculated from equation (51) with suitable interpretation of P_t The required pressure at the end of 4 feet 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 equation (51), the required charge is found to be about 1 gram. The total charge, for thrust and bypass, then, is approximately 1.25 grams.

e. Assume that the ballistician will use H8 propellant for the workhorse studies. H8 is suitably slow-burning, and one grain has adequate size (7/8-inch long, with 3/8-inch O.D.) to fit the chamber and weight (2 grams) to approximate the charge. Equation (57) (appendix V) will give the chamber pressure just before opening of the bypass port. Using the 2-gram charge and 1.28-cubic inch chamber volume, with 3.1×10^5 ft-lb/lb impetus and a B_1 value of .45, the chamber pressure, P_t, is about 5,700 psi. Thus, it satisfies the requirement for a pressure twice the minimum.

(The value of B_1 was chosen near the minimum because the thruster is small, and the work done represents only about one-fifth the total charge requirement.)

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

b. A 72M percussion-type primer is selected for use with the igniter in the cartridge. (See table IX for data on this primer.)

c. The cartridge case selected for this application is 0.550 inch 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 to hold the cartridge and cartridge retainer in place in the assembly. 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.

75. Body. *a*. The body (fig. 68) is a cylinder with external threads on one end for assembly to the end cap and internal threads on the other end for assembly to the breech. The body houses the cartridge at the breech end and houses part of the piston at the other end. The remainder of the piston is housed in the end sleeve.

b. The maximum pressure which the threaded area (between the end cap and the body) will withstand is calculated by using equation (11).

(It is assumed that the body will be made of 705T6 aluminum.)

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

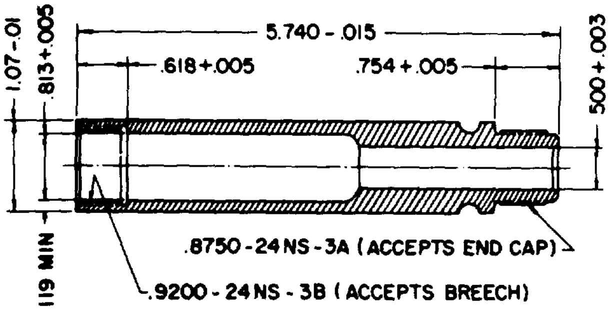


Figure 68. Body of thruster.

therefore:

$$P=\frac{LS_sd}{3R^2}$$

$$P=\frac{0.57\times 46{,}000\times 0.824}{3\times\left(\frac{0.875}{2}\right)^2}$$

$$P=37{,}800 \text{ psi}$$

In the bypass pressure example calculated above for the M3A1 thruster, the peak pressure is only 5700 psi; therefore, the threaded connection will withstand over six times the estimated peak pressure.

c. The wall strength equation (equation 8)† 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.

d. 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 (which provides the highest stress) is used.

$$P=Y\times\frac{W^2-1}{(3W^4+1)^{1/2}} \qquad (10)$$

Where:

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

$$=1.16 \text{ (at undercut of threads, cartridge end)}$$

or

$$W'=\frac{0.824}{0.500+0.003}$$

$$=1.64 \text{ (at undercut of threads, piston end)}$$

$$P=66{,}000\times\frac{1.16^2-1}{[3(1.16)^4+1]^{1/2}}$$

$$P=\frac{8{,}900}{1.15^{\ddagger}}=7{,}700 \text{ psi}$$

On the basis of these calculations, it is apparent that the body, as designed, will withstand the maximum pressure developed (5,750 psi).

76. End Cap. *a.* The end cap (fig. 69) is a short aluminum cylinder with internal threads for attaching the body. A bypass port projects 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.

b. 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-inch interference fit (fig. 69) which extends for 0.1 inch, absorbs most of the kinetic energy of the piston before it strikes the stopping shoulder in the end cap. Tests must be conducted to determine whether the proposed interference fit and shoulder are capable of stopping the piston without causing permanent deformation to the end cap or the piston.

77. Piston Assembly. *a.* The piston assembly 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. 70) 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 inches of the piston are hollow, and the piston locking spring is inserted in this section.

b. The design of the piston locking spring requires a force of 20 pounds 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 assembly, it is described with the locking mechanisms because it contains the locking keys.

c. 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

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

‡ Safety factor.

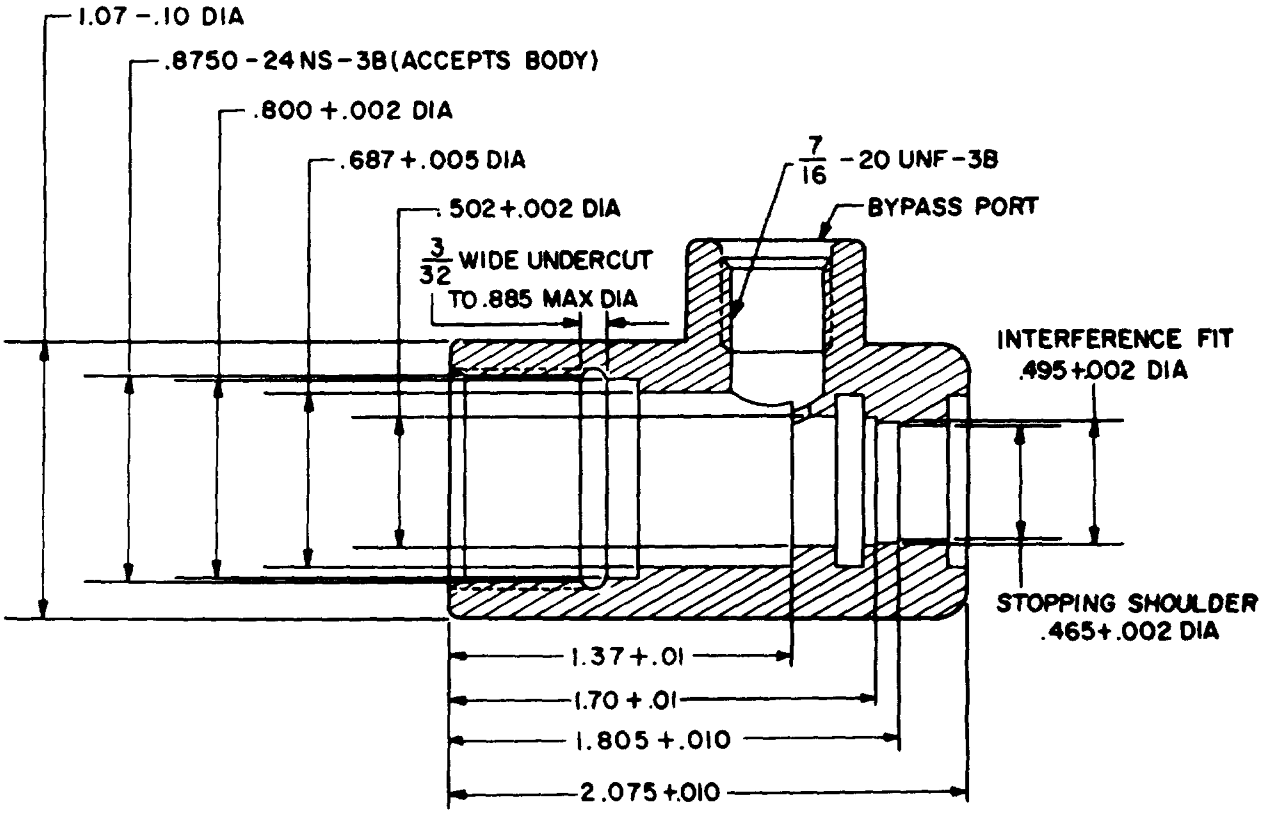

Figure 69. End cap of thruster.

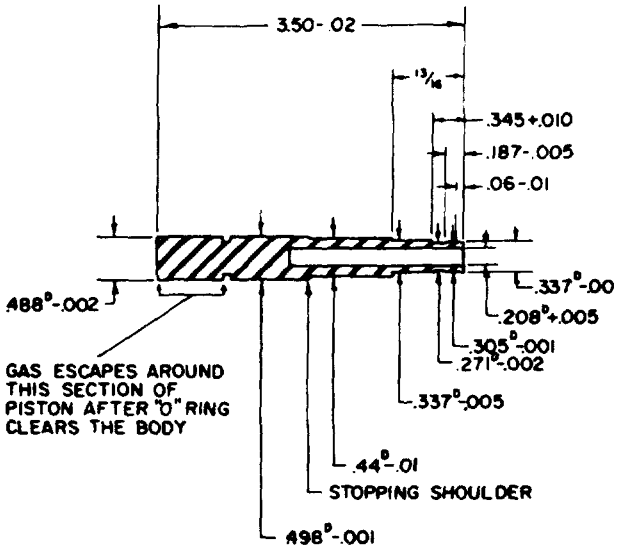

Figure 70. Piston of thruster.

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 steel † and has a slenderness ratio of 22. The slenderness ratio (L/*k*, where L is the length and *k* is the radius of gyration) is found as follows:

$$\text{ratio}=\frac{L}{k}$$

Where:

L = the length of the piston taking the maximum load is 2.7 inch, i.e., 3.5 − 13/16

$$k=\frac{\sqrt{OD_{\min}^2+ID_{\max}^2}}{4}.$$

assuming the hole extended the length of the piston.

$$k=\frac{\sqrt{0.43^2+0.213^2}}{4}=0.119$$

$$\text{slenderness ratio}=\frac{2.7}{0.122}=22.7$$

---

† The modulus of elasticity for steel Is approximately 30 million psi; the modulus of elasticity for aluminum is only about 10 million psi.

d. Steel 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:

$$F=SA$$

$$F=125{,}000\times\frac{\pi}{4}\,(0.43^2-0.213^2)\times\frac{1^\dagger}{1.15}$$

$$F=11{,}800 \text{ pounds}$$

78. End Sleeve and Locking Mechanism. *a.* 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. 71) which are equally spaced around the circumference of the end sleeve.

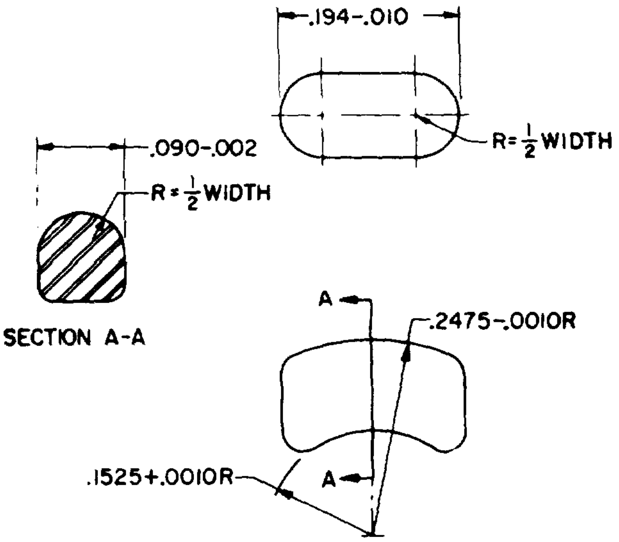

Figure 71. Locking key for thruster.

b. Due to the 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 fully realized 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 greater because the deformed metal obtains some support from the end sleeve.

c. The load capacity under certain sudden unsustained loads is greater than the permissible bearing loads within the elastic region. The criteria used for inspection is that the unit shall not unlock under the suddenly applied load, 800 pounds 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 is, therefore, obtained by experiment. Figure 72 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 pounds, which is the load required in the specifications.

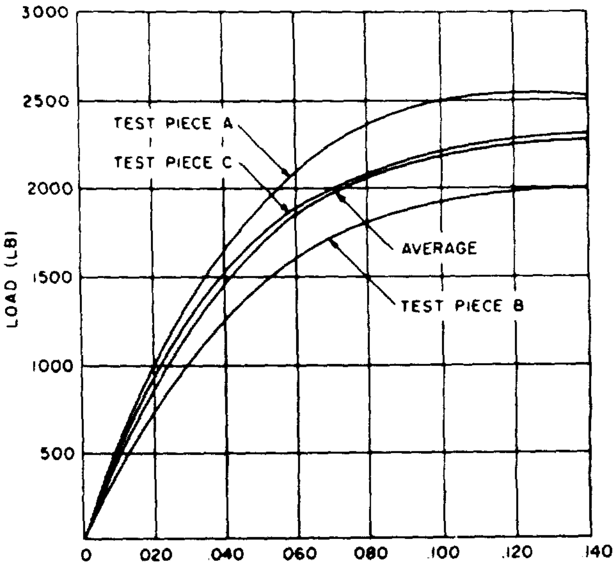

Figure 72. Load deflection curves for keylock mechanism.

d. 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:

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

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† Safety factor.

t = wall thickness
F = maximum load
N = number of webs
S_r = tensile stress
D = circumferential distance between slots

$$t=\frac{800\times 1.15^{\dagger}}{3\times 0.20\times 125{,}000}$$

$$t=0.013 \text{ inch}$$

e. The end sleeve may also fail in compression when the piston is moving the required load. The maximum compression force (F) due to thrust is:

$$F=PA$$

Where:

P = operating pressure (5,750 psi)
A = piston area
$=\left(\frac{\pi}{4}\times 0.488^2=0.19 \text{ in.}^2\right)$
$F=5{,}750\times 0.19=1{,}090$ lb

The minimum thickness for the walls of the sleeve to withstand the compressive force is calculated in the same manner as for the tensile force:

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

$$t=\frac{1{,}090\times 1.15^{\dagger}}{3\times 0.20\times 125{,}000}$$

$$t=0.017 \text{ inch}$$

The walls of the end sleeve are, therefore, made thicker than 0.017 inch.

79. Breech. *a.* The breech (fig. 73) 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 boss to fit the cartridge head. The firing pin protrusion beyond the face of the breech is 0.058+0.010 inch. 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. On the outside of the breech are two sets of threads. The smaller thread accommodates the cartridge retainer, and the larger thread accommodates the body of the thruster.

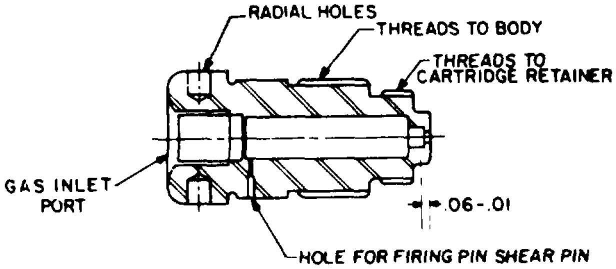

Figure 7. Breech for thruster.

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

80. Firing Mechanism. The firing mechanism consists of a firing pin and a shear pin. The firing pin (fig. 74) is a small alloy-steel cylinder with a projection (tip) on one end and a slot on the other end. A radial shear-pin hole is located in the body of the firing pin. This hole accommodates a 0.040-inch-diameter shear pin which 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 X) and the travel was designed to produce the required 60 inch-ounces of energy to fire the 72M primer (table IX).

81. Trunnion. *a.* The trunnion on the thruster is similar to that used in the example of the catapult. The trunnion (fig. 75), located between the breech shoulder and the end face of the body, is free to rotate a full 360° to facilitate mounting the thruster.

b. In designing any trunnion, the pivots must be located in such a way that there is no free play (side slake) when the thruster is in the mounting; otherwise, the pivots will be exposed to bending stresses as well as

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† Safety factor.

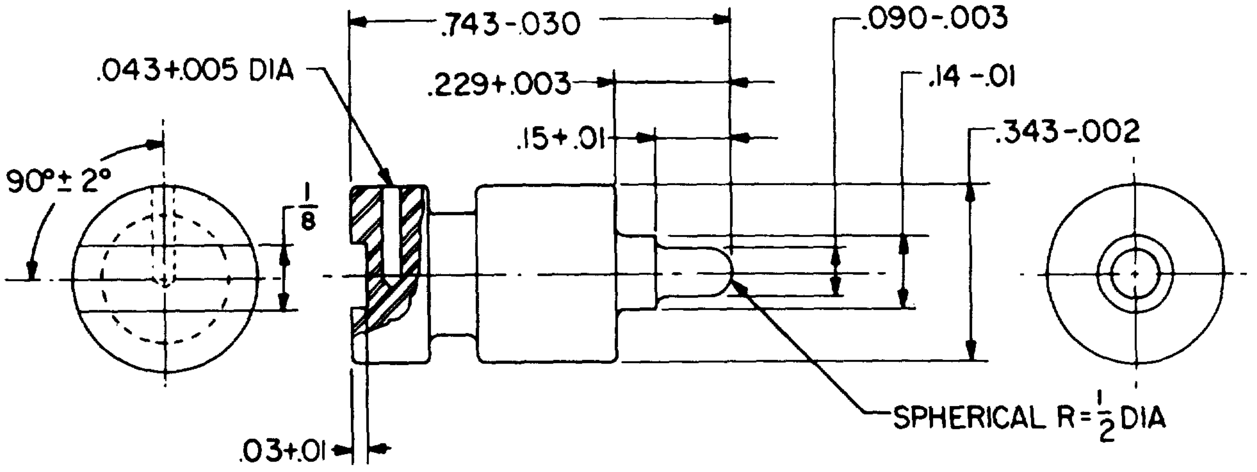

Figure 74. Thruster firing pin.

shearing stresses. Stress concentrations around the trunnion pivots should be minimized by avoiding sharp corners where the pivots join the trunnion ring.

c. 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 which the 0250-inch-diameter pivots can withstand is -

$$F=S_sA$$

Where:

F= maximum load

S_s= shearing stress (60 percent of yield strength)

A= area of one trunnion pivot

$$F=\frac{125{,}000\times0.6\times0.049}{2^{\dagger}}$$

F= 1,840 pounds

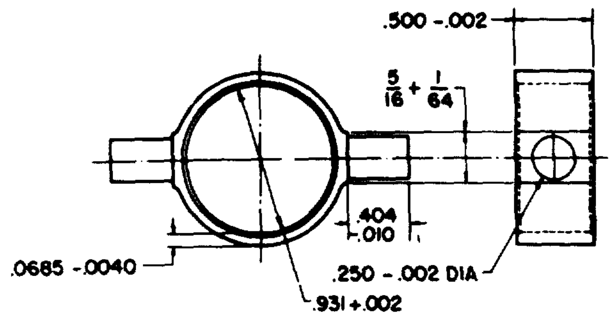

Figure 75. Trunnion for thruster.

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 0.060 X 0.500
A= 0.600 in.^{2}

Section IV. M4 INITIATOR

82. General. The M4 initiator (Delay-Initiator with Cartridge, Lap Belt Release, M4) was designed to operate a lap-belt release or other propellant actuated device. The initiator is operated mechanically and contains a 2-second delay element.

83. Design Requirements. The specifications for the M4 initiator include the following performance requirements and physical characteristics:

Operating temperature range	-65° to 160° F.
Envelope:	
Maximum length	6 inches.
Maximum width	3 inches.
Maximum thickness	2 inches.
Method of operation	Mechanical, with 20- to 35-pound pinpull.

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† Safety factor of 2 is used for structural member.

Lanyard travel	3/4-inch.
Generated pressure	1,500 psi in a 1.00 in.^{3} chamber at end of a 4-foot hose.
Ignition delay	2 seconds.

84. First Order Approximations. *a.* 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 which is to be generated in the pressure gage chamber and the volumes of the pressure chamber, hose, and initiator chamber.

b. The volume of the pressure gage chamber is specified as 1.00 cubic inch. The volume of the hose can be calculated by multiplying the cross-sectional area (0.0276 sq in.) by the length of the hose in inches, and the volume of the initiator can be estimated from the envelope dimensions.

c. The initial volume of the chamber (2.5 cu in.) is computed from its dimensions, taking into account the firing pin, housing, and cartridge retainer. When calculating initial volumes, the case volume is included in the initial volumes, since the instant the cartridge fires, the cartridge case opens and it becomes part of the internal volume.).

d. The computed volumes and equation (51) are used to determine the propellant charge. Since it generally is desirable to burn the propellant as rapidly as possible, a fast-burning propellant, such as M2, is selected. The charge weight is computed as follows:

$$P_t=\frac{12CF^{\dagger}}{V_c+V_t}\left[1-\beta-\frac{h_tS_t(\gamma-1)}{CF}\right] \qquad (51)$$

Where:

P_t = terminal pressure (1,500 psi)
C = charge weight (lb)
F = propellant impetus (3.6×10^5 ft-lb/lb)
V_c = initiator chamber volume (2.5 in.^{3})
V_t = hose and pressure chamber a volume (2.32 in.^{3})
β = heat loss factor (0.30)
h_t = heat loss in hose (27 ft-lb/in.^{2})
S_t = surface area of hose (30 in.^{2})
γ = ratio of specific heats (1.25)

$$1{,}500=\frac{12\times C\times3.6\times10^5}{2.5+2.32}\left[1-0.3-\frac{27\times30(1.25-1)}{C\times3.6\times10^5}\right]$$

$1{,}500 = 9.0 \times 10^5C(0.7 - 56 \times 10^{-5}C^{-1})$ $C = 3.2 \times 10^{-3}$ pounds = 1.5 grams

e. With this calculated charge, the locked-shut pressure may be estimated with equation (13).

$$P\approx0.0264\,\frac{cF}{V} \qquad (13)$$

Where:

c = charge weight (1.5 grams)
V = locked-shut volume of initiator (2.5 in.^{3})

$$P\approx\frac{0.0264\times1.5\times3.6\times10^5}{2.5}$$

$$P\approx5{,}700 \text{ psi}$$

f. The device, therefore, should be designed to withstand a maximum locked-shut pressure of 5,700 psi.‡ The approximations from which the charge is calculated must be accurate enough so that a total redesign of the components will not be necessary when the actual locked-shut pressure is determined.

85. Component Layout. *a.* A rough estimate of envelope size has been obtained during the first-order approximations. The firing mechanism and cartridge are designed to fit into the estimated envelope. The mounting flange, chamber, cap, firing pin, firing pin housing, cartridge, cartridge retainer, initiator pin, initiator spring, and firing pin release balls are designed in conjunction with the estimated envelope and firing mechanism and cartridge designs. Figure 76 shows the layout of components of the initiator.

b. The initiator is operated mechanically by exerting a 20- to 35-pound pull on the initiator pin.

The firing pin is locked to the initiator pin by 3 balls. Withdrawing the initiator pin retracts the firing pin, compressing the initiator spring. When the firing-pin-release balls pass from the smaller to the larger diameter bore in the firing-pin housing, the balls leave the initiator pin locking groove, permitting the initiator pin and firing pin to separate and the compressed initiator spring to drive the firing pin toward the primer. The firing-pin-release balls are returned to their original position in the recess as the firing pin moves into the smaller diameter bore. As the firing pin completes its travel, the firing pin tip passes through the small hole in the forward end of the firing pin housing, striking the cartridge. The motion of the firing pin is arrested by the

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† A factor of 12 is introduced to permit Pt to be expressed in psi.

‡ A workhorse model is fabricated to withstand a pressure far in excess of 6,000 psi and charge-verification firings are conducted. The calculated charge, 1.5 grams of M2 propellant, is the first charge used In the workhorse model. After the charge has been modified to meet the design requirements, locked-shut firings determine the actual pressure which the initiator must withstand.

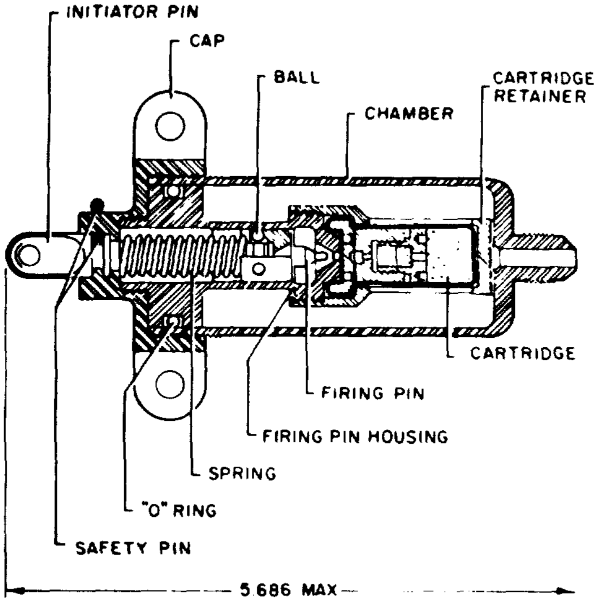

Figure 76. Initiator component layout.

closed end of the firing pin housing. The initiator (lanyard) pin withdraws completely providing a separation between the firing linkage and the initiator. When the firing pin strikes the cartridge, the primer fires and ignites the delay composition. After approximately 2 seconds, the delay charge is burned through, igniting the black powder (igniter) which, in turn, ignites the propellant. Gas generated by the burning propellant in the cartridge causes the cartridge case to rupture at the unsupported areas, and fills the chamber. The propellant gas is metered by the orifices (slots) in the base of the cartridge retainer and is discharged into the hose system.

86. Cartridge. *a.* Prior to choosing a cartridge case for the propellant charge, provisions must be made for the 2-second delay. Figure 77 shows the delay element developed for this initiator. Many standardized delay elements are available and practice is to use the standard elements, if applicable, rather than develop new ones. The delay element consists of four parts: the retainer, body, primer, and delay charge. The delay composition consists essentially of barium chromate, potassium perchlorate, and zirconium nickel alloy.

The delay time is controlled by variations of composition and weight. The mixture is pressed into pellet form and inserted, ill increments, into the delay body. A few tests were made and it was determined that approximately 1050 milligram's

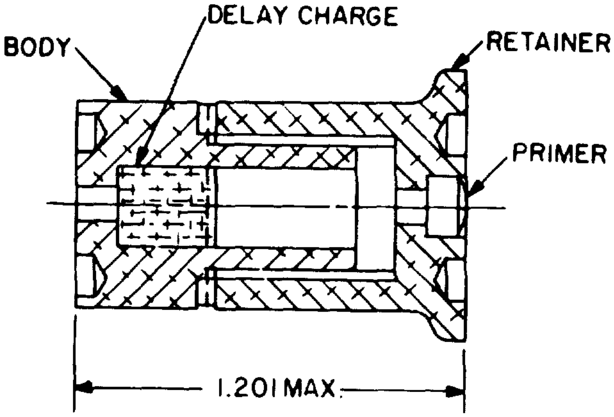

Figure 77. Delay element.

b. 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 igniter is ignited and in turn ignites the propellant. The length of the delay element is approximately 1.2 inches.

c. The cartridge case selected for the delay element and propellant charge had a body diameter of 0.687 inch and length of 2 inches (table VIII). This provided sufficient room for the delay element with its thick walls and allows room for the propellant and igniter and the necessary seals (fig. 78).

d. An M42 percussion primer was selected for use with the cartridge. This primer has an all-fire energy of 26 inch-ounces. The delay element for this initiator was later standardized as the M5, and the cartridge was standardized as the M46 delay cartridge.

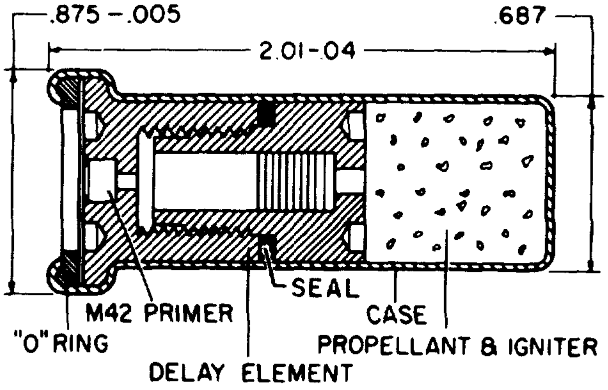

Figure 78. Initiator cartridge.

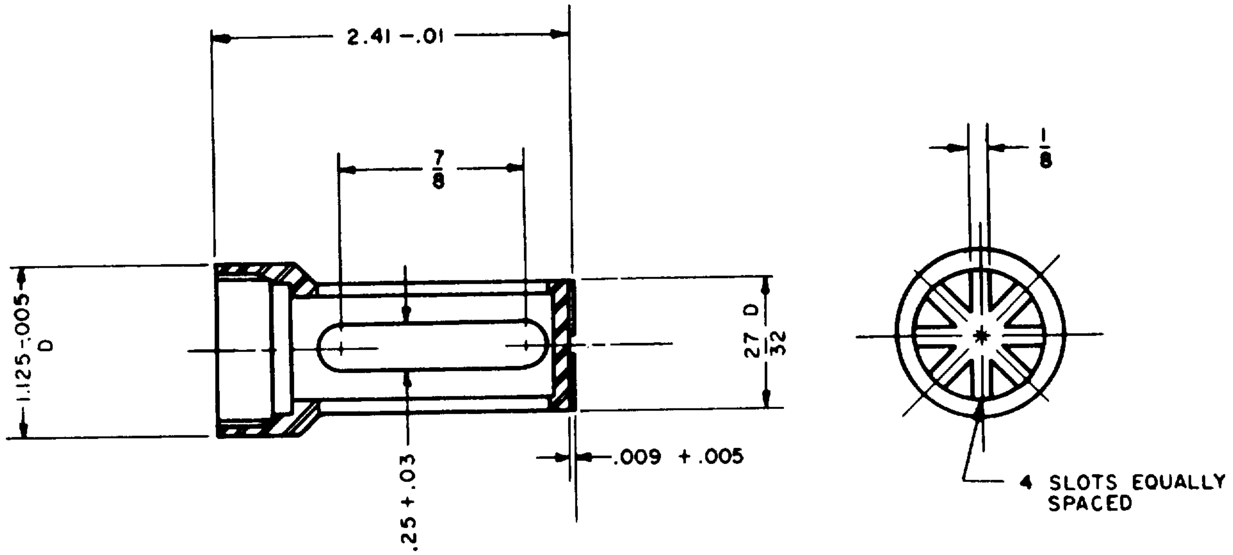

Figure 79. Cartridge retainer.

87. Cartridge Retainer. *a.* The cartridge retainer (fig. 79) is a steel cylinder designed to fit over and support the cartridge. The retainer also serves a second function: it has internal threads at its open end to accommodate the firing pin housing, maintaining firm contact of the housing and cartridge head.

b. Four longitudinal slots, machined in the retainer wall, permit the cartridge to rupture and the propellant gas to flow into the chamber. The closed end of the retainer (the part which supports the base of the cartridge) has four diametral grooves. When the initiator is assembled, the end of the retainer is positioned against the inside face of the exit port end of the chamber directly over the port, and the grooves form eight orifices to meter the propellant gas. Large particles of burning propellant, therefore, are restricted from escaping from the initiator, hose life is greatly extended, and gas flow is not blocked.

c. The wall thickness of the retainer must be chosen to withstand the pressure developed when the cartridge case is ruptured by the propellant gas. The case walls are sheared out or partially sheared out through the slots in the retainer wall when a force, F, is applied.

$F = S_3A$
S_3 = shear stress of 5052 aluminum (18,000 psi)
A = area in shear (periphery of slot X cartridge wall thickness)
$F = 18{,}000 \times 2.535 \times 0.025$
F = 1,130 pounds

This force (1,130 pounds) is calculated as being applied to the area in shear. The pressure applied to the total area of the slot (the pressure necessary to shear the case) will be 1,130 pounds per slot or 4,100 psi. Designing the walls of the retainer to withstand this internal pressure (assuming that the material between two successive slots is a beam with fixed ends) would result in a wall thickness of 0.120 inch. However, since the rate of loading is extremely high, and the balancing of pressures as the slots shear, occur so rapidly, the cartridge retainer may be made thinner without danger of failure. The cartridge retainer has 0.075 inch walls. This thickness was determined by tests.

88. Chamber (Body). *a.* The chamber (fig. 80) of the initiator is a cylindrical body open at the rear and closed

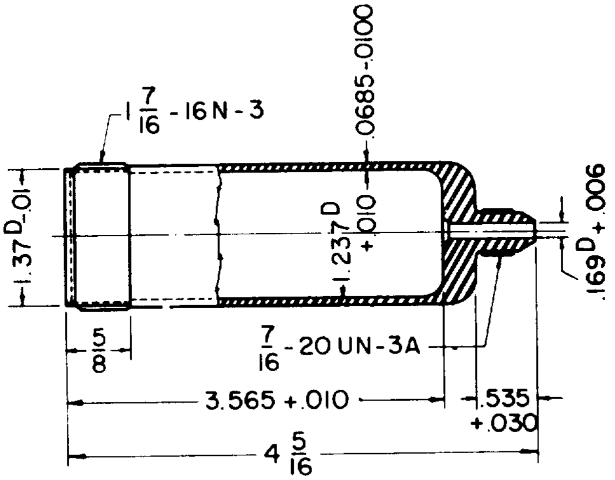

Figure 80. Initiator chamber.

at the forward end, except for the exit port. The exit port is a small projection located along the longitudinal axis of the device, having a standard flared tube fitting attachment.

The other end of the chamber has external threads for connecting the cap.

b. The wall thickness necessary to contain the maximum locked-shut pressure (estimated at 5,700 psi) may be found by using the curves of figure 23, sheet 1. The chamber is made of steel with a minimum yield strength of 125,000 psi. The pressure ratio, therefore, is -

$$\frac{P}{Y}=\frac{5{,}700\times 1.15^{\dagger}}{125{,}000}=0.052$$

Referring to the triaxial stress curve, the required wall ratio is found to be 1.044. Assuming that the outside diameter is to be made 1 3/8 inches, the maximum inside diameter may be calculated as follows:

$$W=1.044=\frac{OD}{ID}$$

$$ID=\frac{1.375}{1.044}=1.32 \text{ inches}$$

Since this size is based on the estimated locked-shut pressure, and the actual pressure may exceed this value, the wall thickness was doubled (0.068 inch). The thickness of the bottom of the chamber where stress concentrations are likely to occur was made considerably larger than the wall thickness.

c. Using equation (11) from paragraph 32, the length of thread engagement necessary to contain the locked-shut pressure may be found as follows:

$$L=\frac{3PR^2}{S_s d} \qquad (11)^{\ddagger}$$

Where:

L=length of thread engagement in inches
P=locked shut pressure (5,700 psi)
R=major radius of female (1.437/2 inches max)
d=minor diameter of male (1.351 inches min)
S_s=shear strength (60% of 125,000 psi)

$$L=\frac{3\times 5{,}700\times 0.718^2}{0.6\times 125{,}000\times 1.351}$$

$$L=0.08 \text{ inch}$$

Since the threads must be engaged by more than 0.08 inch to provide sufficient surface to meet torque, vibration, and sealing requirements, the length of engagement for strength is not the controlling factor. The length of engagement is made 0.4 inch to provide space for inserting Nylok pellets in the joint (para. 15).

89. Cap. *a.* The cap (fig. 81) serves both to close the chamber and to provide a mounting arrangement for the assembled unit. Two lugs on the flat edge of the cap provide space for mounting holes. The cap has two sets of internal threads: a large one for attaching the cap to the chamber and a small one for attaching the firing-pin housing to the cap. A boss with a hole through it is located on the outside face of the cap, and the initiator pin slides through this boss.

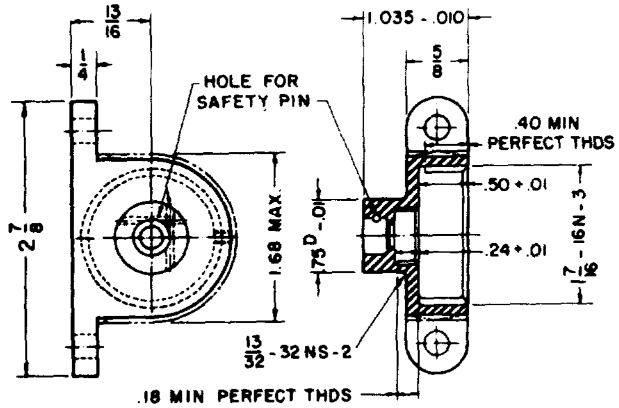

Figure 81. Initiator cap.

b. Two safety-pin holes, perpendicular to each other, pass through the boss so that a safety pin can be placed through the firing pin to prevent accidental firing of the device. Two holes are provided so the safety pin may be inserted parallel to the mounting flange or perpendicular to it.

90. Firing Mechanism. *a.* The mechanical firing mechanism consists of a firing pin, initiator pin, locking balls, and an initiator spring.

b. The firing pin (fig. 82) is a short cylinder with a projection on its closed end which is designed to protrude through an opening in the firing-pin housing to

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† Safety factor.

‡ A 1.5 safety factor is included in this equation.

strike the cartridge primer. The tip of the firing pin must be sufficiently long to indent the primer by the amount shown in table XI (0.025 to 0.030 inch). The rear face contains a 0.375-inch-diameter counterbore to accommodate the initiator spring, and a 0.250-inch-diameter long bore for the initiator pin. Three holes are spaced around the circumference of the firing pin for the locking balls which lock the firing pin and initiator pin together.

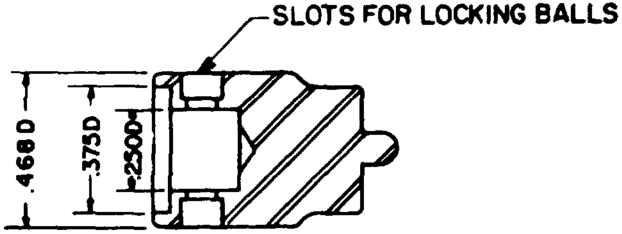

Figure 82. Firing pin for initiator.

c. The steel initiator pin (fig. 83) is a cylindrical rod with a groove on the small end and a flat section on the large end. A hole through the flat section is used to attach the triggering lanyard (or link) to the trigger. The safety pin groove is located on the cylinder near its flat section and is designed so that the initiator pin can be rotated 360° with the safety pin installed. The stopping shoulder is located forward of the safety pin groove. The remaining portion of the initiator pin is smaller in diameter and is positioned within the coils of the initiator spring. A groove is located immediately behind the forward face. This groove is used to lock the firing pin to the initiator pin by means of steel balls.

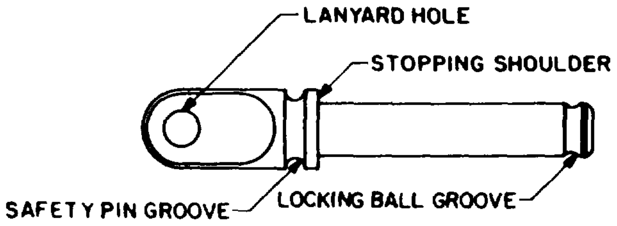

Figure 83. -Initiator pin (sear pin).

d. The initiator spring is designed to supply sufficient energy to the firing pin to fire the M42 primer in the head of the cartridge. The M42 primer has an all-fire energy of 26 inch-ounces (table IX). The force necessary to compress the spring (lanyard pull) must be between 20 and 35 pounds. Since the lanyard travel is specified as 3/4 inch (and "overtravel" must be provided to insure separation of the firing pin from the initiator pin), the spring should supply the required energy after being compressed approximately 5/8 inch.

e. To avoid kinking, the outside diameter of the spring should be made as large as possible. Since the outside diameter of the firing pin is 0.46 inch, it was decided to use a 3/8-inch-outside-diameter spring. Using arbitrary load-deflection tables, it is found that a helical spring with an outside diameter of 0.375 inch will have a 0.0604 inch deflection per coil under a load of 21.76 pounds when the spring wire diameter is 0.054 inch. This spring force is between the required 20- and 35-pound pull, so this spring may be used in the initiator. It has previously been determined that the spring should compress approximately 5/8 inch. Ten active coils should be used to provide this travel since the deflection of each coil is 0.0604 inch. This yields a total deflection of 0.604 inch. Assuming the ends of the spring will be squared and ground, the total number of coils necessary will be two more than the number of active coils, or 12 coils (total). The solid height of the spring will then be 12 times the wire diameter of 0.648 inch. (It is necessary to know the solid height because a spring should never be compressed to its solid height.) The free length of the spring may be found by adding the solid height to the total deflection (0.648 + 0.604 = 1.252 inches).

f. The firing pin should strike the primer before the spring reaches its free length, since the energy contained under the point of the curve diminishes as the free length is reached. This also insures that a preload can be established.

g. Figure 84 shows the spring curve for the initiator spring described above. It will be noted that the usable deflection (distance from "cocked" to "strike primer") is 0.500 inch.

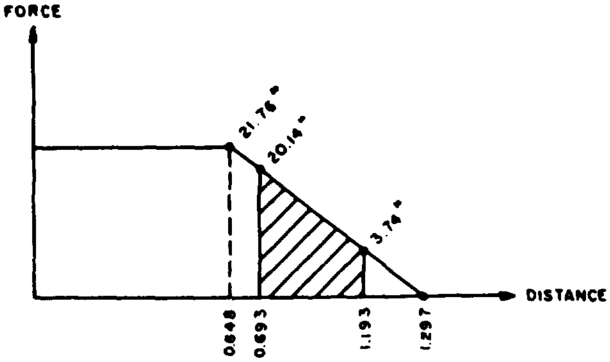

Figure 84. Spring force curve.

h. The energy (E) supplied by this spring is equal to the area under the spring force curve, or:

$$\mathrm{E}=\frac{20.14+3.74}{2}\times(1.193-0.693)$$

$$E=5.97\text{ in.-lb. or }96\text{ in.-oz.}$$

i. This is four times the energy required to fire the primer. A large amount of energy is lost overcoming friction but tests made with mock-up of this firing mechanism showed that sufficient energy was delivered to fire the primer. (The firing pin was propelled into copper crusher cylinders and the indent used to measure the energy delivered by the firing pin.)

91. Firing-Pin Housing. *a.* The firing-pin housing (fig. 85) is cylindrical in shape, open at one end and closed at the other or forward end, except for a small hole through which the end of the firing pin protrudes when it strikes the cartridge primer. The closed portion of the forward end acts as a stopping shoulder to limit the forward travel of the firing pin. The external face of the forward end contains a boss which is shaped to fit the contour of the cartridge head. Immediately behind the forward face a threaded flange is provided. The cartridge retainer is attached to the firing pin housing to insure "zero head clearance." On the outside diameter, the open end of the firing-pin housing is a large flange section which contains an O-ring groove. The O-ring prevents propellant gas from escaping from the chamber. A protrusion on the open end of the housing is threaded externally to provide a means of attaching the housing to the cap. The firing pin bore houses the initiator spring, the firing pin, the greater portion of the initiator pin positioned within the initiator spring, and the firing-pin-release balls. The open end of the housing bore has a larger diameter (fig. 85) to allow the firing pin-release balls to leave the retaining groove in the initiator pin, releasing the firing pin and permitting the spring to drive the firing pin toward the primer.

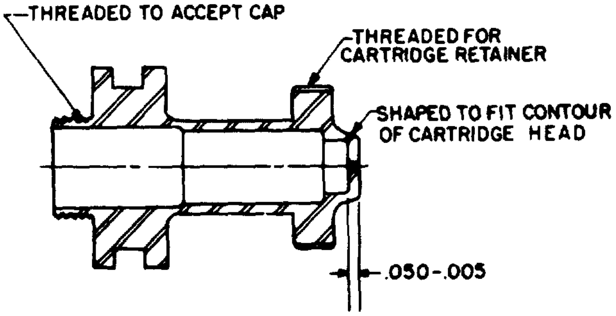

Figure 85. Firing-pin housing for initiator.

b. The firing-pin housing is not subjected to large stresses, but several areas must be manufactured to close tolerances. The dimensions of the closed end of the housing are critical, since they determine the firing-pin protrusion and they insure that the end configuration of the housing supports the cartridge when it fires.

CHAPTER 7

PERFORMANCE EVALUATION

92. General. *a.* Propellant actuated devices are evaluated to determine their compliance with design requirements. Design requirements may call for measurements of any or all of the following:
Velocity, acceleration, rate of change of acceleration, thrust, stroke, and pressure.

b. In the experimental development of propellant actuated devices, the task of obtaining an item with a high degree of reliability, while firing relatively few rounds, is a problem that is prevalent. For example, a seat ejection catapult may be developed while firing only 20 to 30 rounds. It is, therefore, necessary to plan the development program to give maximum statistical validity. Considerable success in this respect has been attained with the use of factorial techniques and analysis in the design of experimental programs with physical interpretations of data in terms of response surfaces. (A response surface gives a three-dimensional picture of response parameters such as velocity, acceleration, and rate of change of acceleration, as a function of ballistic and physical parameters, such as charge weight composition, and temperature.).

c. This chapter describes the instrumentation and basic test fixtures used in the ballistic and performance evaluation of propellant actuated devices, and presents sample evaluation programs. There are two basic evaluation programs: (1) development and (2) qualification analysis. The development phase includes firings with workhorse and prototype models to establish the charge and check newly designed components or complete devices. Qualification and analysis firings are conducted at the conclusion of the development program to qualify the design as usable, after which the design is released to production.

93. Instrumentation. *a. General*.

(1) The instrumentation is to a large extent determined by the design requirements, i.e., the instrumentation is selected generally to measure the performance characteristics which the device is designed to meet. It is desirable to measure several parameters simultaneously to permit cross checking the data obtained. For example, velocity may be measured directly with magnetic pickups and the results can be checked by integrating the acceleration-time curve. Pressure-time or thrust-time data can be converted to acceleration-time data for comparison with experiments. In a properly designed, maintained, and calibrated system, there will be little differences in the results obtained by these various methods. (Pressure-time curves normally give greater values than other methods because of internal friction.).

(2) If inconsistencies show up in the comparisons, either the basic data, the method of data reduction, or both are at fault. Performance evaluation should be, so far as possible, based on data obtained directly by use of accelerometers, pressure gages, and the like rather than on derived data, e.g., that obtained by differentiation or integration since some error inevitably creeps in as a result of the derivation methods, and this error in many cases may be extremely large.

(3) A simple block diagram of the instrumentation used for determining performance characteristics in propellant actuated devices is shown in figure 86. Several types of transducers are used to obtain various types of information.

(4) These transducers may be pressure gages of either the piezoelectric or strain-resistance type, load cells, or accelerometers. The coupling network and calibrator will depend on the type of

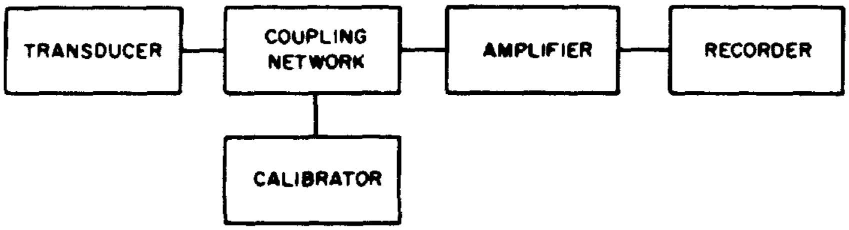

Figure 86. Teat instrumentation.

transducer selected while the amplifier may be the same for all transducers although a piezoelectric gage requires a special type (high-input impedance) of coupling stage.

(5) A number-of transducers and amplifiers are commercially available. Examples of several types of transducers and an amplifier are described in b through e below. As an aid in selecting a transducer, table XVI is presented. This table lists the possible calibration error (as listed by the manufacturer) for several types of transducers, and also lists the "possible total error" of measurement based on the assumption that a ±2 percent error may occur due to amplifiers, oscilloscope or oscillograph, and other instrumentation, as well as errors in observation. Furthermore, when using pressure gages to measure acceleration, there may be errors in the assumed relationship between pressure and acceleration, which may be arbitrarily set at ±0.5 percent.

Table XVI. Possible Errors Involved in Acceleration Measurement

Transducers	Minimum calibration error (percent)	Minimum error of measurement (percent)
Piezoelectric gage	±0.5	±3.0
Strain resistance pressure gage	±1.0	±3.5
Pressure pickup	±2.0	±4.5
Load cell	±0.5	±2.5
Accelerometer	±1.7	±3.7

(6) Propellant actuated devices generally are fired electrically to synchronize the firing with triggering of the associated instrumentation. A universal firing head using electrically fired primers has been designed to be inserted in the gas entry port of gas actuated firing mechanisms. Figure 87 shows the universal firing head. An electric primer, such as the M52A3, is held in place in the firing head by the primer retainer, maintaining contact between the contact on the head of the primer and the contact pin. The firing head is inserted in the gas entry port of the device to be tested and the firing and ground cables are connected to the firing head. When the firing circuit is closed, current flows through the contact pin and primer and ignites the charge contained in the primer. The gas produced by the primer operates the firing mechanisms of the propellant actuated device being - tested. The universal firing head may also be used to operate an initiator which, in turn, fires the propellant actuated device.

b. Amplifiers and Recorders.

(1) The amplifying system used may be of any convenient type, i.e., direct coupled or carrier frequency type. The primary requirement is that the amplifiers are kept linear, free of drift, and properly calibrated. An example of piezoelectric amplifier with an input impedance of 1,000 megohms or greater is shown in figure 88.

(2) The recorder may be a combination of oscilloscope and still camera or high

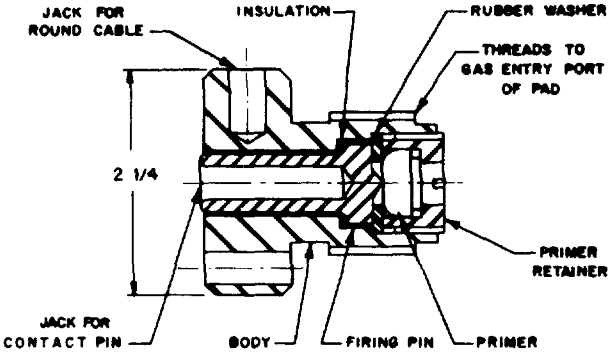

Figure 87. Universal electric firing head.

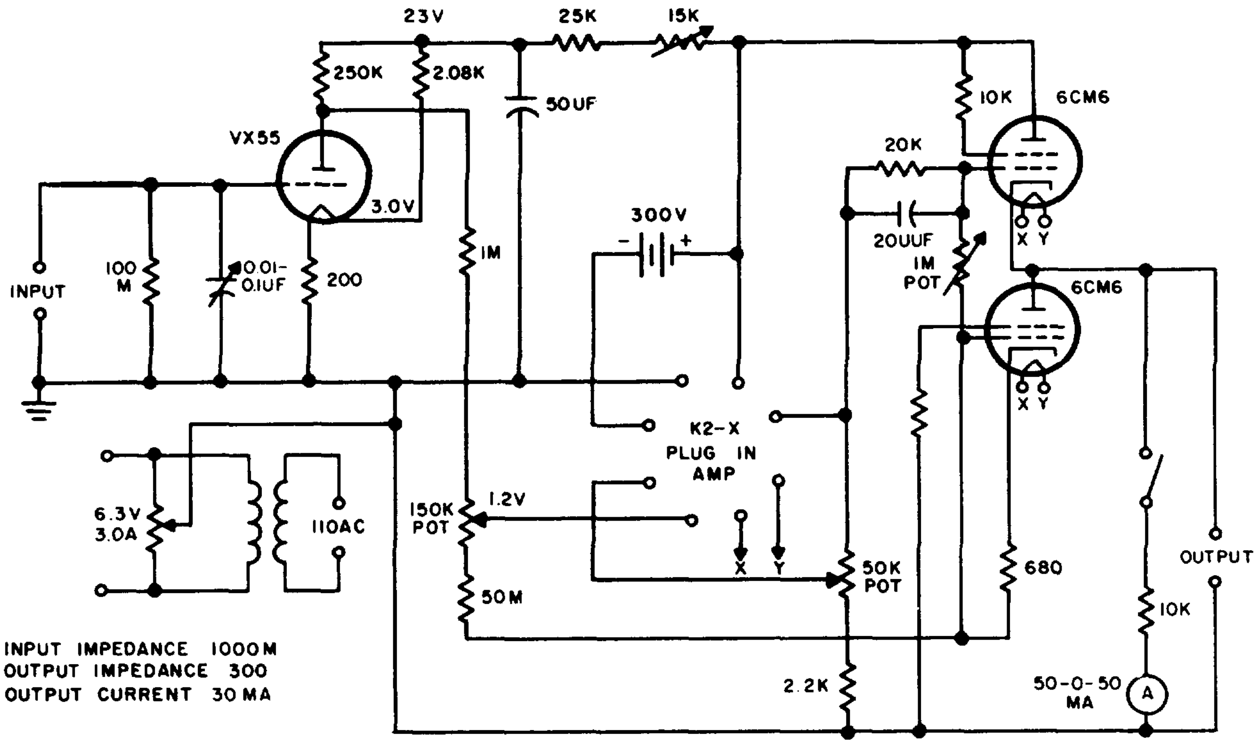

Figure 88. Piezoelectric amplifier.

speed moving film camera. More desirable is a multichannel oscillograph since many simultaneous curves can be obtained. The recorder must have a suitable frequency response. If filters are included to eliminate noise from the record, they must be so chosen that they will not significantly distort the data.

c. *Prepare Gages.*

(1) Piezoelectric gage.

(a) The piezoelectric gage is a device which contains discs of quartz (crystal) and collecting electrodes (steel) so disposed that mechanical force applied to the gage results in the generating of an electric charge proportional to the force. The chamber gas pressure acts upon a piston which compresses the crystal. A typical gage used in propellant actuated device evaluation generates a charge of about 0.01 microcoulomb per 500 pounds of force. A capacitor is connected across the terminals of the gage, and the voltage across the capacitor is measured to determine the force applied to the gage. This capacitor must be of laboratory precision grade. A pressure pulse in propellant actuated devices may have a duration of about 1 second; therefore, the time constant of the gage circuit must be of about 100 seconds for adequate accuracy. Since suitable capacitors are not available in sizes larger than about 1/10 microfarad, this means that the input resistance must be of the order of 1,000 megohms. The piezoelectric gage is capable of very high frequency response and is very rugged.

However, they are difficult to use in the field because of their extremely high-Ii input impedance and the maintenance they require. Barium titanate gages are not satisfactory for these applications.

(b) The gage must be designed so that it has a frequency response high enough that the pressure-time curve is not distorted.

(c) Piezoelectric gages have been used more extensively in testing propellant actuated devices than any other transducer since they are the only type that will consistently stand up under high rates of

pressure rise, shocks, and vibrations of typical firings. Errors resulting from the use of piezo-type gages are the result of friction of the gage piston and the possible pressure gradient within the device. With the addition of errors due to the nonlinearity of amplifiers, oscilloscopes, or oscillographs and film shrinkage, the data. may be in error by ±3 percent under the best possible field conditions.

(2) *Strain Resistance Gages*.

(a) The active element of a typical strain resistance pressure gage is a thin-walled ferrule. Bonded to the exterior of the ferrule is a winding of fine resistance wire. As the pressure increases, the ferrule expands, straining the wire winding and increasing its electrical resistance.

(b) Another type of strain resistance pressure gage used in testing propellant actuated devices is the pressure pickup. At one end, the pressure pickup has a diaphragm which is acted upon by the pressure in the chamber of the propellant actuated device. Inside the gage, a steel strain tube contacts the diaphragm. Two 1,000-ohm single layer strain-gage windings are cemented to the tube in such a way that straining the tube increases the resistance of one winding and decreases the resistance of the other.

(c) Strain-type pressure gages are low impedance devices. They are not so susceptible to moisture as are piezo-type transducers and do not require high-input impedance amplifiers. They have the disadvantage, however, of not standing up as well as piezo gages under repeated firings. They also have much lower frequency responses.

(d) Other models of strain resistance pressure gages have all four of the strain gage windings mounted within the gage (as in the load cell to be discussed next). They may be bonded or unbonded. The unbonded type have a higher frequency response but are very susceptible to damage when used on propellant actuated devices.

d. Load Cells.

(1) The load cell uses a high-strength load carrying member as its sensing element to which four strain-gage windings connected in the form of a Wheatstone bridge are bonded. The load cell, mounted opposite the stroking end of the propellant actuated device, measures reactive thrust.

(2) A schematic diagram of a coupling network which may be used with any bridge type gage, such as the pressure pickup, accelerometer, load cell, etc., is shown in figure 89. This circuit, when used with the load cell, produces a thrust-time plot on the recorder.

(3) Figure 90 is a reproduction of a catapult performance (thrust-time) curve obtained with a load cell. The shift in the base line is explained by the fact that at the start of the record, the cell was loaded with the weight of the carriage and device while at the end of the record the weight of the carriage and part of the device were absent. The "noise" appearing at the start of the curve probably is caused by a shock load on the cell at the start of motion. The "noise" on the rising portion of the curve probably results from mechanical imperfections of the carriage track system. The disturbance which appears after the curve peak is caused by the sudden stopping of the telescoping tube of the device at the end of its travel. The second curve shown in figure 90 is a stroke-time curve. Each peak on the stroke-time curve represents one inch of travel. The lines to the left of the curves are record calibration lines. Each space between the calibration lines represents 1,000 pounds of thrust. "Calibration" marks are placed customarily on each photographic record at the time the record is made by applying appropriate signals through the coupling network.

(4) Load cells are used to produce thrust-time curves. This data may also be converted to pressure-time curves, since the area of the stroking member of the device is known. Thrust-time data also are used in determining acceleration or velocity at

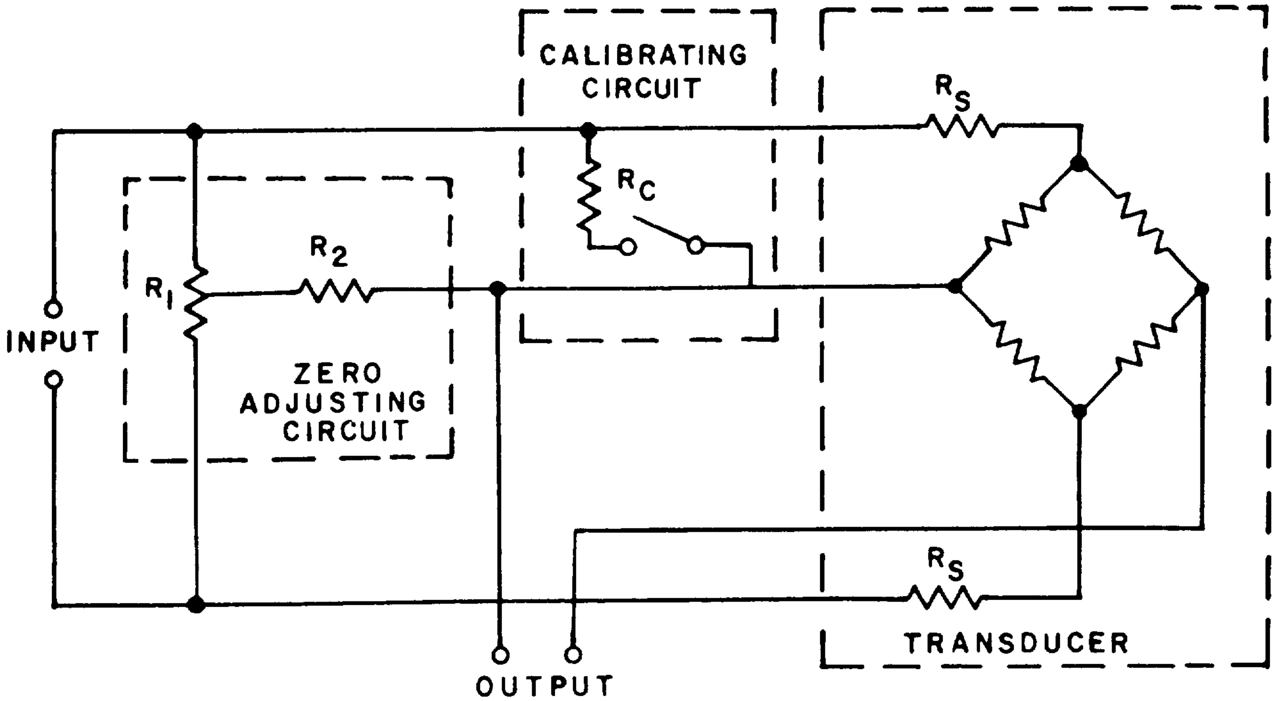

Figure 89. Coupling network for use with bridge-type gages.

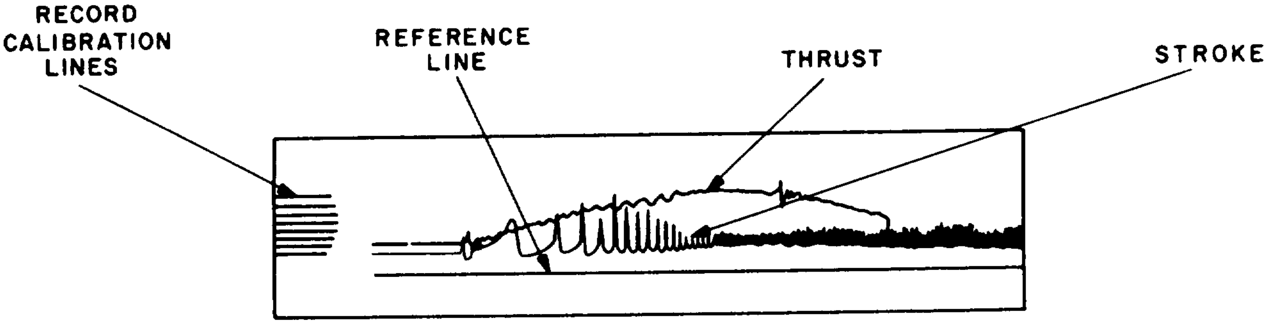

Figure 90. Moving film oscillogram record of travel and thrust vs time .

separation or at. the end of stroke. It is unnecessary to modify a propellant actuated device to adapt it to use of a load cell. The load cell does require a somewhat complicated mounting, however, since it must act as a structural link between the device to be tested anti a rigid mass fixed to the earth.

(5) Care must be taken in using load cells with propellant actuated devices, since they are essentially static measuring devices. While they have performed admirably on propellant actuated devices, repeated use, shock overloads, and excessive rise times will change the calibration of the cell or ruin it.

e. Accelerometer. Commercially available accelerometers recommended for use in connection with propellant actuated devices are of the straingage type. When a small mass in the accelerometer is accelerated, a force is developed which, when measured, indicates acceleration. Electrically, accelerometers are similar to the strain gages mentioned previously, except that the accelerometer must, move with the load instead of being stationary. Consequently, it must have long flexible leads and possibly disconnects. If used on a free-flight device, it may be damaged by the high deceleration encountered on landing. If used on a track, since the accelerometer is moderately sensitive to transverse acceleration, the track should be as smooth as possible.

f. Travel Measurement.

(1) Travel-time curves may be differentiated to determine velocity, acceleration, and rate of change of acceleration. However, the values obtained are relatively inaccurate. Several means are used to plot travel versus time: high-speed motion pictures, magnetic pickups, and variable resistors.

(2) The use of high-speed movies to determine travel time and all of its derivatives is obvious; in addition, movies also serve another purpose: they may be used to look for gas leaks or tube bending.

(3) Travel-time curves may be obtained by the use of a vertical tower, with a series of travel markers located along a track. The markers, are placed to mark 1-inch intervals along the region traversed during the power stroke of the device, and at 3-foot intervals beyond the power stroke. A magnetic pickup impulse generator is used as a marker. The magnetic pickup is 3/4 inch in diameter and 2 inches long. The stainless steel body of the pickup contains an Alnico magnet energizing a pole piece surrounded by a coil of wire. A voltage pulse is generated when its external magnetic field is distorted by the motion of an external ferromagnetic object. A steel arm extending from the carriage -and passing close to the pickups during carriage travel is used to create field disturbance in the measuring system.

(4) In place of a single steel arm, a steel comb may be fastened to the moving carriage to measure travel. This comb (toothed rod) consists of 23 teeth on 1-inch centers. A series of magnetic pickups (similar to those described above) is mounted along the track at 24-inch intervals. The pickups are mounted so that the teeth of the comb pass close to the pickups during carriage travel and generate impulses used to mark the 1-inch intervals of travel. A pulse-shaping circuit (fig. 91) may be used to couple the impulse generators to the recording instrumentation. (Many pulse-shaping networks are commercially available.) Figure 90 shows the record produced when the impulse generators are used as travel markers.

(5) Magnetic pickups may also be used to determine the velocity of a device at separation by triggering a counter chronograph with two pickups spaced a known distance apart. In the past, the velocity of propellant actuated devices at separation was determined by inserting

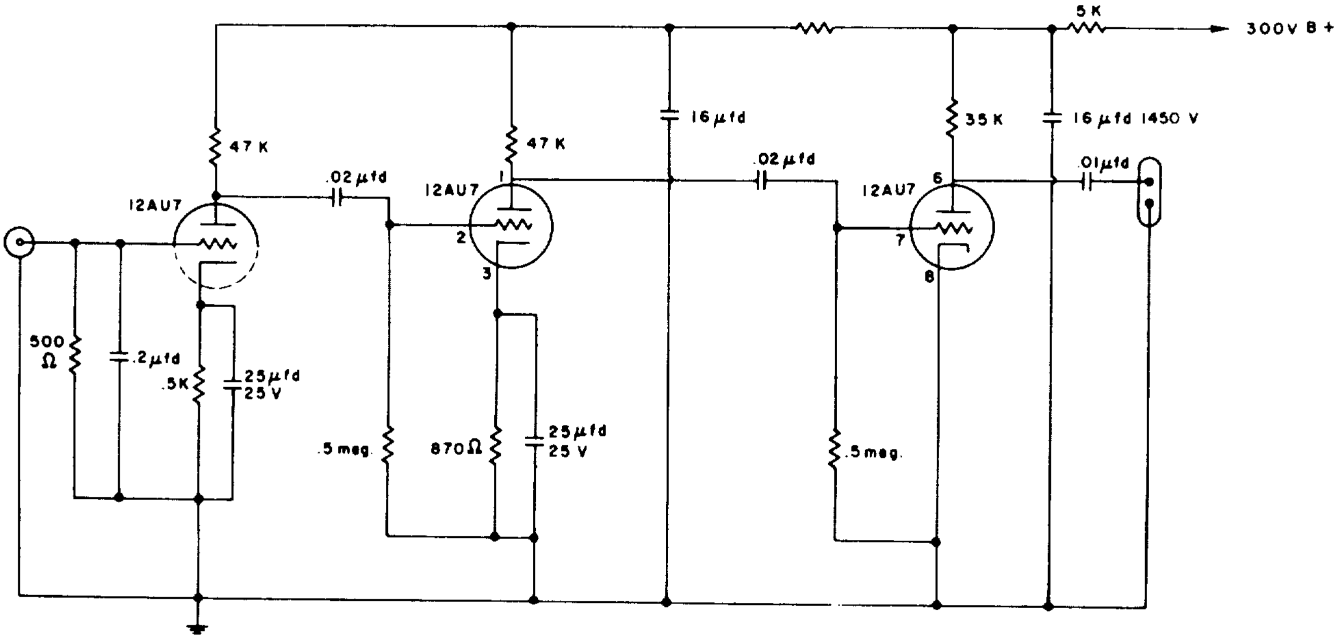

Figure 91. Shaping circuit used with magnetic pickup impulse generators.

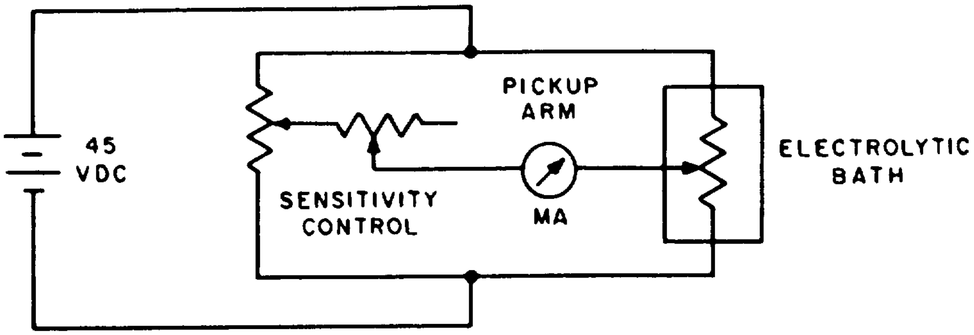

Figure 92. Schematic diagram of linear electrolytic positioning transducer.

carbon rods at specific intervals (arranged so they will be broken by transit of the carriage) and using these carbon rods as part of a "make" or "break" circuit to start and stop counter chronographs. Photoelectric cells have also been used in conjunction with counter chronographs.

(6) A recently developed linear electrolytic positioning transducer is shown in figure 92. This transducer consists of an insulated container filled with an electrolyte. One end of a pickup (wiper) arm is rigidly connected to the stroking member of the propellant actuated device, and the other end is suspended in the electrolytic solution. The transducer is connected to a helipot, to form a Wheatstone bridge, with the pickup arm acting as the balance (galvanometer) arm. The helipot. is used to balance the bridge. As the pickup arm moves, it unbalances the bridge. This unbalance is directly proportional to the movement of the arm, thus it is directly proportional to the stroke. A microammeter in the balance arm indicates the amount of bridge unbalance. The transducer is calibrated by simulating various amounts of wiper arm displacement and recording t-he meter readings at these points.

g. Velocity Measurements.

(1) Several methods of measuring velocity have been described above. These methods included integrating acceleration time curves and using counter chronographs, magnetic pickups, or other stroke-time markers. Although the methods already described are the most commonly used at the present time, a few of the original techniques are presented to suggest the many ways in which velocity may be measured.

(2) The velocity of a catapult load in free flight has been measured by measuring the time of flight from the moment of separation, when the catapult inner tube and the ejected mass move upward until the ejected mass falls to a horizontal plane a few feet above a recovery pit. To use this technique, the catapult is mounted a few degrees from the vertical and oriented with respect to the recovery pit. A light beam is directed across the trajectory of the weight to a photoelectric cell so that the beam is interrupted by the weight at a time corresponding to tube separation. This interruption starts a counter chronograph. As the descending weight passes through a plane of light slightly above the ground level, an amplifier is triggered causing the counter chronograph to stop. The velocity of the catapult at separation may then l)e computed using the following equation:

$$V_m = V_v + \frac{x^2}{2V_v t^2} \qquad (52)$$

and

$$V_v = \frac{gt}{2} - \frac{h}{t} + \frac{pg^2t^3}{48} \qquad (53)$$

Where:

V_m = velocity at separation
x = horizontal distance of flight
t = time of flight
g = acceleration due to gravity
h = difference in height between the beginning and end of trajectory
p = air drag force divided by ejected mass and velocity squared

(3) Another indirect method of measuring the velocity of catapults, which is useful when the propelled weight is fully guided, is to calculate the separation velocity on the basis of the height of travel. This may be calculated from the following formula if the height of travel of the ejected mass, h, and the acceleration, a, are known:

$$V_m = \sqrt{2ah} \tag{54}$$

The velocity determined in this manner is slightly lower than the actual velocity, unless a correction for friction is applied.

h. Typical Instrumentation Setup.

(1) A typical instrumentation setup permitting cross-checking of test results is presented in figure 93. When the firing switch (1) is thrown, current flows to the electric firing head (2), which fires the propellant actuated device (3). When the device is fired, the reactive thrust is measured by the load cell (4), and the internal pressure of the device is measured by the piezoelectric gage (5). The signals generated by the load cell and piezoelectric gage are passed through coupling networks (6), amplified (7), and fed into a dual-beam oscilloscope (8).

(2) The firing switch (1) not only fires the device, but supplies current to fire a thyratron (9), which triggers the scope, and therefore, synchronizes the sweep of the scope with the firing of the propellant actuated device. One-half millisecond time dots are generated by a time-mark generator (10), and after amplification (11), they are fed into the oscilloscope (8) in the form of Z axis modulation of the trace. They appear as dashes along the trace.

(3) Figure 94 shows a typical record obtained with the instrumentation described above. The sweep speeds of the oscilloscope were adjusted to separate the curves for easier reading. With most propellant actuated devices (particularly catapults), additional transducers are used and all curves are shown on a common time base by using a multichannel oscillograph as the recorder.

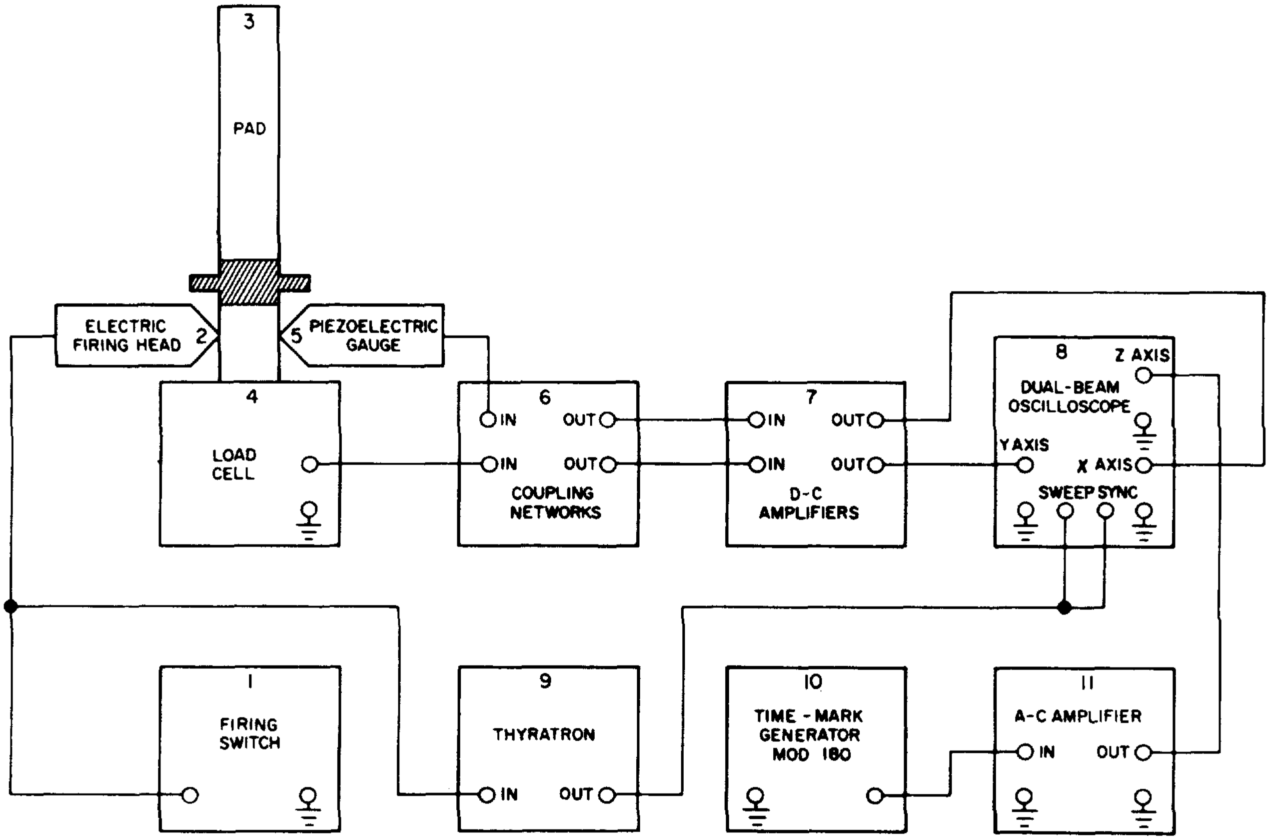

Figure 98. Complete test instrumentation block diagram.

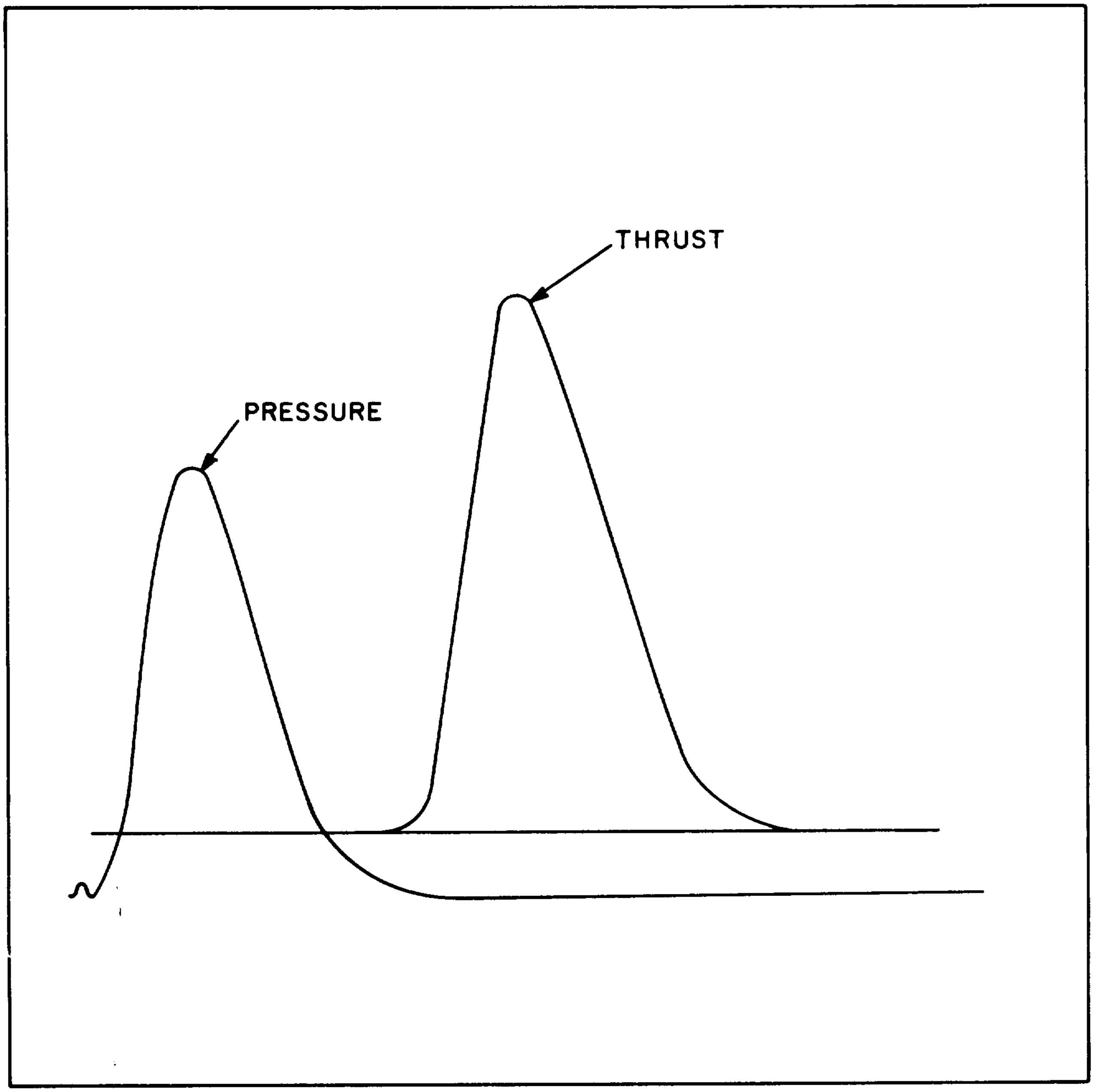

Figure 94. Oscillogram obtained with test setup of figure 93.

94. Fixtures for Performance Evaluation. *a. General.* Although an unlimited number of fixtures for propellant actuated device evaluation are possible, there are three basic types: simulated flight, constant load cylinders, and pressure chambers. A vertical tower is used to simulate flight conditions for evaluating removers, catapults, and some thrusters. A horizontal track is also used, particularly for rocker catapults. Constant load cylinders are used to apply force loads to thrusters over the entire stroke. Pressure chambers are used to measure the gas pressures generated by initiators and gas generators.

b. Vertical Tower.

(1) One of the most effective test fixtures for testing catapults and removers is the vertical tower. Catapults and removers can stroke against a load and propel the load upward along a vertical track. The

tower (fig. 95) uses a 150-foot vertical track (comparable to a vertical lathe bed) on which a carriage travels. Three carriages permit a weight range from 60 pounds to 1,200 pounds. One end of the propellant actuated device is secured to the base of the tower and the other end is attached to the carriage. When the device strokes, it propels the carriage up the track. At the 72-foot level, a pair of brake shoes on the carriage contact rails and decelerate the carriage. An endless chain, running the length of the tower, is normally 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 spins 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 to its starting place. The chain may also be driven upward to raise the carriage for adjusting the propellant actuated device, under test.

(2) The instrumentation used in tests on the vertical tower normally includes the following: a stroke marker and an accelerometer mounted on the carriage with a quick-disconnect, and a piezoelectric gage, load cell, and a pressure pickup as shown in figure 96.

(3) Another type of vertical tower is shown in figure 97. This tower consists of a 30-foot section of 12-inch ID tubing, supported by guy struts in two directions. The top of the tube is capped. There is a large vent hole at the 15-foot level, and the bottom is open for installation of the catapult and instrumentation. The catapult is installed on a base at the bottom of the tower, and a weighted piston (simulating the weight of the canopy or ejection seat and man) is lowered on the catapult. Upon firing, the catapult drives the piston up the tube; the catapult completes its stroke prior to the tower piston passing the vent hole.

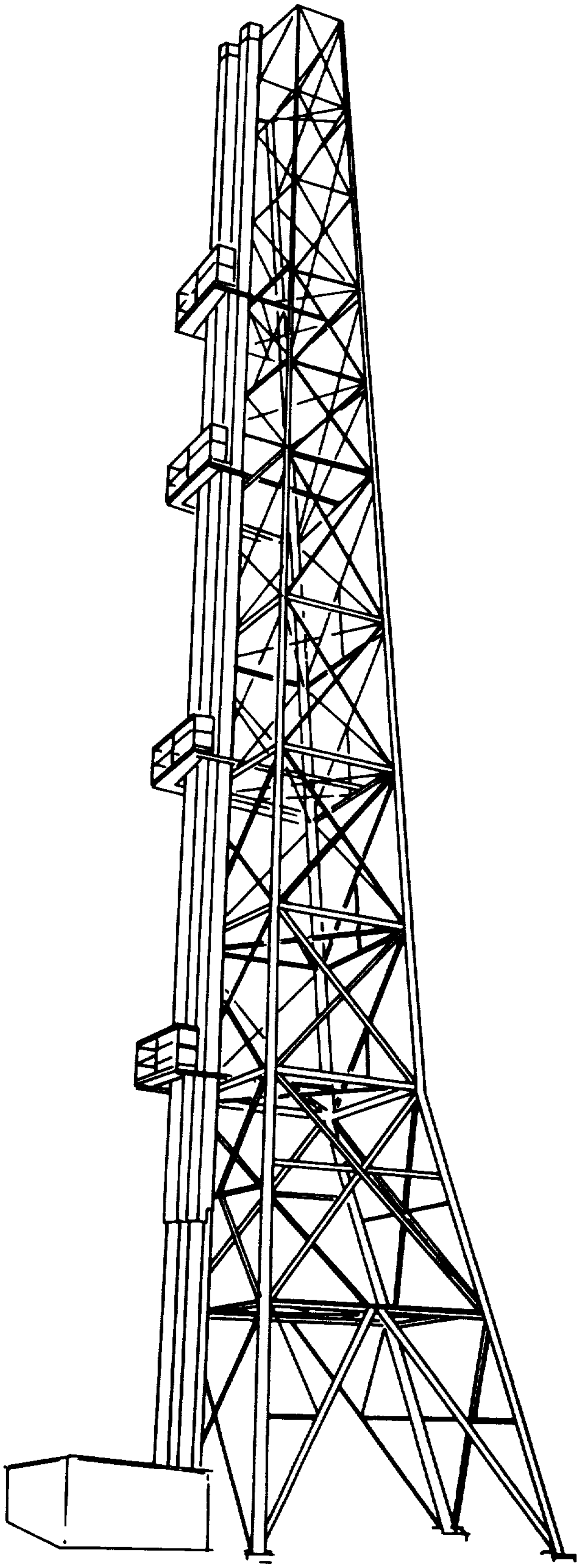

Figure 95. Vertical test tower.

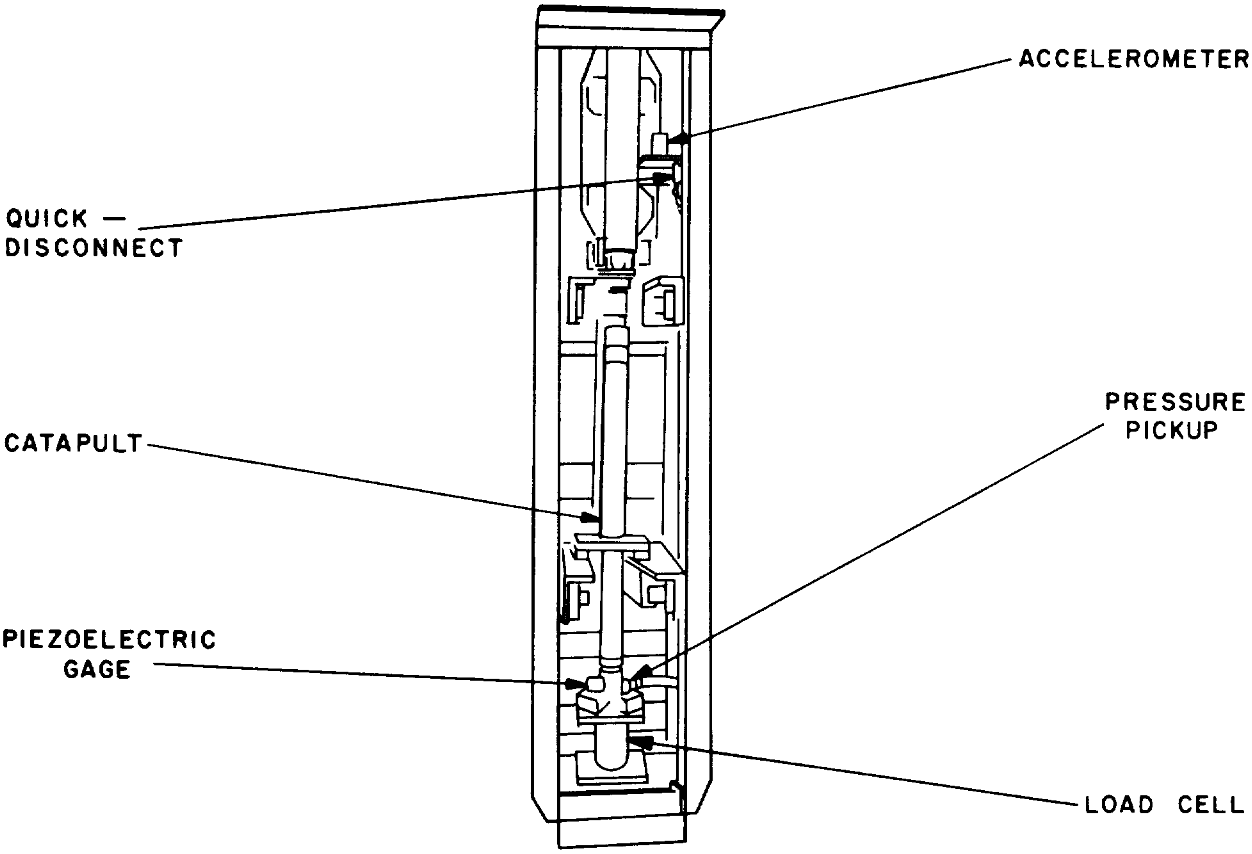

Figure 96. Test tower showing catapult, transducers, and wiring on test track.

As the piston continues past the vent hole, it compresses the air entrapped above it. The compressed air slows the piston and a spring loaded brake mechanism stops it downward motion after stopping.

c. *Pressure Cylinders.*

(1) The vertical tower is effective in testing propellant actuated devices with long strokes and relatively light loads, but many thrusters have short strokes and operate against constant loads of thousands of pounds. Pressure cylinders were designed to evaluate these thrusters. The thruster is positioned (fig. 98) so that its stroking member moves a piston ill a cylinder against pressurized air or some other gas. The initial volume of the cylinder is so large that the change in volume resulting from the moving piston is negligible. Therefore, the pressure in the cylinder (the load which opposes the motion of the thruster) can be assumed to be constant. Although many propellant actuated devices (thrusters in particular) operate against varying loads, the load requirements may be converted into terms of constant loads for the purpose of evaluation and development. _The conversion is possible by estimating $\overline{F}_r$ as in chapter 5.

(2) Figure 99 illustrates an air cylinder with an inlet at the end farthest from the thruster under test and permits injection of air or gas. This cylinder incorporates an 8-inch piston (50 square inches) and is used with air pressures as high as 100 psi. Other cylinders, similar in design to the air cylinder depicted, use nitrogen instead of air and may be pressurized to 2,000 psi.

(3) Another model cylinder utilized for testing thrusters is designed with a double acting piston which permits air or gas pressure to 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 the pushing type thruster. In either case, mechanical stops prevent the ' cylinder piston from returning to its initial position after the thruster completes its stroke. This method prevents damage not only to the device being tested but protects the instrumentation as well.

(4) As mentioned briefly in paragraph 93d, the strain-resistant type of load cells shown are subject to damage and nonlinearity when used for extremely fast rise time measurements. To overcome this problem, a hydraulic load cell was developed. This device, not illustrated, is made from a hydraulic jack which is modified by adding a pressure tap to the fluid chamber. The fluid pressure is measured by a pressure transducer.

(5) The stroke marker indicated in figure 100 is a lucite rod wound with nichrome wire. A voltage is impressed across this wire. The pitch of the windings is 0.1 inch. The wiper, driven by the thruster piston, contacts each turn of the wire as it moves forward, producing a series of electrical impulses for display on recorder.

(6) A rectilinear potentiometer can also be used in the conventional way to provide a stroke-time record. However, the high accelerations and vibrations of thrusters during the stroke often damage the potentiometer. Therefore, in spite of problems of wiper skip, the lucite rod stroke marker has proved more useful.

(7) The electrolytic bath type stroke marker, described in paragraph 93, instrumentation tion, may also be used.

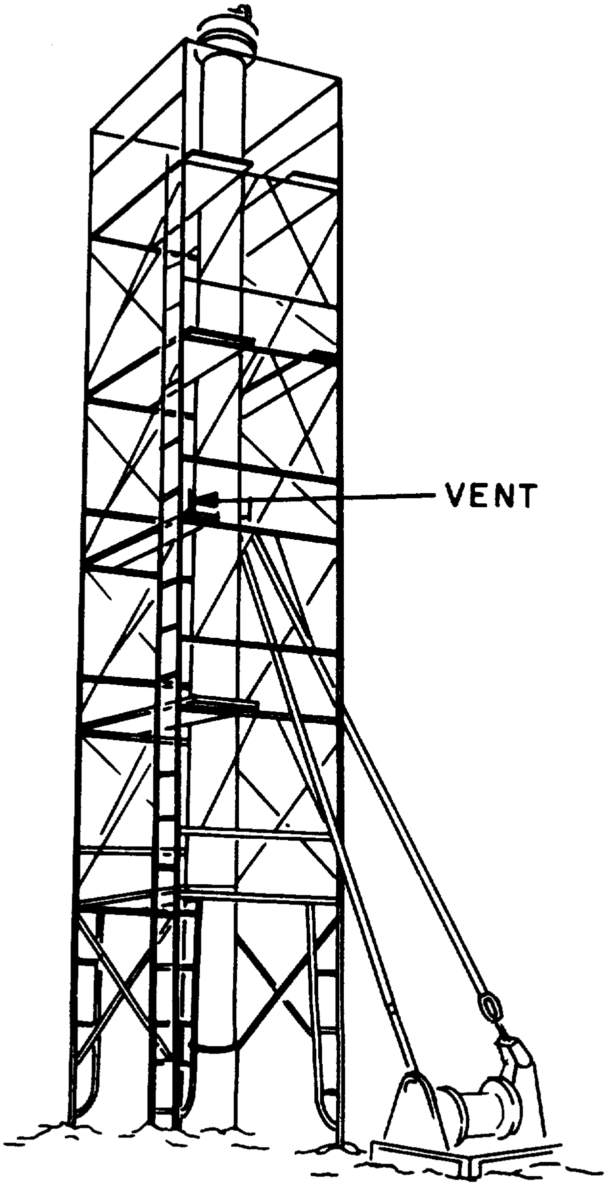

Figure 97. Another type of vertical test tower.

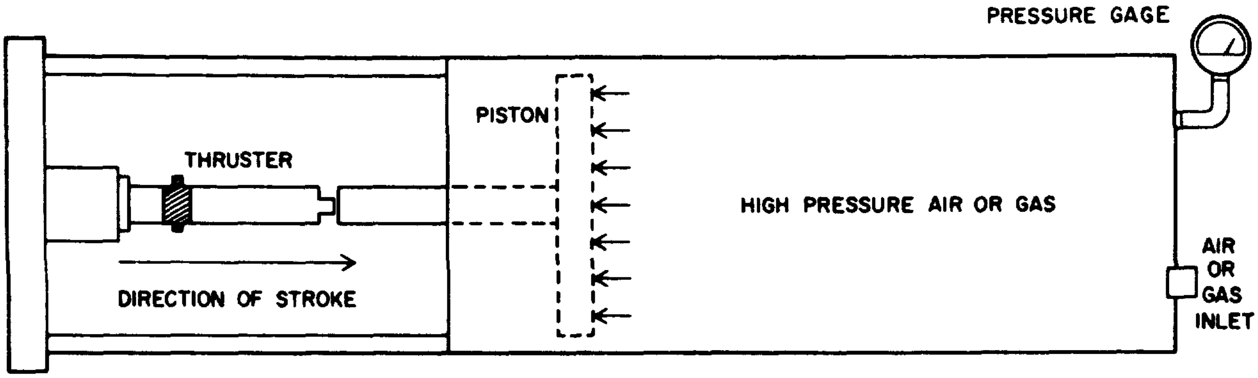

Figure 98. Pressure cylinder.

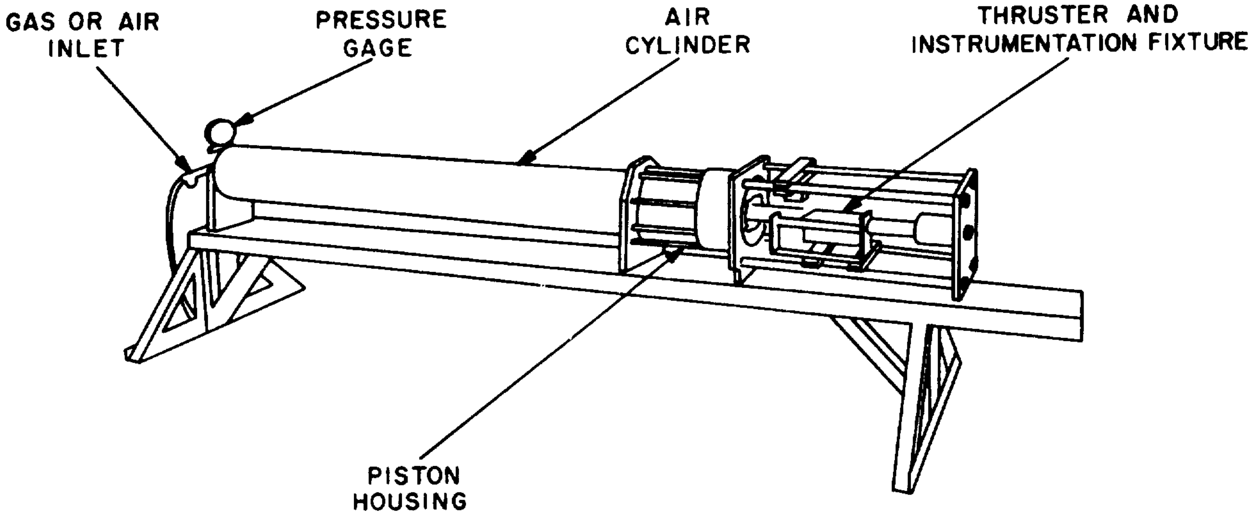

Figure 99. Air cylinder for testing propellant actuated devices.

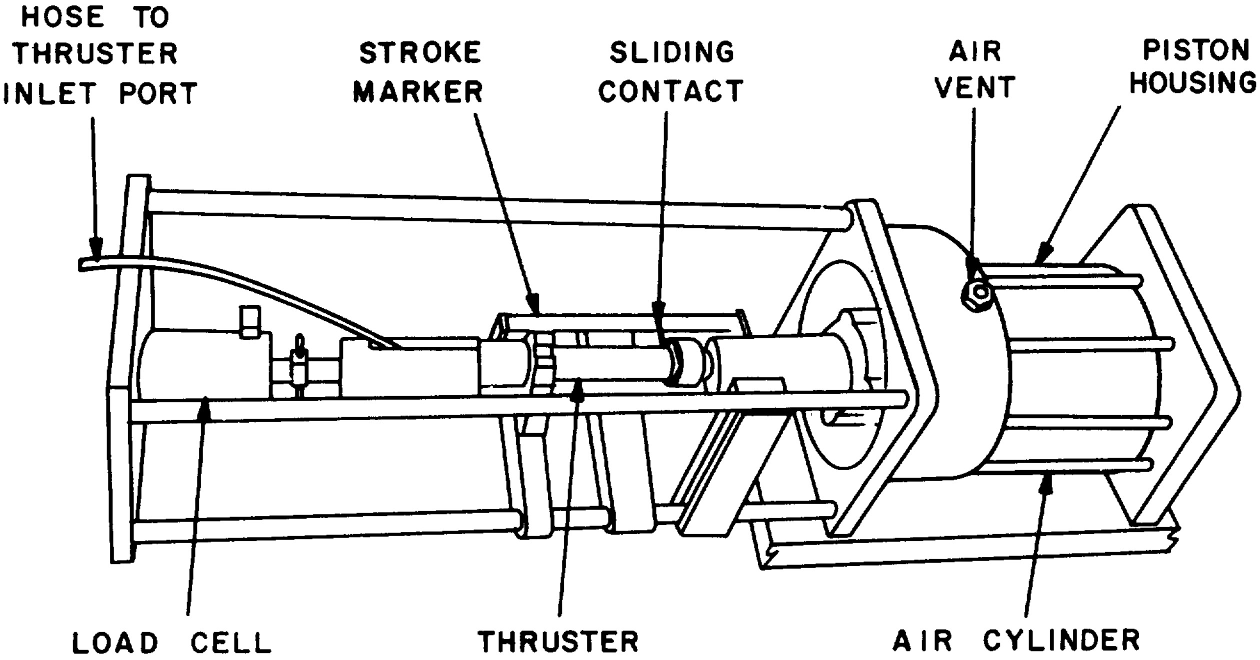

Figure 100. Thruster and instrumentation fixture.

This transducer is very sensitive, does not load down the thruster, and eliminates problems resulting from vibrations during the stroke.

d. Pressure Chambers. Pressure chambers are used for testing gas-generated devices. The fixture is a cylindrical chamber of a specified volume, usually 0.062 cubic inch of 1 cubic inch. The chamber is provided with 2 ports: one for the hose which leads the gas into the chamber, and the other to permit insertion of a piezoelectric gage or pressure pickup (fig. 101). The pressure-time curve produced with this instrumentation is used to determine peak pressure and time-to-peak pressure.

e. Leak-Detection Fixture.

(1) Ordinarily, cartridges are the only items which are tested for leaks. For this purpose, a radioactive tracer method is used.

(2) In this test, a sealed cartridge is placed in a pressure chamber and exposed to radioactive gas (Krypton 85). The difference between the internal and the

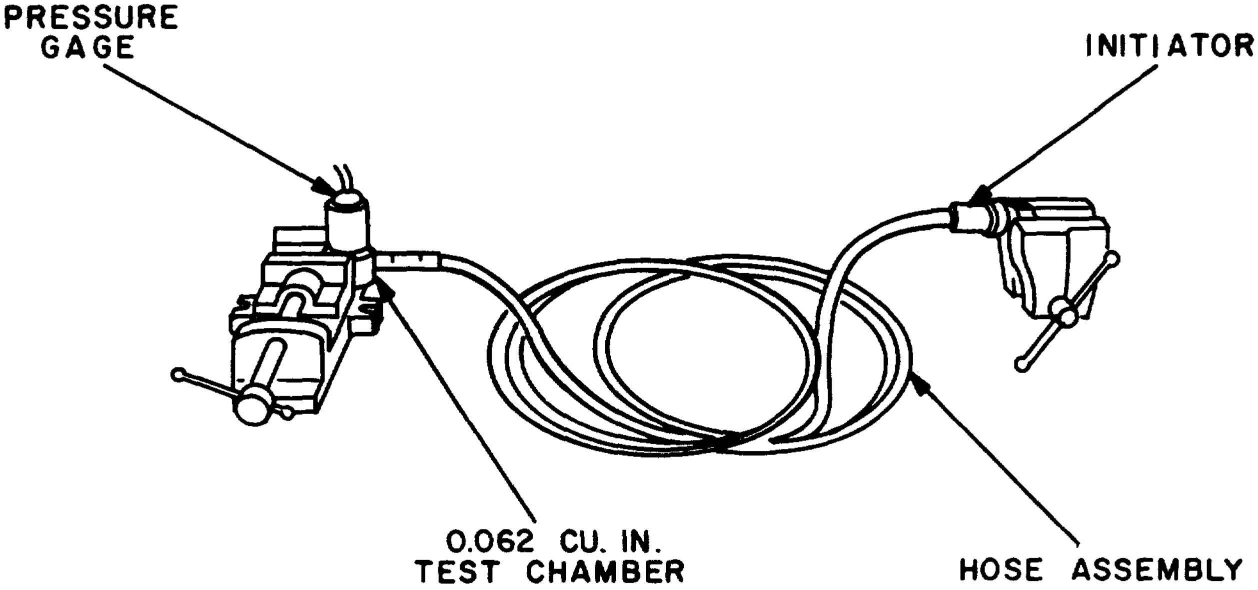

Figure 101. Teat setup for initiators.

controlled pressure of the Krypton gas causes radioactive gas to flow through any leakage paths. Cartridges that have leaked contain radioactive gas and emit small amounts of gamma radiation. The radiation is measured, which indicates the amount of material that has leaked into the cartridge. This process detects leak rates so small it would take an undetected leak thousands of years to leak one cubic inch of air into an evacuated chamber.

This test also may be used to test small propellant actuated devices for leaks.

95. Development Evaluation Program. *a. General.*

(1) 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.

(2) 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.

(3) The firings which must be conducted and the characteristics which must be recorded are determined by the design requirements. The following ballistic firing program 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.

b. Workhorse Model Evaluation.

(1 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 which may not be measured in later models; for example, it may be designed to accept pressure pickups or piezoelectric gages to record internal pressure.

(2) Normally, the following test program is utilized. 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° 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.

(3) 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.

(4) The satisfactory completion of these firings qualifies the device for prototype evaluation.

c. *Prototype Evaluation.*

(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.

(2) Structural evaluation program.

(a) 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.

(b) At least three units are vibrated in accordance with Military Specifications.

Three units which have been vibrated are dropped 6 feet 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.

(c) 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 is often used to test wall strength in catapult tubes.

(d) 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.

(e) 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 using the methods described previously under the heading "Leak Detection."

(f) If a failure occurs during the structural tests, the deficiency must be corrected before the program is resumed. The satisfactory completion of the structural evaluation program qualifies

the design for the second phase of the prototype evaluation program: performance evaluation.

(3) Performance evaluation program.

- *(a)* 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 below.
- *(b)* At least 10 firings at each temperature, -65°, 70°, and 200° F., are conducted to ensure 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 are usually done using only the cartridge and firing mechanism portion of the device.
- *(c)* 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.
- *(d)* Four prototype units are subjected to environmental conditioning. These evaluations include vibration, high- and low-temperature, temperature-shock-cycling, and temperature-altitude-humidity tests.
- *(e)* A new development program must be initiated if a failure occurs during any evaluation and a design modification is necessary. The completion of the development program qualifies the device for qualification and analysis evaluation (also referred to as final engineering evaluation).

96. Qualification and Analysis Evaluation Program.

a. General. The qualification and analysis program qualifies a propellant actuated device for use and terminates its development. Table XVII presents a list of the tests to be performed and the number of units and cartridges required for each evaluation. Since some units can be used more than once, about 40 must be fabricated for the complete program.

b. Structural Evaluation. A minimum of two devices are subjected to maximum tension and compression loads at -65°, 70°, and 200° F. after which the trunnions and initial looks are inspected for deformation.

c. Endurance Evaluation. Two units are subjected to cycling tests if the design requirements specify that the units will be subjected to alternating tension and compression loads. In these evaluations, 3,000 cycles of tension and compression loads are applied to each device. Each cycle consists of one maximum tension load and one maximum compression load.

d. Demagnetization Evaluation. All units submitted for qualification and analysis evaluation are checked for freedom from residual magnetism resulting from the manufacturing process.

e. Hydrostatic Evaluation. All units submitted for qualification and analysis evaluation are subjected to hydrostatic tests. The pressure chambers or tubes are mounted in a test fixture and subjected to internal pressures above the maximum pressure expected during service. The pressure is maintained for several seconds, during which the chambers or tubes are inspected for leaks. After each test, the chambers and tubes are inspected j for dimensional conformance.

f. Torque Evaluation. A minimum of two devices are checked for conformance with the torque requirements of threaded joints, as specified. The breakaway torque and running torque (if applicable) are measured for each unit. The units are assembled and disassembled and the torque measured again on the fifth, tenth, and fifteenth disassembly of each threaded joint.

g. Environmental Evaluation.

(1) Six assemblies are subjected to vibration tests, after which two units are disassembled and inspected for damage. All six assemblies then are subjected to salt-spray, sand-and-dust, high- and low-temperature, and temperature-shock evaluations. The 6 units and 15 additional cartridges are exposed to cycles of temperature, altitude, and humidity as illustrated graphically in figure 102. The device is exposed to the same cycle of temperature and pressure (altitude) for 5 days. On the seventh hour of the first day, moisture is introduced into the test

Table XVII. Qualification and Analysis Evaluation Schedule

Test	Temp (°F)	Cartridges required	Units required	Firings required	Remarks
Structural	-65	...	2	...	
	70	...	2	...	
	200	...	2	...	
Endurance	70	...	2	...	
Demagnetization	...	†All	†All	...	
Hydrostatic	70	...	†All	...	
Torque	70	...	†All	...	
Environmental	...			...	
Vibration	†All	6	6	...	The same 6 units through all environmental tests
Salt spray	...	...	...	...	
Sand and dust	...	...	...	...	
High temperature	...	...	...	...	
Low temperature	...	...	...	...	
Temperature shock	...	...	...	...	
Temperature-altitude humidity cycle.	...	15+6	6	6	Fire all cartridges as well as the 6 units.
Firing mechanism					
Mechanical	70	...	†All	...	
Gas	65- 6	...		...	
	70	...	6	...	
	200	...	6	...	
Electrical	65	...	20	...	Tested for no-fire and all-fire con -ditions.
	70	...	20	...	
	200	...	20	...	
Ignition system	-90	10	10	10	
Drop	70	3 Inert cartridges	3	...	
Locked shut	-65	2	2	2	Use units from drop test.
	200	8	8	8	
No-load	65	2	2	2	
	200	8	8	8	
Performance	-65	20	20	20	At least 5 new units for each tem perature group.
	70	20	20	20	
	200	20	20	20	

† "All" means every unit fabricated for qualification and analysis tests.

chamber to establish a relative humidity (RH) of 95 to 100 percent. This humidity is maintained for the remainder of the test.

(2) As soon as possible after completion of the environmental tests, two units are disassembled and inspected for signs of moisture or deterioration. If moisture is detected or if deterioration has progressed to the point where the unit may malfunction, the design must be modified and a new series of tests initiated. If the two units pass the test, they are reassembled and all six units are fired at -65° F.

(3) Five of the cartridges subjected to temperature, altitude, and humidity tests are disassembled and inspected for signs of moisture or deterioration of the propellant or primer charges. The remaining cartridges are fired (five at -65° and five at 200° F.) to check their functioning only, so it is unnecessary to record performance data. Should cartridge modification be necessary as a result of these tests, a new series of tests must be initiated.

h. Firing Mechanism Evaluation.

(1) Mechanical firing mechanisms generally are required to function when the sear (initiator pin) is pulled with a specific force. The sear actuation force may be determined by placing the device in a vise and pulling the sear with a spring scale.

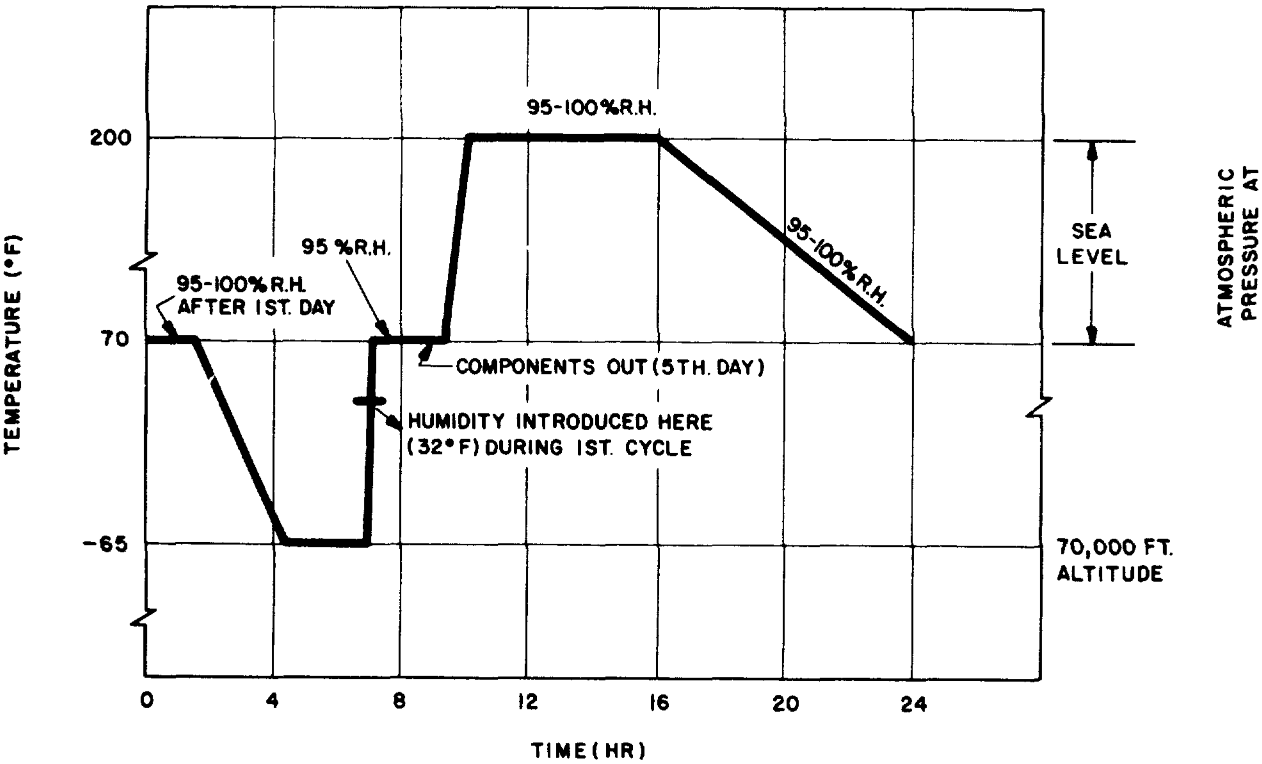

Figure 102. Temperature-altitude-humidity test cycle.

(2) Gas-firing mechanism should be tested under the conditions simulating those of design requirements. For example, it may be specified that the firing mechanism function when gas pressure is supplied by a specific initiator at the end of a specific length of hose or that the gas-firing mechanisms function when 500 psi gas pressure is supplied to the rear of the firing pin. The firing mechanisms of at least six devices should be tested at- 65°, 70°, and 200° F.

(3) Electric firing mechanisms (ignition elements) must fire with a specific current, but must not fire with currents under a specified value. A minimum of 20 elements are evaluated at -65°, 70°, and 200° F. for both the no-fire and all-fire conditions.

(4) If any firing mechanism fails to meet the design requirements, the reason should be determined, and if modification of the device is required, a new evaluation program must be initiated.

i. Ignition System Evaluation. Ten cartridges in devices are conditioned at -90° F. to evaluate propellant ignition at very low temperatures. Should malfunction occur, additional tests are necessary to insure that the ignition system is reliable at -65° F., the lowest temperature specified.

j. Drop Tests. Three units previously unfired are dropped 6 feet onto a concrete slab. Two of the units are dropped, once on each end (four drops), so as to strike the concrete with their longitudinal axes perpendicular to the concrete. The third unit is dropped with its longitudinal axis parallel to the concrete slab, and its lateral attitude is such as to effect maximum stress on internal parts. The third unit is disassembled, inspected, reassembled, and dropped again with its longitudinal axis parallel to the slab. All three units are disassembled and inspected for internal damage.

k. Locked-Shut Firings. The three units used in the drop tests and seven additional units Pre fired looked shut: two at -65° F. and eight at 200° F. Failure of any of these devices necessitates modification of the propellant actuated device and a new evaluation program for the modified design.

l. No-Load Firings. When no-load requirements are specified, 10 units are fired under no-load conditions: 2 at -65° F. and 8 at 200° F. The units then are disassembled and inspected for component deformation. Any sign of deformation will require modification of the device and a new evaluation program.

m. Performance Evaluation.

(1) Performance evaluation is conducted to insure that the propellant actuated device meets the design requirements at each temperature specified. The units are fired under conditions simulating those of service operation as closely as possible, and using hose lengths (if required) specified in the design requirements. An aircraft hose assembly should not be temperature conditioned, nor should it be used for more than five firings. After each test, the hose should be blown clean of residue with dry, compressed air. Hose connections should be reversed after each firing so that one end of the hose is not connected to the device for two consecutive firings.

(2) Twenty firings are conducted at each temperature:-65°,70°, and 200° F. In each series of firings, 5 of the 20 firings should be conducted in previously unfired units.

(3) Any firings failing to meet the design requirements are analyzed and, if redesign is necessary, a new complete evaluation program is initiated with the modified design.

APPENDIX I

CONVERSION OF DISTORTION ENERGY EQUATION TO MORE USEFUL FORMS FOR PROPELLANT ACTUATED DEVICES

---

1. Triaxial Stresses. *a. General.*

$$2\sigma_e^2=(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2 \qquad (7)$$

Where:

σ_e = minimum yield stress = Y
σ_1 = radial stress = $-P$
σ_2 = tangential stress
σ_3 = axial stress
P = maximum internal pressure

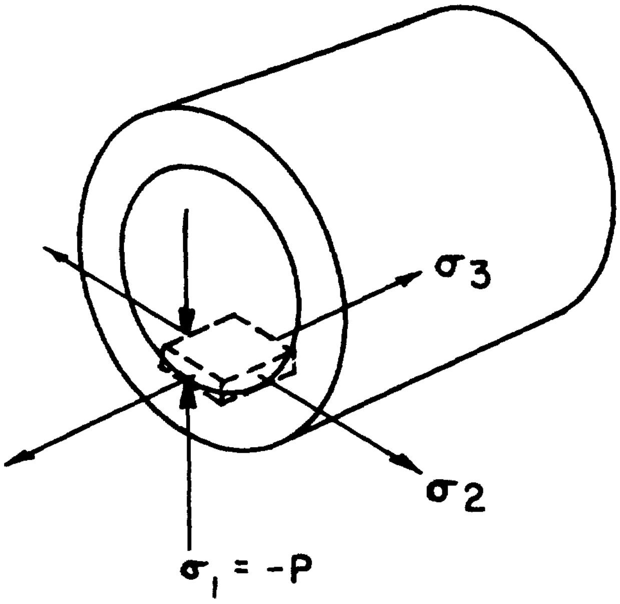

Figure 103. Stress parameters.

b. Tangential Stress.†

$$\sigma_2=P\left(\frac{W^2+1}{W^2-1}\right)=\left(P\,\frac{D^2+d^2}{D^2-d^2}\right) \qquad (55)$$

---

†Lame's Formula.

Where:

W = wall ratio of tube $\left(\frac{D}{d}\right)$
d = inside diameter
D = outside diameter

c. Axial Stress.

$$\sigma_3=\frac{F}{A\text{ out}-A\text{ in}}=\frac{\frac{P\pi d^2}{4}}{\frac{\pi D^2}{4}-\frac{\pi d^2}{4}}$$

$$=P\left(\frac{d^2}{D^2-d^2}\right) \tag{56}$$

Where:

F= force delivered to end
A= cross-sectional area

Substituting the values of σ_1, σ_2, and σ_3 from equations (55) and (56) into equation (7) yields

$$2Y^2=\left(-P-P\,\frac{D^2+d^2}{D^2-d^2}\right)^2+\left(P\,\frac{D^2+d^2}{D^2-d^2}-P\,\frac{d^2}{D^2-d^2}\right)^2+\left(-P-P\,\frac{d^2}{D^2-d^2}\right)^2$$

$$2Y^2=\frac{6P^2D^4}{(D^2-d^2)^2}$$

$$\therefore P^2=\frac{Y^2(D^2-d^2)^2}{3D^4}$$

$$P=\frac{Y}{\sqrt{3}}\left[1-\left(\frac{d^2}{D^2}\right)\right]$$

$$P=\frac{Y}{\sqrt{3}}\left(1-\frac{1}{W^2}\right)$$

$$\frac{P}{Y}=\frac{1}{\sqrt{3}}\left(\frac{W^2-1}{W^2}\right) \tag{8}$$

2. Biaxial Stresses.

$$\frac{P}{Y}=\frac{W^2-1}{(3W^4+1)^{1/2}} \tag{10}$$

The derivation of equation (10) is identical with that of equation (8), except that the axial stress, σ_3, is zero. A derivation of this equation and tables of values of W for values of $\frac{P}{Y}$ are presented in a report on the design of gun tubes.

APPENDIX II

TABLE OF WALL RATIOS

Where:

P = maximum internal pressure (psi)
Y = minimum yield strength of material (psi)
W = wall ratio (outside dia/inside dia)

	W			***W***	
P/Y	**Biaxial**	**Triaxial**	***P/Y***	**Biaxial**	**Triaxial**
0.010	1.0101	1.0088	0.050	1.0526	1.0463
0.011	1.0111	1.0097	0.051	1.0537	1.0473
0.012	1.0122	1.0106	0.052	1.0549	1.0483
0.013	1.0132	1.0114	0.053	1.0560	1.0493
0.014	1.0142	1.0123	0.054	1.0571	1.0503
0.015	1.0153	1.0132	0.055	1.0583	1.0513
0.016	1.0163	1.0141	0.056	1.0594	1.0523
0.017	1.0173	1.0151	0.057	1.0605	1.0533
0.018	1.0183	1.0160	0.058	1.0616	1.0543
0.019	1.0194	1.0169	0.059	1.0628	1.0554
0.020	1.0204	1.0178	0.060	1.0639	1.0564
0.021	1.0215	1.0187	0.061	1.0651	1.0574
0.022	1.0225	1.0196	0.062	1.0662	1.0584
0.023	1.0236	1.0205	0.063	1.0674	1.0595
0.024	1.0246	1.0214	0.064	1.0685	1.0605
0.025	1.0257	1.0224	0.065	1.0697	1.0615
0.026	1.0297	1.0233	0.066	1.0709	1.0626
0.027	1.0278	1.0242	0.067	1.0720	1.0636
0.028	1.0288	1.0251	0.068	1.0732	1.0647
0.029	1.0299	1.0261	0.069	1.0743	1.0657
0.030	1.0309	1.0270	0.070	1.0755	1.0668
0.031	1.0320	1.0280	0.071	1.0767	1.0678
0.032	1.0331	1.0289	0.072	1.0779	1.0688
0.033	1.0342	1.0299	0.073	1.0790	1.0699
0.034	1.0352	1.0308	0.074	1.0802	1.0710
0.035	1.0363	1.0318	0.075	1.0814	1.0721
0.036	1.0374	1.0327	0.076	1.0826	1.0731
0.037	1.0385	1.0337	0.077	1.0838	1.0742
0.038	1.0395	1.0346	0.078	1.0849	1.0753
0.039	1.0406	1.0356	0.079	1.0861	1.0763
0.040	1.0417	1.0365	0.080	1.0873	1.0774
0.041	1.0428	1.0375	0.081	1.0885	1.0785
0.042	1.0439	1.0385	0.082	1.0897	1.0796
0.043	1.0450	1.0395	0.083	1.0910	1.0807
0.044	1.0461	1.0404	0.084	1.0922	1.0818
0.045	1.0472	1.0414	0.085	1.0934	1.0829
0.046	1.0482	1.0424	0.086	1.0946	1.0840
0.047	1.0493	1.0434	0.087	1.0958	1.0851
0.048	1.0504	1.0443	0.088	1.0971	1.0862
0.049	1.0515	1.0453	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	1.1056	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	1.1313	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	1.1753	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	1.2143	1.1949
0.174	1.2159	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 III

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

$$L = \frac{3PR^2}{S_s d} \qquad (11)$$

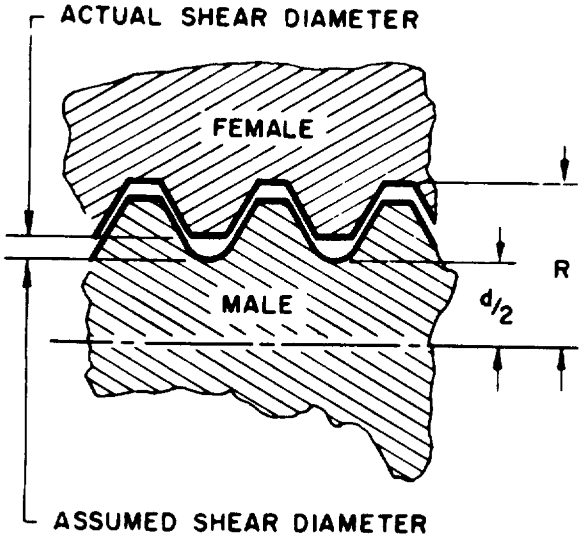

Figure 104. Thread parameters.

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†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 IV

DERIVATION OF WEB THICKNESS EQUATION FOR TELESCOPING TUBE DEVICES

$$P-\frac{ma}{A} \qquad (3)$$

Where:

P = internal pressure
A = equivalent average area of inner and telescoping tubes
m = mass to be propelled
a = instantaneous acceleration

$$P^n=\left(\frac{m}{A}\right)^n a^n$$

Where:

n = **pressure exponent of burning rate**

$$r=BP^n=B\left(\frac{m}{A}\right)^n a^n \qquad (18)$$

Where:

r = linear burning rate
B = constant of proportionality in burning rate equation

$$\frac{w}{2}=\int_0^{t_b} BP^n dt=\int_0^{t_b} B\left(\frac{m}{A}\right)^n a^n dt \qquad (29)$$

Where:

t_b = time at "all burnt"

Refer to figure 44 for the acceleration-time curve from which the following is deduced:

$$a=\dot{a}t \qquad 0>t>t_1$$

$$a=a_m \qquad t_1>t>t_2$$

$$a=0.82a_m \qquad t_2>t>t_3$$

$$\frac{w}{2}=B\left(\frac{m}{A}\right)^n\left\{\int_0^{t_1}(\dot{a}t)^n dt+\int_{t_1}^{t_2} a_m{}^n dt+\int_{t_2}^{t_3}(0.82a_m)^n dt\right\}$$

$$w=2B\left(\frac{m}{A}\right)^n\left\{\frac{\dot{a}^n t_1{}^{n+1}}{n+1}+a_m{}^n(t_2-t_1)+(0.82a_m)^n(t_3-t_2)\right\} \qquad (30)$$

APPENDIX V

DERIVATION OF EQUATION FOR BYPASS TUBE PRESSURE

---

1. Assuming that the propellant is all-burnt at the time the bypass port is uncovered, the equation of state is given by

$$P_f V_d = CF(1-\beta_1) \tag{57}$$

Where:

P_f =pressure in the device just before the port is uncovered
V_d =volume of the device
C =propellant charge weight
F =propellant impetus
$ß_1$ = fraction of the total energy, CF, taken from the propellant gas by work and heat loss just before the port is uncovered (this quantity can vary from about 0.35 to nearly 1.0, depending on the amount of work done and the nature of the thruster design)

2. After the port is uncovered, the system again achieves an approximate equilibrium condition. The equation of state becomes:

$$P_t = \frac{CF}{V_d + V_t}(1-\beta_1-\beta_2) \tag{58}$$

Where:

V_t = tube volume
P_t = tube pressure (pressure in complete system)
$ß_2$= fraction of total energy lost as heat transferred to walls of tube after port is uncovered

3. It is assumed that external work has been completed at the time the port is uncovered, and that the process can be represented as a quasi-static adiabatic expansion where the work done, W, is proportional to the internal surface area of the tube, S_t, i.e., W = $h_t S_t$ where h_t, is an empirical proportionality constant. Therefore,

$$h_t S_t = \frac{P_f V_d - P_t(V_d + V_t)}{\gamma - 1} \tag{59}$$

or

$$\beta_2 = \frac{h_t S_t}{CF}(\gamma - 1) \tag{60}$$

γ=ratio of specific heats.

From equations (57) and (58)

$$\frac{P_f V_d}{(1-\beta_1)} = \frac{P(V_d + V_t)}{(1-\beta_1-\beta_2)}$$

or

$$P_t = P_f\left(\frac{V_d}{V_d + V_t}\right)\left(\frac{1-\beta_1-\beta_2}{1-\beta_1}\right)$$

and

$$P_t=P_f\left(\frac{V_d}{V_d+V_t}\right)\left[\frac{(1-\beta_1)-\dfrac{h_tS_t(\gamma-1)}{CF}}{(1-\beta_1)}\right]$$

but as

$$CF=\frac{P_fV_d}{(1-\beta_1)}$$

$$P_t=P_f\left(\frac{V_d}{V_d+V_t}\right)\left[\frac{(1-\beta_1)-\dfrac{h_tS_t(\gamma-1)(1-\beta_1)}{P_fV_d}}{(1-\beta_1)}\right]$$

Finally,

$$P_t=P_f\left(\frac{V_d}{V_d+V_t}\right)\left(1-\frac{h_tS_t(\gamma-1)}{P_fV_d}\right) \tag{61}$$

4. In order to account for the additional high heat losses that may occur in the tube entrance where high velocity flow is generally experienced, the final equation (61) is multiplied by the factor (1-*ß*), resulting in

$$P_t=P_f\left(\frac{V_d}{V_d+V_t}\right)\left(1-\frac{h_tS_t(\gamma-1)}{P_fV_d}\right)(1-\beta) \tag{49}$$

APPENDIX VI

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310-1	Index of Administrative Publications.
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GLOSSARY

Adiabatic-Occurring without gain or loss of heat.

Adiabatic flame temperature-The temperature attained by the gaseous products of the combustion of a propellant if no heat is lost to the surrounding medium.

Ballistic cycle-The elapsed time between the ignition of propellant actuated device and the completed function of the device.

Buffer-(See Damper.)

Burning rate, linear-The rate of regression of a burning propellant surface measured normal to the surface. Generally expressed in inches per second.

Burning rate, mass-The rate of consumption of a propellant charge, generally expressed in pounds (or grams) per second.

Cartridge actuated device (CAD)-(See Propellant actuated device.)

Catapult-A propellant actuated device designed to propel an ejection seat with personnel from the aircraft.

Conditioning temperature-The temperature at which a propellant actuated device is "soaked" before test firing.

Cutter-A propellant actuated device designed to sever cables or parachute shroud lines.

Damper-A hydraulic or pneumatic device incorporated in or attached to a propellant actuated device to limit the velocity of the stroking member.

Double-base propellant-A propellant which contains two explosive ingredients, commonly nitrocellulose and nitroglycerin.

Efficiency, piezometric (ballistic)-The ratio of the mean ballistic cycle pressure to peak pressure in a propellant actuated device during the ballistic cycle.

Efficiency, thermal-The ratio of the mechanical energy of an accelerated mass to the energy resulting from propellant combustion.

Ejector-A stroking-type propellant actuated device designed to eject small masses.

Expansion ratio-The ratio of the final to the initial volume available to the propellant gases in a stroking type device.

Form function-The property of a propellant which describes the amount of gases produced with the burning of a given fraction of the propellant web.

Function time-In a stroking-type propellant actuated device, it is the interval of time from the initiation of operation to the completion of the stroke.

Gas generator-A propellant actuated device designed to supply gas pressure to another device.

Granulation, propellant-The geometry of propellant grain, e.g., solid cylinder, single-perforated, and multi-perforated cylinders.

Head space-The distance between the cartridge head and the breech face. Propellant actuated devices are designed with "zero" head space.

Ignition delay-The interval between the actuation of the firing mechanism and the beginning of sustained pressure in the propellant chamber.

Impetus-The energy released by the burning propellant per unit weight of propellant, generally expressed in foot-pounds per pound.

Initiator-A propellant actuated device designed to supply gas pressure to initiated propellant actuated devices.

Inverse of molecular weight-The number of moles in a unit weight of propellant.

Isochoric adiabatic flame temperature-Adiabatic flame temperature attained in a constant volume system.

Key-A small mechanical component in a locking mechanism which acts to restrain the motion of a stroking member.

Latch-(See Key.)

Neutral burning-(See Neutral granulation.)

Neutral granulation-Propellant granulation in which the surface area of a grain remains constant during the burning. The burning of a propellant with neutral granulation is termed "neutral burning."

Nonplateau-A propellant whose burning rate varies with pressure over the full pressure range.

Pin, safety-A manual locking member used on a propellant actuated device to prevent accidental operation.

Pin, shear-A pin used as a locking member which is released by shearing.

Plateau propellant-A propellant whose burning rate is almost constant over a range of pressures.

Pressure-time curve-A curve of the internal pressure of a propellant actuated device plotted as a function of time.

Primer blow back-The escape of propellant gas through the primer cup in the cartridge head.

Progressive burning-(See progressive granulation.)

Progressive granulation-With progressive granulation, the surface area of a grain increases during the burning. The burning of a propellant with progressive granulation is termed "progressive burning".

Propellant actuated device (PAD)-A device that employs the energy supplied by gases produced by propellants to accomplish or initiate a mechanical action, other than expelling a projectile. Propellant actuated devices were formerly referred to as cartridge actuated devices.

Regressive burning-(*See* Regressive granulation.)

Regressive granulation-With regressive granulation, the surface area of a grain decreases during burning. The burning of a propellant with degressive granulation is termed "regressive burning" or sometimes "degressive burning".

Reliability-The probability of a device performing its purpose adequately for a period of time intended under the operating conditions encountered. For a system with independent components, the overall reliability is based on the product of the individual reliabilities; e.g., three components with a 90 percent reliability each will have an overall reliability of 0.9 x 0.9 x 0.9 or 72.9 percent.

Remover-A stroking-type actuated device similar to a catapult, but usually of shorter stroke.

Sear-A component in the firing mechanism of a mechanically actuated propellant actuated device used to cock and release the firing pin.

Single-base propellant-A propellant which contains only one explosive ingredient.

Single-perforated grain-A cylindrical propellant grain having a single perforation located along its axis.

Stroke-The distance the piston moves in a thruster or the sum of the motions of the tubes in a multitube propellant actuated device (to the point where the system opens, if applicable).

Stroke time-The elapsed time between the first movement and the end of stroke of the stroking member of a propellant actuated device.

Surface-time history-The relationship between burning rate of a propellant and pressure.

Thruster-A propellant actuated device designed to provide thrust for opening or closing latches, moving loads and the like.

Web-In a grain propellant, the minimum thickness of the grain between any two adjacent surfaces. In designs of solid or single-perforated grains, the propellant is entirely consumed when the web is burned through. In multiperforated grains, this is not true, as "slivers" are formed at this stage which then burn to completion.

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- Gen Dep (2)
- Ord Sec, Gen Dep (2)
- Ord Dep (5)
- Army Dep (5)
- Ord PG (5)
- Arsenals (10) except
  - Watertown (2)
  - Watervliet (2)
- Springfield Armory (2)
- Ord Proc Dist (2)
- USAAPSA (10)
- MAAG (3)
- Mil Msn (2)
- NLABS (2)

NG: State AG (3); Units-same as Active Army except allowance is one copy to each unit.
USAR: None.
For explanation of abbreviations used, see AR 320-50.

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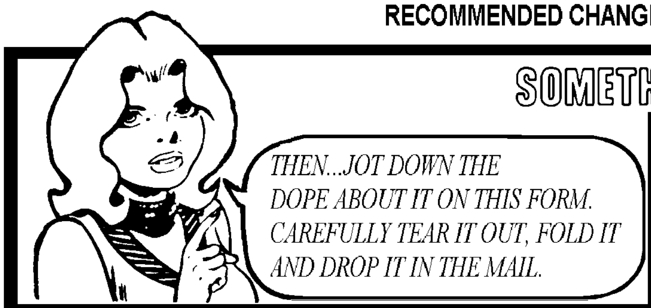
RECOMMENDED CHANGES TO EQUIPMENT TECHNICAL PUBLICATIONS



SOMETHING WRONG WITH PUBLICATION

FROM: (PRINT YOUR UNIT'S COMPLETE ADDRESS)

DATE SENT

PUBLICATION NUMBER	PUBLICATION DATE	PUBLICATION TITLE

BE EXACT PIN-POINT WHERE IT IS

PAGE NO.	PARA-GRAPH	FIGURE NO.	TABLE NO.

IN THIS SPACE, TELL WHAT IS WRONG AND WHAT SHOULD BE DONE ABOUT IT.

PRINTED NAME, GRADE OR TITLE AND TELEPHONE NUMBER

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DA FORM 1 JUL 79 2028-2

PREVIOUS EDITIONS ARE OBSOLETE.

P.S.--IF YOUR OUTFIT WANTS TO KNOW ABOUT YOUR RECOMMENDATION MAKE A CARBON COPY OF THIS AND GIVE IT TO YOUR HEADQUARTERS.

The Metric System and Equivalents

Linear Measure

1 centimeter = 10 millimeters = .39 inch
1 decimeter = 10 centimeters = 3.94 inches
1 meter = 10 decimeters = 39.37 inches
1 dekameter = 10 meters = 32.8 feet
1 hectometer = 10 dekameters = 328.08 feet
1 kilometer = 10 hectometers = 3,280.8 feet

Weights

1 centigram = 10 milligrams = .15 grain
1 decigram = 10 centigrams = 1.54 grains
1 gram = 10 decigram = .035 ounce
1 decagram = 10 grams = .35 ounce
1 hectogram = 10 decagrams = 3.52 ounces
1 kilogram = 10 hectograms = 2.2 pounds
1 quintal = 100 kilograms = 220.46 pounds
1 metric ton = 10 quintals = 1.1 short tons

Liquid Measure

1 centiliter = 10 milliters = .34 fl. ounce
1 deciliter = 10 centiliters = 3.38 fl. ounces
1 liter = 10 deciliters = 33.81 fl. ounces
1 dekaliter = 10 liters = 2.64 gallons
1 hectoliter = 10 dekaliters = 26.42 gallons
1 kiloliter = 10 hectoliters = 264.18 gallons

Square Measure

1 sq. centimeter = 100 sq. millimeters = .155 sq. inch
1 sq. decimeter = 100 sq. centimeters = 15.5 sq. inches
1 sq. meter (centare) = 100 sq. decimeters = 10.76 sq. feet
1 sq. dekameter (are) = 100 sq. meters = 1,076.4 sq. feet
1 sq. hectometer (hectare) = 100 sq. dekameters = 2.47 acres
1 sq. kilometer = 100 sq. hectometers = .386 sq. mile

Cubic Measure

1 cu. centimeter = 1000 cu. millimeters = .06 cu. inch
1 cu. decimeter = 1000 cu. centimeters = 61.02 cu. inches
1 cu. meter = 1000 cu. decimeters = 35.31 cu. feet

Approximate Conversion Factors

To change	*To*	*Multiply by*	*To change*	*To*	*Multiply by*
inches	centimeters	2.540	ounce-inches	Newton-meters	.007062
feet	meters	.305	centimeters	inches	.394
yards	meters	.914	meters	feet	3.280
miles	kilometers	1.609	meters	yards	1.094
square inches	square centimeters	6.451	kilometers	miles	.621
square feet	square meters	.093	square centimeters	square inches	.155
square yards	square meters	.836	square meters	square feet	10.764
square miles	square kilometers	2.590	square meters	square yards	1.196
acres	square hectometers	.405	square kilometers	square miles	.386
cubic feet	cubic meters	.028	square hectometers	acres	2.471
cubic yards	cubic meters	.765	cubic meters	cubic feet	35.315
fluid ounces	milliliters	29,573	cubic meters	cubic yards	1.308
pints	liters	.473	milliliters	fluid ounces	.034
quarts	liters	.946	liters	pints	2.113
gallons	liters	3.785	liters	quarts	1.057
ounces	grams	28.349	liters	gallons	.264
pounds	kilograms	.454	grams	ounces	.035
short tons	metric tons	.907	kilograms	pounds	2.205
pound-feet	Newton-meters	1.356	metric tons	short tons	1.102
pound-inches	Newton-meters	.11296			

Temperature (Exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C