SPECIAL ROCKETS AND PYROTECHNICS PROBLEMS

By J. G. Thibodaux

Langley Research Center
Langley Field, Va.

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INTRODUCTION

All of the previous papers presented on the use of rocket vehicles in flight research have shown that rocketry, radar, radio telemetry, and engineering ingenuity are the principal ingredients necessary for successful execution of a research program. The speakers have emphasized the necessity for simplicity and have indicated that the various research techniques should provide the maximum amount of research information from each flight. They have stressed that a high degree of reliability is required as the program costs are relatively high. These requirements are somewhat contradictory. The severity of test conditions is always increasing, and multistaged primary propulsion systems must often be used. In the interest of securing more research information, the models become more complex, and require programming of many functions along the mission profile. In a single flight, it may be necessary to program one or more of the following functions shown in figure 1.

Programmed Functions

1. Arm
2. Ignite or initiate
3. Release, separate, or jettison
4. Actuate switches or valves
5. Provide forces, torques, or moments

The use of engineering ingenuity allows accomplishment of these programmed functions while still retaining a high degree of simplicity and reliability. Complex mechanical design can be avoided and a considerable saving in weight and volume can be achieved by use of numerous pyrotechnic devices and small auxiliary rockets. The design, operation, and application of a few of these devices will be presented, and considerations of safety, failure modes, and circuit design will be discussed.

<u>Squibs</u>.- The basic component in any pyrotechnic device is the squib, initiator, or detonator. A squib in its simplest forms is shown in figure 2. It consists of two electrical leads which are separated by a plug of insulating material, a small bridge wire or electrical resistance heater, and a bead of heat-sensitive chemical composition in which the bridge wire is embedded. Application of an electric potential across the lead wires causes the bridge to heat up, and this in turn causes the chemical composition to react, liberating chemical energy in the

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*Aerospace Technologist.

form of heat. The bottom diagram in the figure shows a more complex squib. It consists of the basic squib and a small explosive charge, all of which are incorporated in a sealed metal or plastic container. More complex designs incorporating threaded couplings, pressure tight leads, additional bridge wires, and other elements in the explosive train are available for special applications. It can be seen that the squibs are very small in size, and for this reason, redundancy is easily obtained by use of more than one squib.

The electrical current required for initiation, the sensitivity to firing from spurious sources of current, the energy liberation, and the brisance of squibs can be varied over a wide range by proper choice of bridge wire size and material, ignition bead composition, and main charge composition. Squibs requiring only a few hundred ergs of energy for firing can be obtained by using fine carbon filaments for bridge wire construction. Other squibs which require voltages of 1,000 volts and higher for initiation can be obtained by use of large, noble metal bridge wires and a bead of materials which can be initiated only by explosion of the bridge wire. This type of squib is called the Exploding Bridge Wire or EBW. When successively less sensitive materials are added to the explosive train, and the final material is a high explosive which detonates, the device is called an initiator or detonator.

Time delay squibs.- Shown in figure 3 is a squib to which has been added a delay element or train between the basic squib and the main charge. The delay element consists of a mixture of chemicals which react in the solid phase with liberation of heat, but no gas. The heat travels as a wave through the delay train, and upon reaching the main charge, causes the squib to function in the desired manner. Delay compositions are available in burning rates between 0.1 to 0.3 inch per second; therefore, the squib length will be dependent on the delay time required and the composition and design of the delay train.

The actual delay time accuracies which can be attained are relatively poor when compared to good mechanical or electrical timers; however, this does not preclude their use for many applications. During the first nine years of operation of the NASA's Wallops Station, delay squibs were the sole type of programming devices which were used. Shown in figure 4 is a histogram of the statistical deviation of actual delay time from a nominal delay time as a function of the percentage of squibs which had this deviation. The nominal time is the arithmetic mean of the measured time for numerous tests of individual squib batches and lots. Squibs varying in delay times from 1 to 40 seconds were used in preparation of these data. Approximately 20 percent of each lot of squibs was tested. It can be seen that 90 percent of the squibs have less than ±5-percent variation from the nominal time, therefore for a 40-second delay squib we could expect a variation of ±2 seconds 90 percent of the time. It should also be noted that when more than one squib is used for redundancy, this distribution will be skewed in the direction of squibs which fire before the nominal time as the first squib which fires causes the desired function to be programmed.

Propellant actuated devices.- By using these basic squibs, initiators and detonators in conjunction with various pyrotechnic compositions which produce gas and chemical energy in the form of heat or pressure, families of simple, one shot devices can be designed to perform a number of functions. The addition of large amounts of black powder or metal-oxidant compositions produces an igniter for rockets or an illuminating flare to aid in tracking. Addition of combustible compositions which produce heat and liberate gases at a controlled rate provides pressurization for the expulsion of liquids, or produces a force which moves a piston. By connecting the piston shaft to a linear or rotary actuator, valves and switches can be opened or closed, shear pins can be removed, and umbilicals can be disconnected. The addition of a shearing device to the piston shaft allows the cutting of tubing, cords, or wiring. The use of highly confined deflagrating or detonating explosives produces explosive bolts which can release objects from one another. Specially designed high explosive shaped charges can destruct a rocket motor which is veering off course, or provide controlled cutting action to separate components.

Widespread use of these simple pyrotechnic devices has led to the growth of a sizeable industry in the United States. Hundreds of individual designs of each device are available. These devices utilize the same principles of operation; however, each may possess some special design feature for a unique application. It would be impossible to illustrate each separate design; however, details of design and operation are available in catalogs from such companies as Hercules Powder Company, Dupont, Atlas Powder Company, U.S. Flare, Holex, McCormick-Selph, Conax, and others. Some typical designs will be shown in the following figures.

Rocket igniters.- A simple igniter for a small rocket is shown in figure 5. It consists of two basic squibs mounted in a pressure tight housing and a sealed container filled with pellets of a metal-oxidant pyrotechnic material. The igniter is designed for mounting in the head end of the rocket. Upon application of current, the squibs fire, igniting the pellets. As the pellets burn, they generate pressure, rupturing the closure disc, and allowing a mixture of hot gases and incandescent particles to flow through the port. The gas mixture washes the propellant surface of the rocket causing ignition.

Igniter design is a complex procedure. The ignition process should produce no initial pressure peaks, and should occur in a few milliseconds. Various factors which influence igniter design are (1) squib, (2) pyrotechnic mixture, (3) degree of confinement, (4) basic rocket design parameters, (5) type of propellant, (6) duration of igniter,

(7) environmental storage and operating conditions, and (8) proposed location of the igniter. These factors are merely called to your attention and no further discussion of igniter design will be presented. The complexity of igniter design is increased by our lack of knowledge of the interrelationship between these various factors, and thus relegates igniter design to an "art" rather than a science.

Gas generators.- A gas generator is, in effect, a small rocket which produces a high volume of gas at a relatively low temperature. The rate of production of gas must be such that it maintains a constant pressure with a changing volume. These devices are usually used for supplying pressure to a hydraulic accumulator, replacing a pressurized cool gas system. These gas generators offer substantial savings in weight and volume over the system they replace. A typical gas generator is shown in figure 6. It consists of an ignition system and a propellant charge. The propellant burns, giving off hot gases which escape through small ports. The generator shown produces a pressure of approximately 1,500 pounds for a duration of over 30 seconds. These generators are usually a "constant demand" type; consequently, the rate of charge of volume must be constant or else the pressure will increase above the allowable limits. A nonconstant demand type would require a pressure relief valve. The charge designs must be such that they compensate for heat losses through an increasing amount of exposed wall surface if they are to provide near constant pressure.

Force-displacement actuators.- Figure 7 illustrates three different types of force-displacement actuators. The first is called a "dimple motor." It is essentially a squib with a specially designed concave dome. Upon firing, pressure forces this dome into a convex shape. Force, time, displacement characteristics of this dimple motor are matched to the requirements for opening or closing microswitches, or the device itself can be used to bridge two open circuit contacts, providing continuity in the circuit on firing. This dimple motor finds widespread use in arming, or in programming electrical functions such as firing circuits, starting motors, etc.

The dimple motor illustrated produces a force of 8 pounds through a distance of 0.11 inch, and requires 15 milliseconds for actuation.

The second device is called a "caterpillar" or bellows motor. It consists of a bellows type case which expands when pressurized. It is used in place of the dimple motor where greater force, displacement, time characteristics are needed. The force characteristics are related to the displacement which is allowed by confinement, and varies with time because of heat loss. The caterpillar motor illustrated produces a force of 10 pounds through a distance of 1 inch, and requires 30 milliseconds for actuation.

The third device provides greater force characteristics than either the "caterpillar" or "dimple" motor. It is called a piston actuator. It has a heavier case than either the caterpillar or dimple motor, and the pressure force is transmitted through a piston with an "O" ring seal. The piston actuator shown produces 40 to 50 pounds of force through a distance of 0.34 inch and requires 30 milliseconds for actuation. All of these devices are available in various size ranges, and can be designed to produce reasonable variations in force, displacement, and time characteristics.

Two more specific applications of the principle of the piston actuator are the squib switch and guillotine shown in figure 8. In the switch, the housing is redesigned to accommodate numerous insulated electrical pins, and the piston shaft is replaced by a plastic electrical insulator with numerous spring loaded contacts. Upon firing, the shaft moves a prescribed distance, and the spring loaded contacts open or close circuits through the pin outlets. Squib switches can be designed with any number of pins and contacts, and can simultaneously open or close any reasonable number of circuits.

In the guillotine, the shaft is filled with a knife and the housing is redesigned to retain the object to be cut. For some applications, a restraining anvil is incorporated in the housing. Upon actuation, the guillotine can sever hydraulic lines, cables, wiring, or cards. A conventional application of a guillotine is the reefing cutter which severs the reefing line on large recovery parachutes, allowing them to be de-reefed and to fully inflate.

Specific illustrations of explosive valves, shear pin disconnects, and umbilical disconnects will not be presented; however, it does not require much imagination to see how various other types of mechanical action can be accomplished with one of the force-displacement actuators.

Explosive disconnects.- Explosive bolts come in two principal designs as shown in figure 9. The first bolt uses a detonating charge to shatter the bolt body. This type produces a large amount of high-velocity fragments and may be undesirable for many applications. The second bolt is so designed with a relief in the wall which produces stress concentration, and causes tension-type failures to occur at the relief. Tension stress in excess of the ultimate stress in the bolt is produced by deflagration of a propellant in a confined volume inside the bolt which produces extremely high pressures. Poorly designed bolts of this type which are highly stressed prior to initiation of the explosive can also produce fragments. Tests must be conducted under actual stresses produced by torqueing the bolt to determine if fragmentation is produced, and if it is produced, whether it is acceptable.

Other explosive disconnects utilizing the "Monroe effect," produce high-velocity metal jets which have a great penetrating power, and can cleanly sever interconnecting structure. These devices are called linear-shaped charges and are illustrated in figure 10. It consists of a hollow channel filled with high explosive, a primer or detonator, and a metal liner which has a triangular depression. The liner is in contact with the explosive. Upon initiation, the explosive force generated collapses the liner at the apex of the depression first, then progresses towards the base. The pressure forces liquify the metal liner, and cause a high-velocity jet of liquid metal to be projected in a direction normal to the direction of the channel. This jet will cut light gauge metal along a clean parting line. Linear-shaped charges are available in various sizes. Some types are quite flexible and can easily be shaped to conform to any contour.

All of the force-displacement-time devices operate on the same basic principle. Chemical energy and working fluid are the products of decomposition of the explosive. These manifest themselves as a gas having certain thermodynamic properties and heat which gives this gas a certain temperature. The time characteristic is controlled by the reaction rate of the explosive, the shape and size of the explosive used, and the degree of confinement of the explosive. In general, the maximum pressure produced by an explosive, as a function of these properties can be evaluated experimentally. It is found that the pressure produced by a confined explosive can be expressed by the following type of empirical equation shown in figure 11: $P = c(m/v)^n$. Where P is the pressure, c is an empirical constant for the specific explosive, m is the mass of explosive, v is the confined volume, and n is an empirical constant. The pressure P thus estimated is an approximate, first-order value. In actual use, the value of pressure will depend on the time constant and the geometry of the confined volume through which heat is lost. For very fast reaction times, the maximum initial pressure can be accurately estimated by this type of equation. The pressure-time relationship after maximum pressure is reached will be controlled by heat losses. In the event the confined volume is changing, as would be the case in a piston actuator, maximum pressure will also be dependent on the inertia and resistance of the piston to motion, and the acceleration of the piston will be dependent on the force, time, and displacement characteristics of the system. Generally, it is best to design for the desired pressure based on the volume which exists after the piston is fully displaced, and to accept the intermediate pressures, unless the accelerations of the piston are intolerable. If accelerations are intolerable, the size and shape of the explosive particles can be altered to give a slower reaction rate.

Various explosives are available which can give maximum pressures at high degrees of confinement in excess of 1,000,000 pounds per square inch. Such pressures are actually achieved in explosive bolt designs.

Many of the pyrotechnic devices described so far provide forces to move objects which are constrained with respect to each other. In free flight, the models have no such relative constraint, and if it is desirable to produce forces or torques or moments on free flying models this can be accomplished with small auxiliary rockets. A pulse rocket is shown in figure 12. The rocket furnishes nonaerodynamic disturbing moment, usually in the pitch or yaw plane. The rocket shown has the nozzle mounted at right angles to the rocket axis, and the igniter installed along the rocket's axis. The igniter can be easily replaced with a delay type of igniter merely by using a longer extension tube. The nozzle can be designed to thrust along the rocket's axis, and the igniter can be placed at an angle to the rocket's axis to adapt to any peculiar installation requirement. By using many of these rockets with different delay times, the model can be periodically disturbed during coasting flight as the Mach number varies. The response of the model to these periodic disturbances can be measured by instruments, and many of the principal dynamic stability coefficients can be obtained on models with fixed aerodynamic surfaces.

A control typical of rockets used to produce small acceleration or decelerations, or to produce spin or despin moments, is shown in figure 13. Its principal use has been to furnish retrograde thrust for separation of expended boosters and their payloads under conditions where there are no relative aerodynamic forces which would cause separation, for spinning rockets to reasonably high rotational velocities so that they are inertially stabilized in space, and for despinning these rockets and payloads where spin of the payload would be detrimental to the experiment.

The use of numerous of these small rockets and some of the pyrotechnic devices is illustrated in figure 14. Here we see spin rockets to stabilize the final stage and payload, explosive bolts to release the rocket from the spin table, despin rockets to bring the expended rocket and payload to near zero rolling velocity, and retrograde rockets to separate the rocket from the payload. In some of the small black boxes, there are numerous pyrotechnic devices for programming functions, and internally around the sphere's equator in a linear-shaped charge for parting the two halves of the sphere.

While all of the basic pyrotechnic devices have a high inherent reliability, there are numerous opportunities for malfunctions when they are used in complex circuits and exposed to severe environmental operating conditions. The squib itself is usually designed to operate at ambient atmospheric conditions and has a basic reliability of 0.9999. When two are used for redundant operation, a misfire would hardly be anticipated. When the expected environmental storage and operating conditions are known, the squibs can be specially designed to perform reliably under these operating conditions. The choice of squib or pyrotechnic device for any application requires qualification testing for reliable operating under the conditions shown in figure 15.

Environmental Effects

1. Humidity and moisture
2. Chemical atmosphere resistance
3. Temperature extreme
4. Vacuum or pressure
5. Acceleration in all directions
6. Vibration
7. Aging characteristics

The squib may be subjected to excessive humidity or moisture during long storage prior to use. If it is incorporated inside the rocket motor during storage, the propellant may liberate chemical gases such as ammonia. Depending on the location of the squibs on the models, aerodynamic heating may cause excessive squib temperatures. High-altitude operation, or operation inside closed pressure vessels may impose extremes of vacuum or pressure. Acceleration due to aerodynamic force or boost acceleration can occur in all directions. Vibration during boost may impose severe limitation on operation. The squib characteristics may also change during aging because of chemical instability of pyrotechnic materials.

Delay squibs have certain peculiarities not common to other squibs. Some of the newer delay train pyrotechnic compositions have severe aging characteristics which cause considerable changes in nominal delay times. Delay squibs are somewhat sensitive to high accelerations in various directions and delay times may change with the magnitude of acceleration. They must be tested while being subjected to the maximum value of acceleration anticipated to determine their behavior. Merely subjecting the squib to acceleration, then static testing the squib will not provide the proper data. On occasions, delay squib lots have been found in which the squib case ruptures instantaneously upon application of current as shown in photo figure 16. The squib if in contact with pyrotechnic ignition materials at this point would cause premature ignition. Even though the type of malfunction is experienced, the delay train and main charge will fire on schedule; therefore, the squibs installation should be such as to preclude premature ignition. The outer case of the squib heats up as the delay train burns; therefore, the outer squib case should not be in direct contact with heat-sensitive pyrotechnic materials.

A squib is normally fired by application of the proper voltage electrical source across the bridge wire, and the squib's sensitivity to firing from stray currents through the bridge wire is fairly easy to determine. Unfortunately, there exists many opportunities to fire squibs through unusual circuits which are not made through the bridge wire. The use of black powder containing a carbon or graphite glaze or metallic powder-oxidant mixtures as the main charge provides many opportunities to make extremely sensitive circuits between the metal outer case and the pins or wires to which the bridge wires are attached. In some squibs, because of manufacturing procedures, the bridge wire overhangs the pins and may actually contact the case during assembly. Both of these hazards can be eliminated by better manufacturing tolerance and by isolating or insulation of the squib case from any electrical source.

Static electricity and electromagnetic radiation are considered potential sources of accidental ignition of pyrotechnic devices. While there are numerous research programs to establish the amount of hazard from these sources, there is little credible documentation which proves conclusively that these sources have caused accidental ignition through the bridge wire circuit. The static hazard can be eliminated to some extent by providing a common ground for all elements of the missile system which can collect static charges. The electromagnetic radiation problem can be minimized by suitable shielding of all wiring and by using less sensitive bridge wire circuits where possible.

Another potential source of trouble in complex circuitry stems from the fact that the bridge wire is not necessarily broken by firing the squib, and continues to draw current, or that the squib shorts out on firing. Numerous squibs in a complex circuit which continue to draw current can cause excessive drain on the power supply and cause malfunction of squibs which are programmed to fire subsequently. Fundamentally, this squib feature should be eliminated by design changes. Where this cannot be done, it is possible to switch the squib out of the circuit, to provide fuses or resistors in the circuit to minimize current drain, or even to utilize specially designed squibs which open their own circuits.

Pyrotechnic devices such as switches, valves, etc., can have mechanical malfunction because of poor construction, poor handling, or faulty installation designs. The devices should never be installed where they are highly stressed, and where possible, design should be such that their actuation can be checked before use.

Once the pyrotechnic device is properly designed and qualified for use under all anticipated operating conditions, the principal causes of malfunctions can be traced to a condition where the device <u>never</u> receives the proper firing current, or where the device receives a premature signal to fire. Both of these are due to faulty circuit design or use of faulty components in the circuits. A schematic diagram of one simple circuit which resulted in a serious accident is shown in figure 17. The model was installed on the launcher and the final countdown was being carried out. The firing leads consisted of a few hundred feet of copper wire, and were shorted and unconnected to any power source. An external telemeter power source was connected to the model through an umbilical plug. The power source was grounded. Upon pulling the power plug, the model ignited prematurely, injuring the technician who was working on the model. It was determined with reasonable confidence, that a potential of 245 volts was applied to the outer case of the squib which was installed in the rocket igniter, and that this potential caused a circuit which charged the ignition leads which had some capacitance with respect to ground potential. This was verified in laboratory tests by utilizing capacitors with the same value as the ignition leads, power supplied identical to that used with the model, and squibs identical in design to those used in the igniter. Because of wide variations in the circuit formed between the squib case and bridge wires, the conditions could not be repeated on every trial, and numerous squibs had to be tested in this manner before one could be caused to ignite.

In complex circuits, numerous sneak or unanticipated circuits have been uncovered and were responsible for losses of models. These circuits involved hundreds of components, and would be impossible to illustrate and discuss in the time or space allocated. They required hundreds of hours of trouble shooting and investigation. In one case, a circuit was made through a relay solenoid in the destruct system, and upon charging the batteries prior to launching, the rocket fired as soon as the battery voltage was sufficient to cause initiation.

A second malfunction involved interaction between the preflight test equipment and the ignition circuits. The umbilical connector was pulled, and all pins did not disengage simultaneously. Two of the pins caused a relay to close and to light a telltale lamp on the indicator panel. Because of circuit interactions, this caused a firing current to be sent through two pins of the umbilical which were still engaged. The whole sequence of events occurred in a few milliseconds time. The circuit had been tested numerous times before with no evidence of trouble because all pins had disengaged simultaneously.

In complex pyrotechnic circuits, there are numerous opportunities for unanticipated failures as evidenced by the fact that most accidents or loss of research models can be traced to this cause. It is absolutely necessary to conduct a good network analysis considering the requirements and operational characteristics of every pyrotechnic device and circuit element. The complete circuit should be set up on a "breadboard" and tested. Sufficient instrumentation should be provided in these tests to locate weak points in the design. Finally, the complete system should be tested in the field for proper sequential operation, and should be exposed to all potential sources of stray current which exist because of internal power sources or external electromagnetic radiation.

CONCLUDING REMARKS

The use of small pyrotechnic devices and auxiliary rocket systems makes it possible to provide programming of nearly all desired functions in a free-flight research model.

A high degree of reliability in the basic pyrotechnic device requires extensive testing and qualification under conditions which exist in actual use.

Complex pyrotechnic circuits require detailed analysis and testing in the laboratory and in the field in order to achieve a high degree of reliability and safety.

The design and operational simplicity of these devices provide a higher degree of safety and reliability at less cost than a comparable electromechanical or mechanical programming device.

The small size of these devices allows inclusion of more units in a model of given size, and thus increases the amount of data which can be obtained from each model flight, or reduces model costs.

ARM

IGNITE OR INITIATE

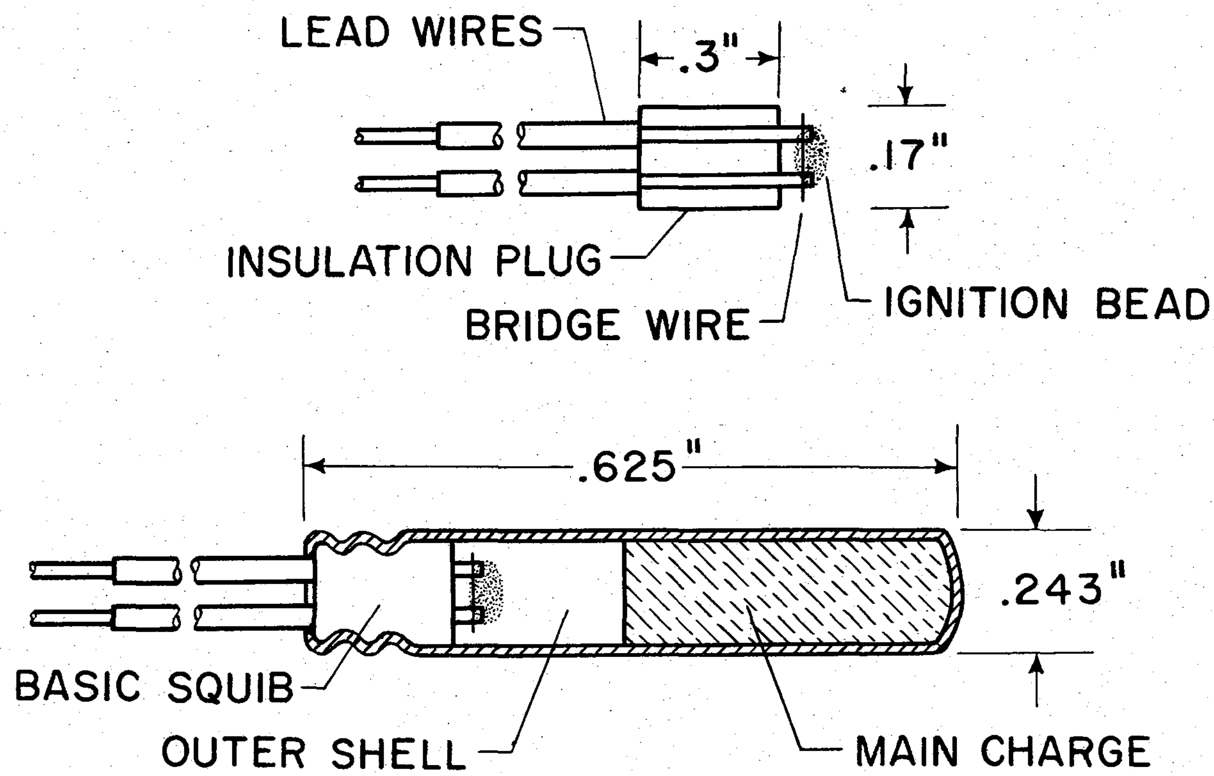
RELEASE, SEPARATE OR JETTISON

ACTUATE SWITCHES OR VALVES

PROVIDE FORCES, TORQUES OR MOMENTS

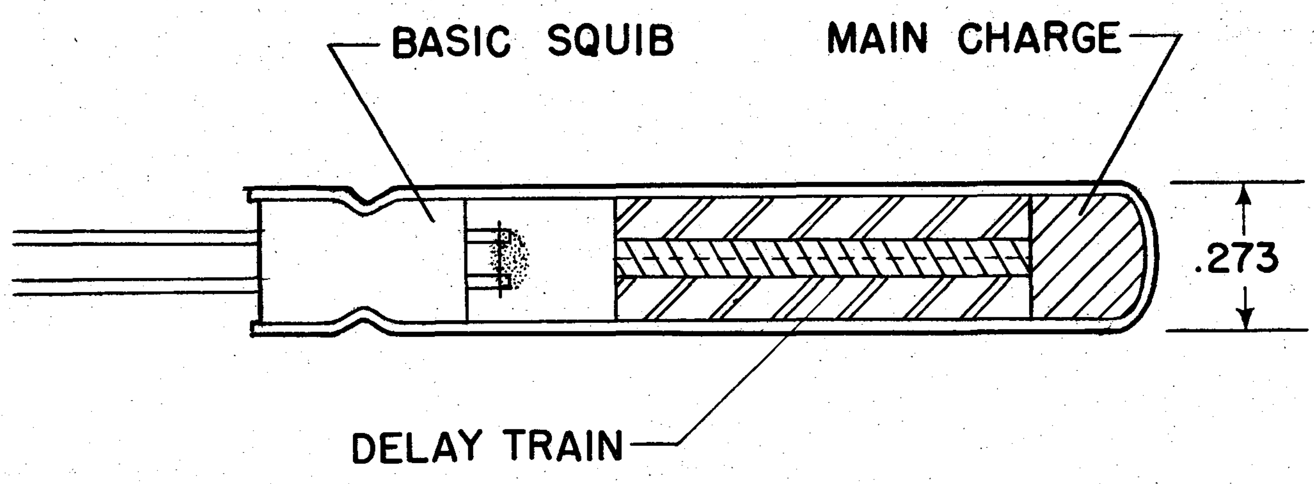
NASA

Figure 1.- Programmed functions.



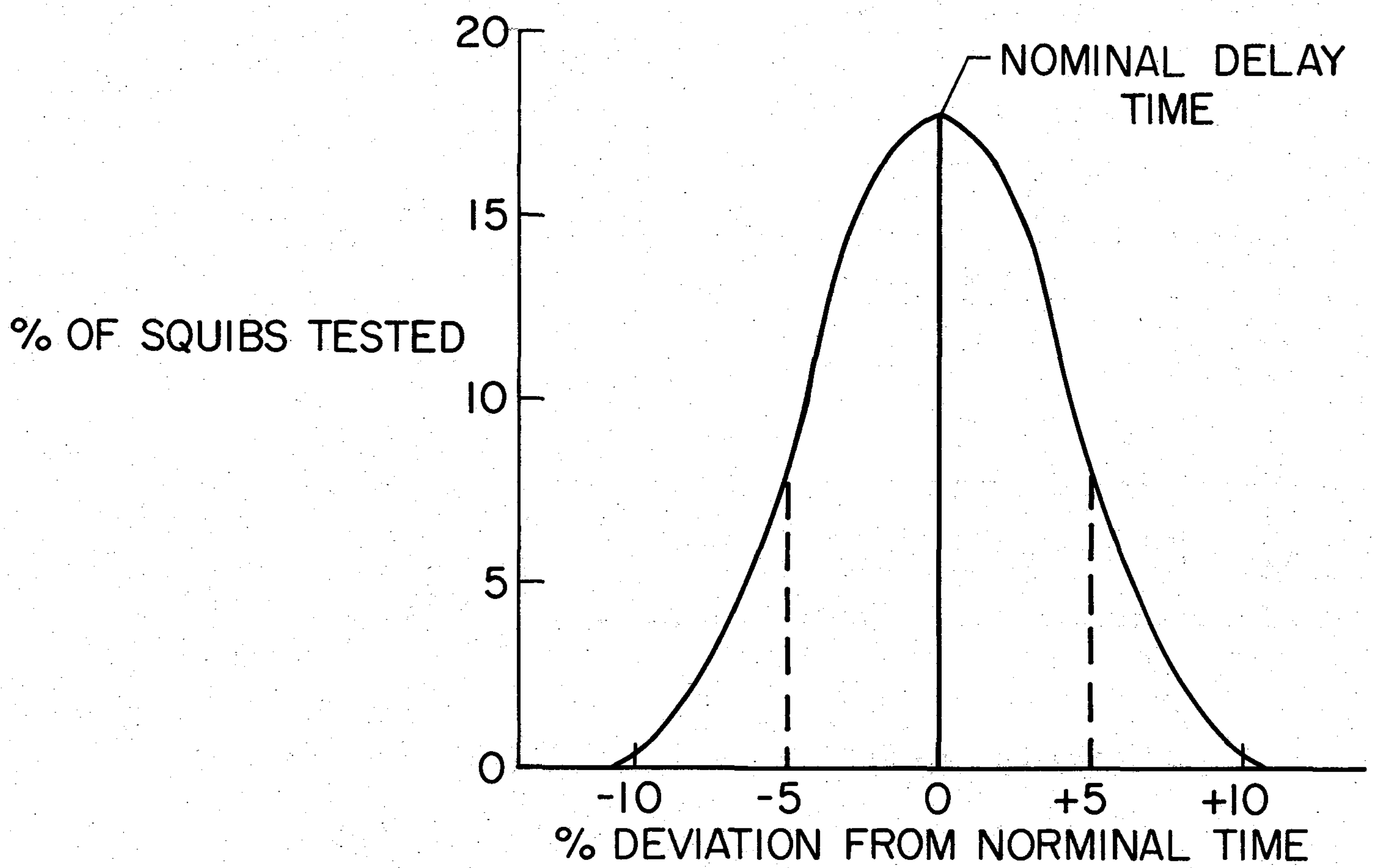
NASA

Figure 2.- Basic electric squib.



NASA

Figure 3.- Delay squib.



NASA

Figure 4.- A delay squib histogram.

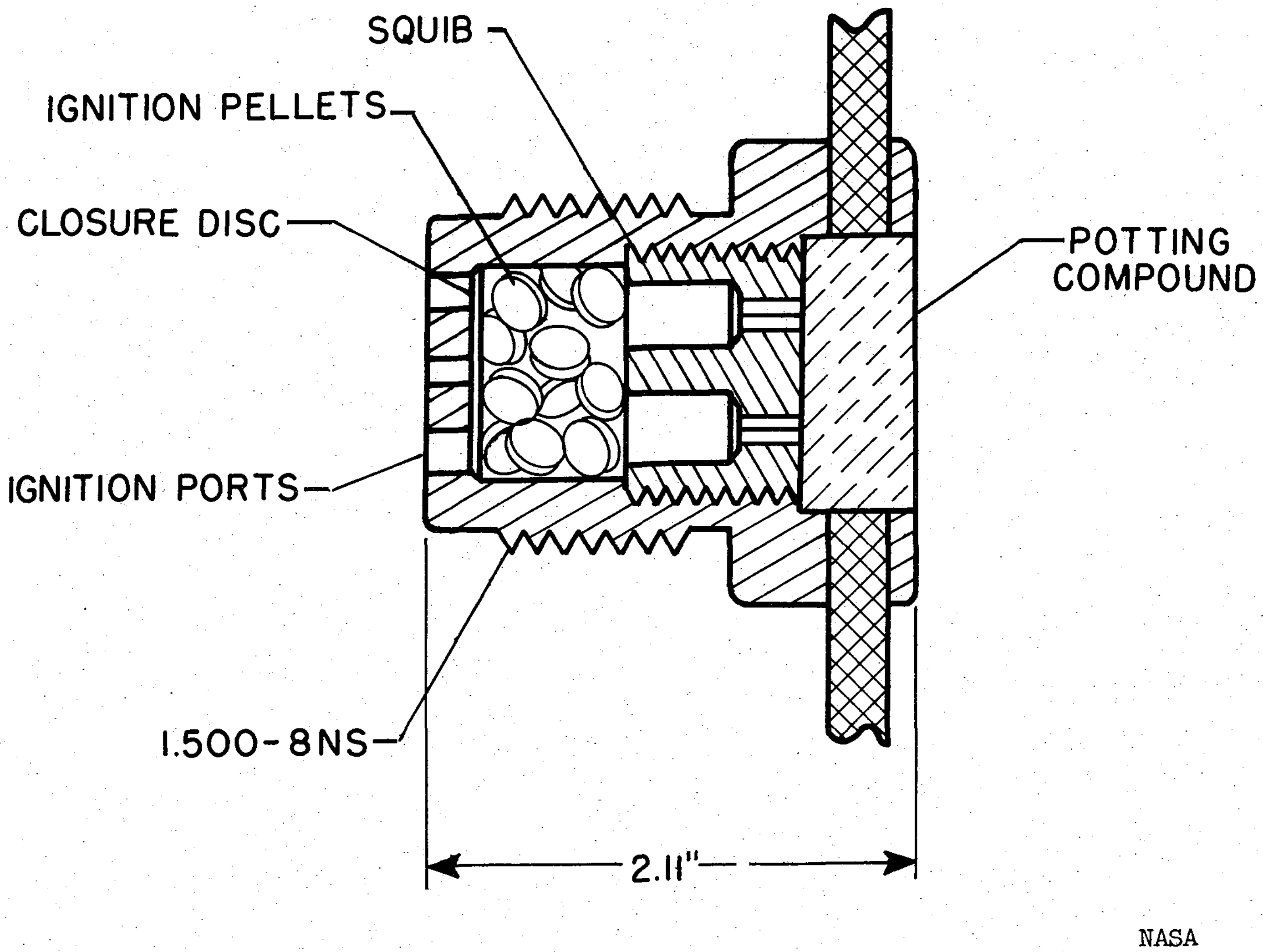
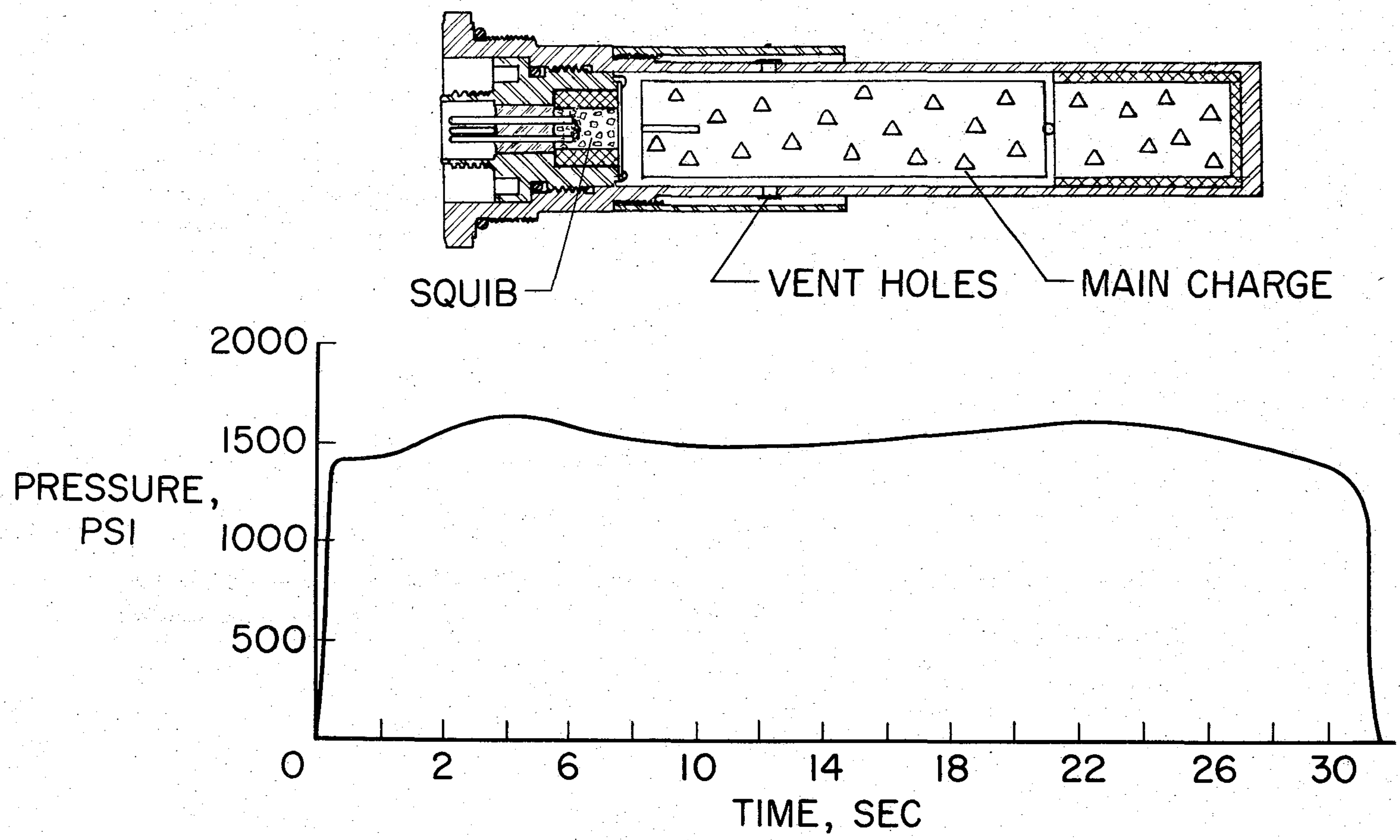


Figure 5.- Rocket igniter.



NASA

Figure 6.- Gas generator.

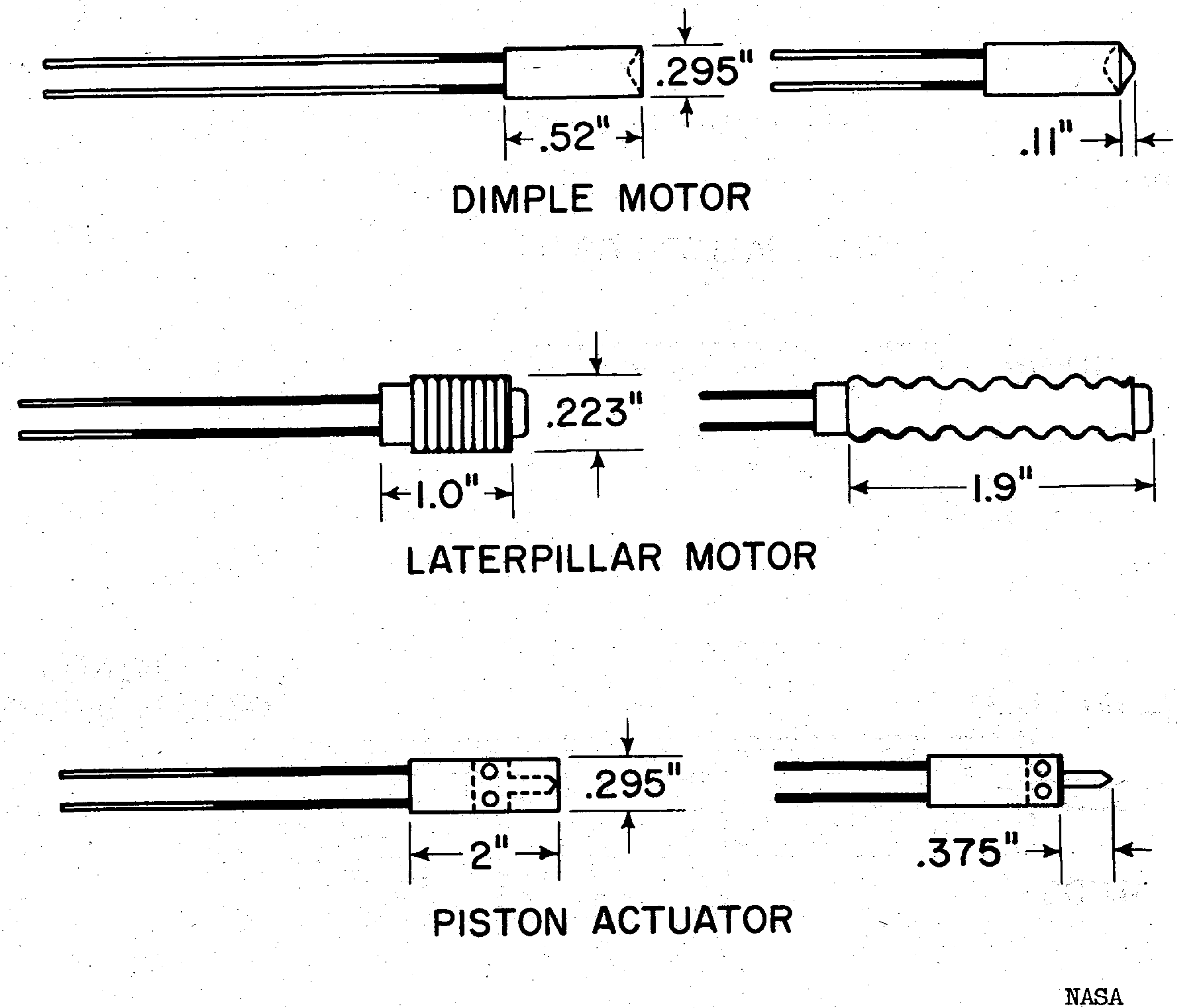


Figure 7.- Force-displacement actuators.

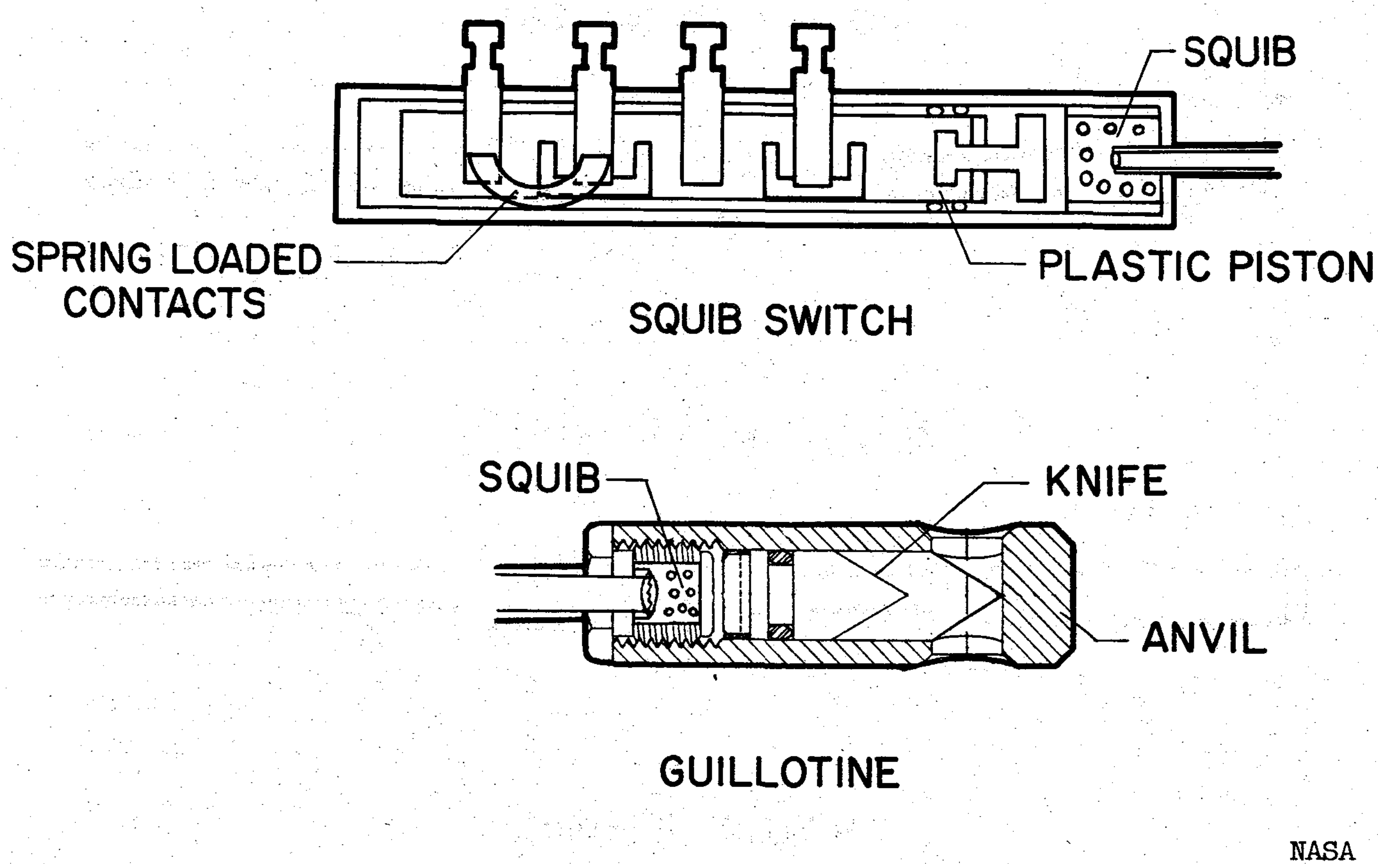


Figure 8.- Electrical pins.

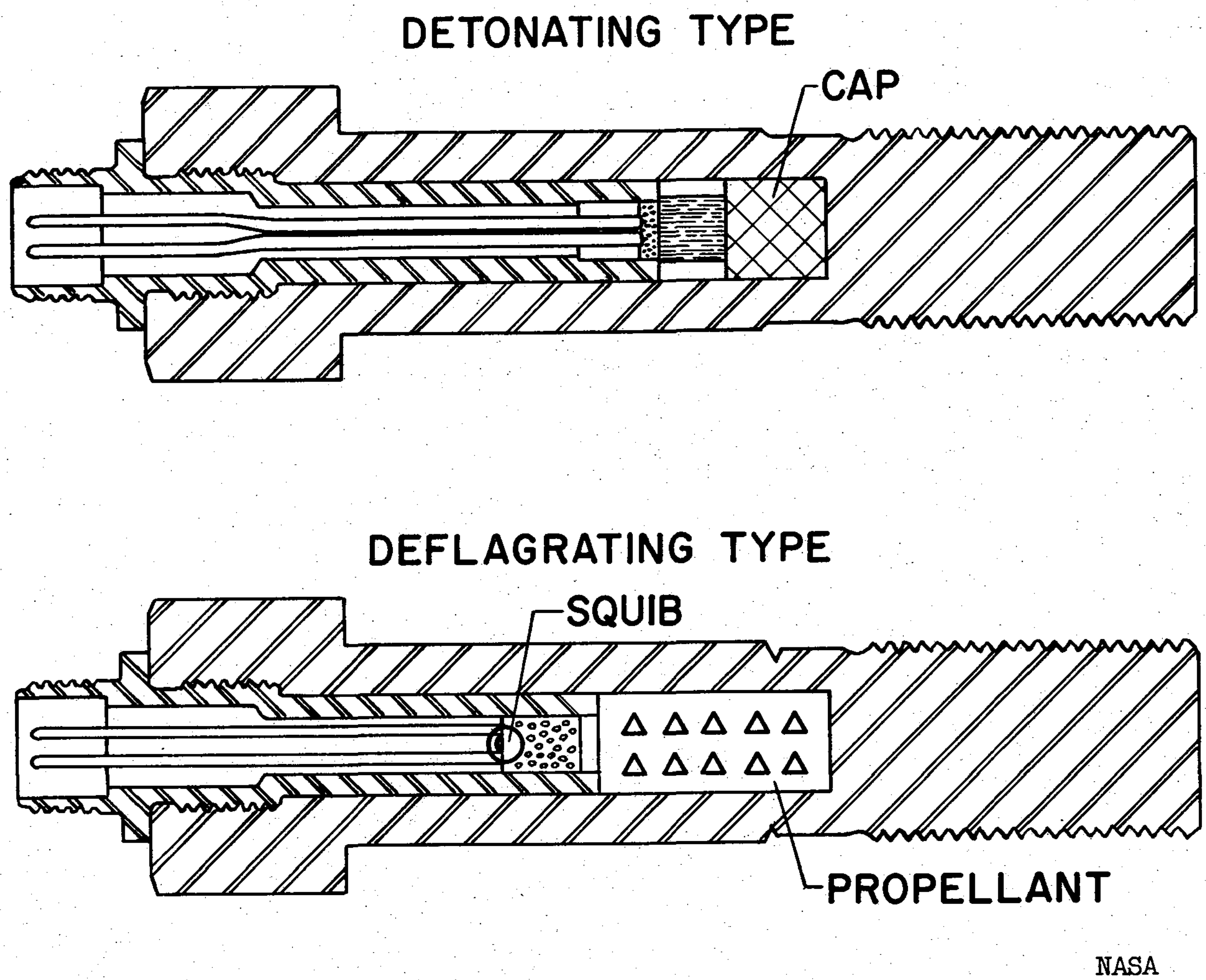


Figure 9.- Explosive bolts.

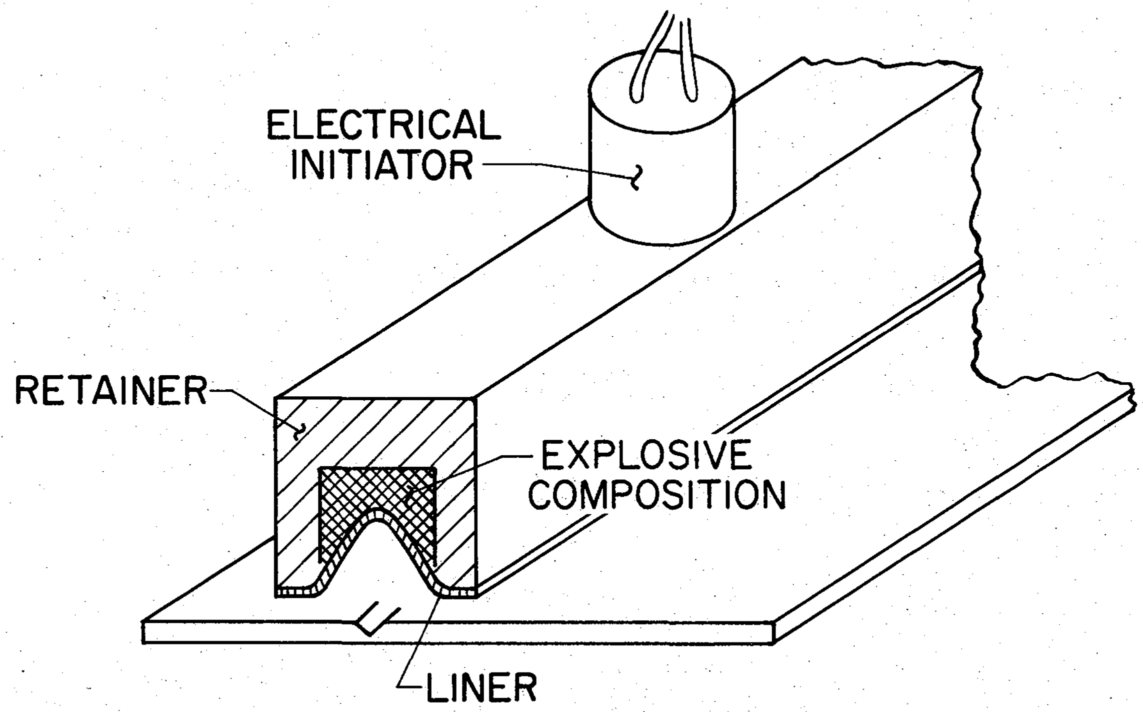


Figure 10.- Linear-shaped charge.

$$p = c\left(\frac{m}{v}\right)^n$$

p = PRESSURE

c = EMPIRICAL CONSTANT

m = MASS OF EXPLOSIVE

v = CONFINED VOLUME

n = EMPIRICAL CONSTANT

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Figure 11.- $p = c\left(\frac{m}{v}\right)^n$

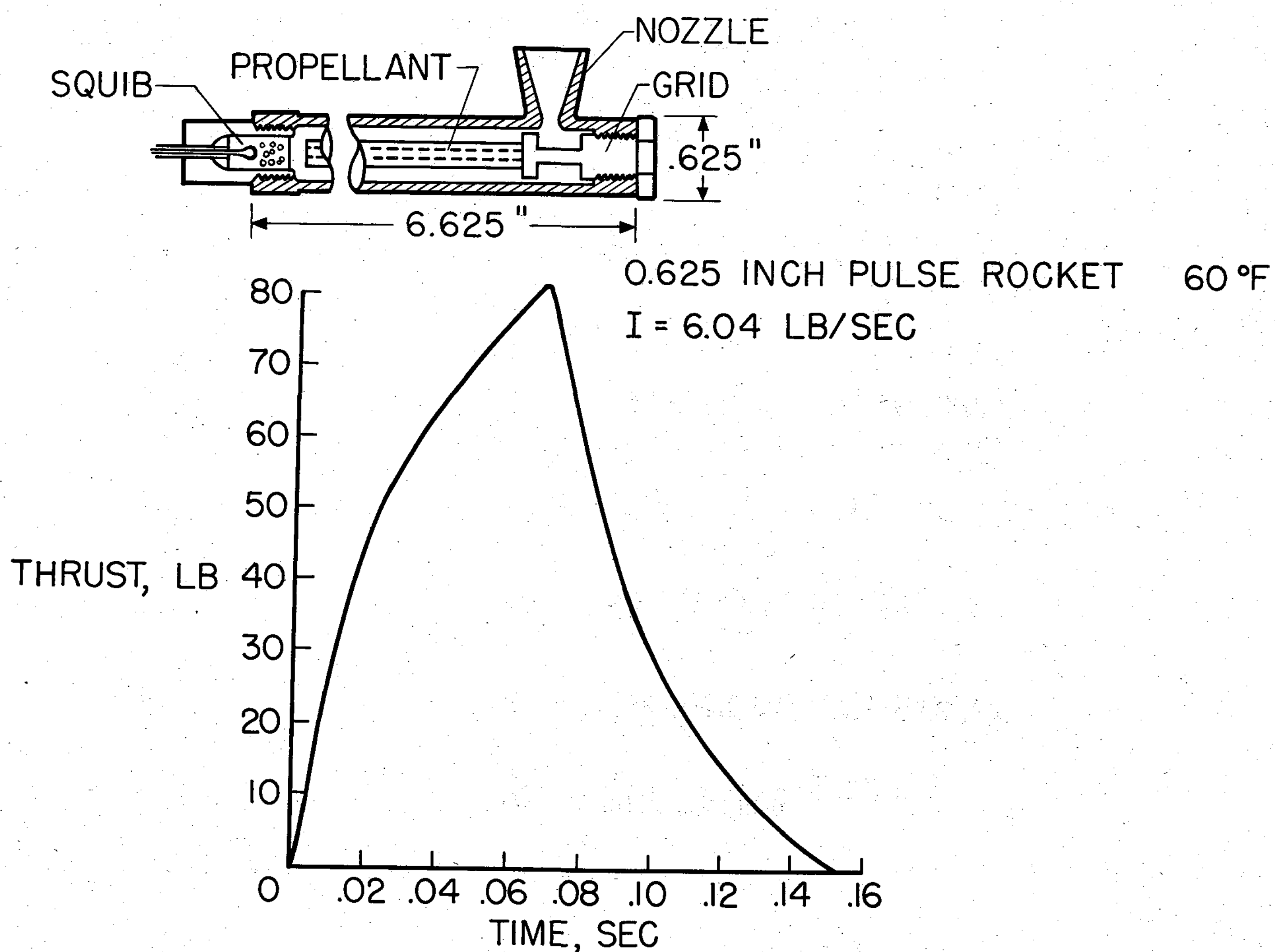

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Figure 12.- Pulse rocket.

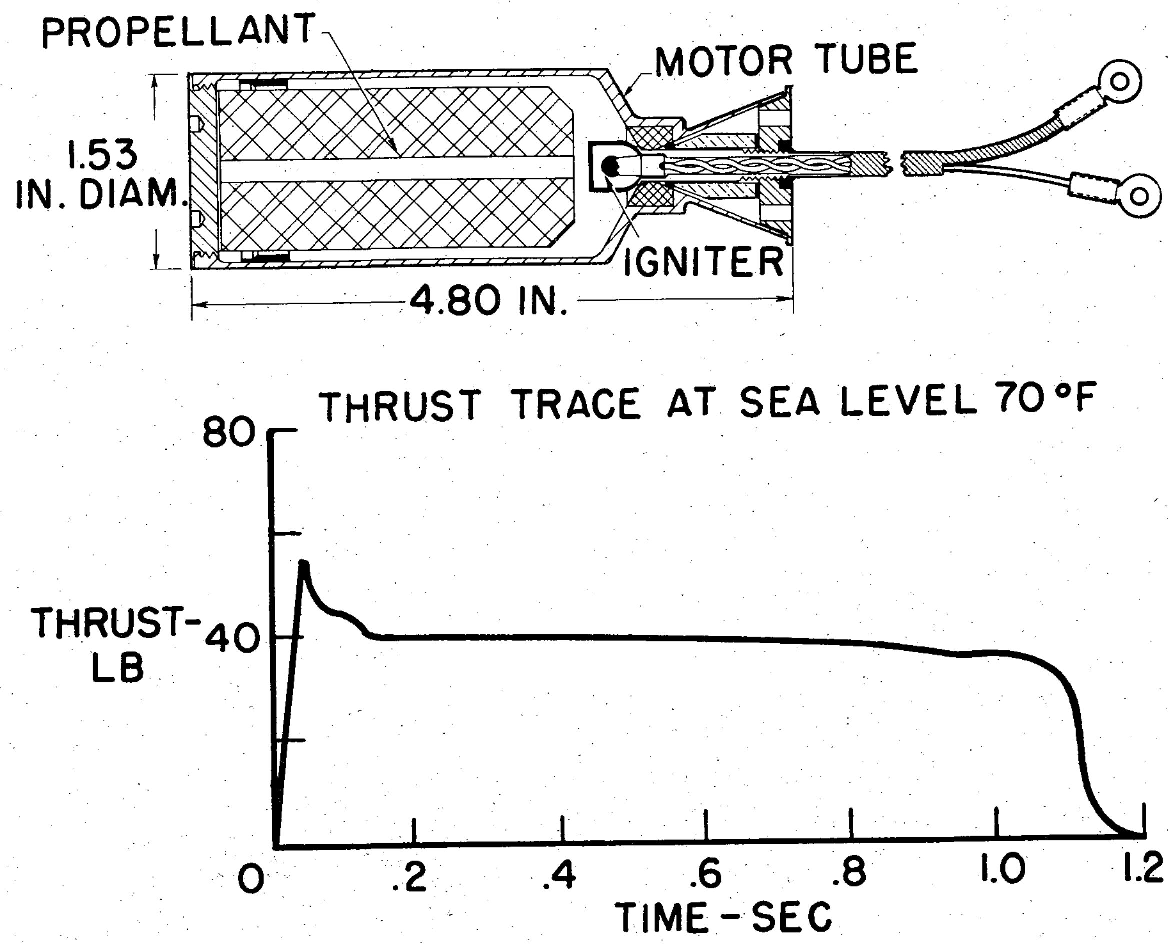

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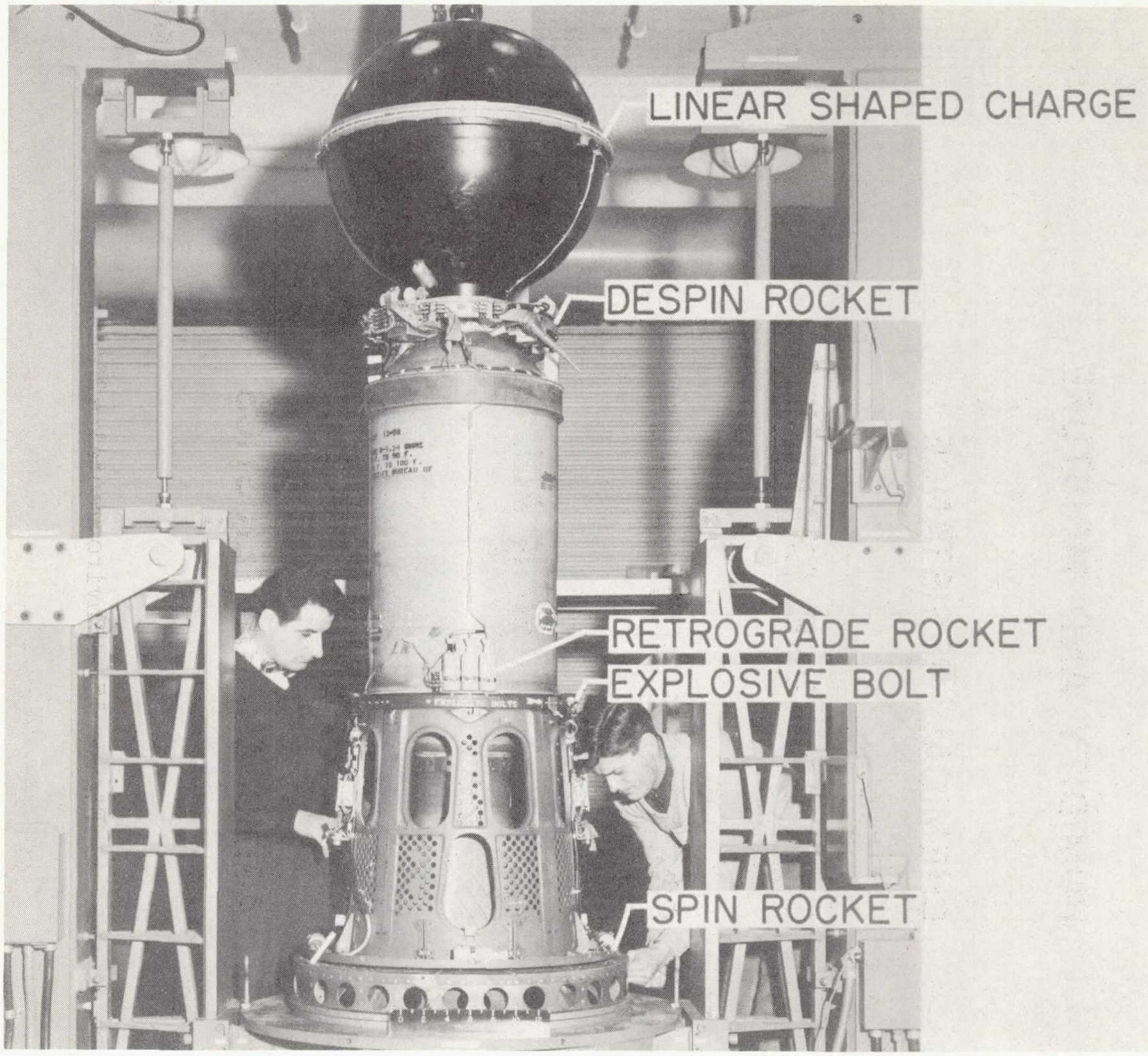
Figure 13.- Control rocket.



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L-60-490

Figure 14.- Use of pyrotechnics and special rockets.

HUMIDITY AND MOISTURE

CHEMICAL RESISTANCE

TEMPERATURE EXTREMES

PRESSURE AND VACUUM

ACCELERATION IN ALL DIRECTIONS

VIBRATION

AGING CHARACTERISTICS

NASA

Figure 15.- Environmental effects.

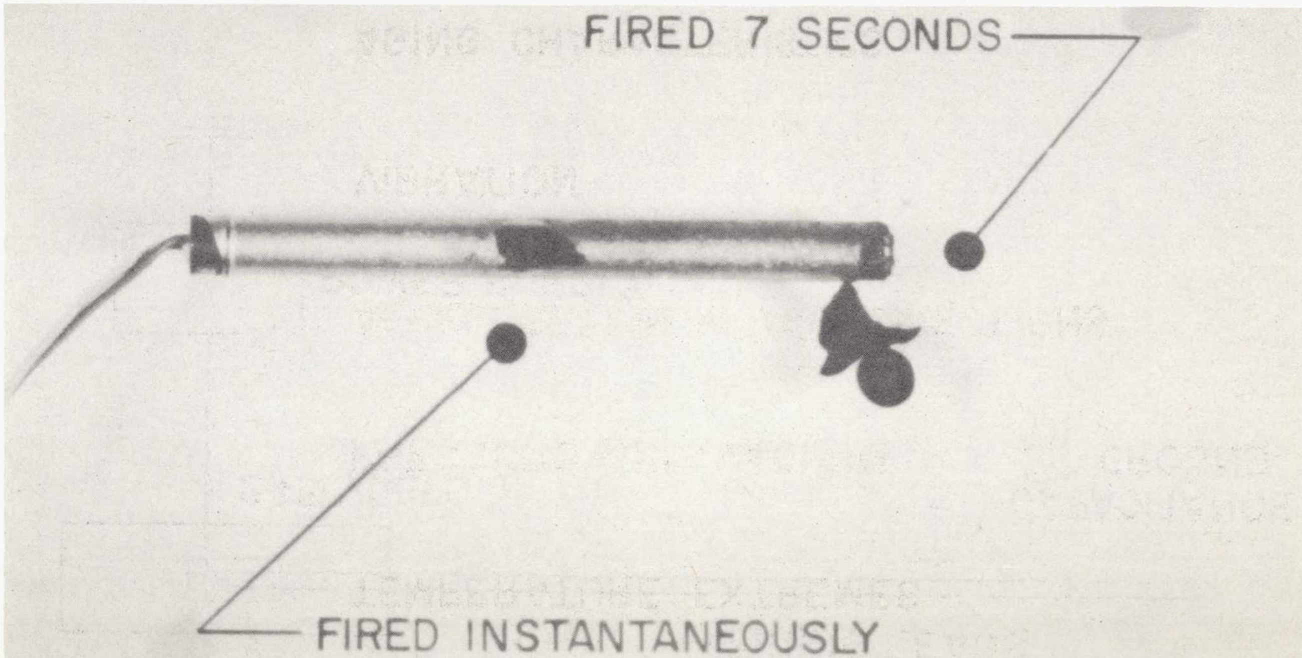

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Figure 16.- Delay squib malfunction.

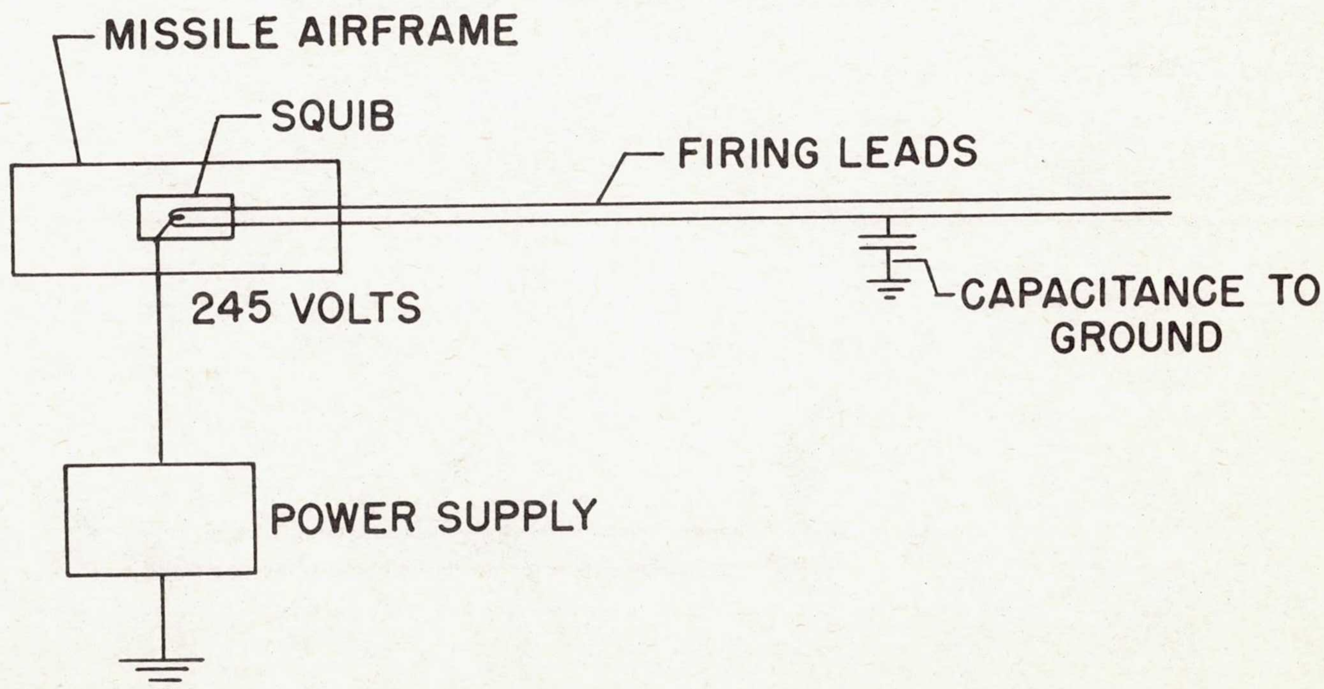

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Figure 17.- Accidental circuit.

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