HANDBOOK OF PYROTECHNICS

by
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Introduction

During the last twenty years, the field of pyrotechnics, which was limited mainly to applications in military ordnance, fireworks, and rock blasting, has been developed to a highly advanced science and to a widely used technology. Today, pyrotechnics find extensive applications in spacecraft, aircraft and underwater vehicle systems, and also in production methods, for example for metal forming, cladding, and riveting.

Pyrotechnics are ideally utilized in applications where space is limited and where low weight is a major requirement, as for instance in aircraft crew ejection systems, or in external fuel tank release mechanisms. Optimum utilization of the small size, low weight and high reliability of pyrotechnics is made in spacecraft and missile applications. Many space missions would be impossible without pyrotechnic devices and pyrotechnic systems. Escape tower release, stage separation, fairing release, recovery and landing systems, location aids, and flotation systems are some typical examples of ideal utilization of pyrotechnics in spacecraft. Pyrotechnic devices are widely used in missile systems for ignition, control, booster separation, fairing release, and, in cases of malfunction, for destruction.

"Pyrotechnic" means "explosive-actuated" and refers especially to devices in which explosives are burned rather than detonated. In aerospace applications, all electrically fired explosive devices are referred to as "electro-explosive".

The main advantages of pyrotechnic devices are: High power-to-weight ratio, high reliability, small size, low operating current, simple circuit requirement, reasonably low cost, ability to deliver more energy in a shorter time than any other mechanical device, and precisely controllable force.

Another advantageous feature of some pyrotechnic devices is the possibility of providing time delays by placing elements with fixed burning times between sections of fuze, or by mounting time delay trains in the explosive devices themselves.

In recent years, it was difficult for engineers, technicians, designers and students to solve some problems connected with the design, development, testing and evaluation of pyrotechnic devices and systems because of lack of sufficient data, design rules, and experience. Sparse data about some explosive materials and only a few reports about the performance and reliability of a certain type of squibs and power cartridges were available. As a result of this lack of sufficient data, until a few years ago, a newly developed pyrotechnic device could only be qualified by a very extensive and costly series of tests to warrant reliable functioning. The author, who was instrumental in the development and design of several well-known revolutionary aircraft, missiles, spacecraft and underwater vehicles in Europe and in the United States, for example the first multi-engine turbojet aircraft, the first tactical transport aircraft Ar 232, the first turbojet bomber of the world, Ar 234, the Dolphin and Polaris missiles, drones, aircraft crew ejection systems, Paraglider systems, recovery and landing systems for the Gemini and Apollo spacecraft and instrument capsules, re-entry vehicles, and underwater vehicle systems, experienced this lack of design guides and data for the development and design of pyrotechnic devices and systems for many years.

It is the purpose of this handbook to provide useful data and information about theory and practical application of pyrotechnics for engineers, designers, technicians and students. The contents of this handbook are divided into six parts: Explosive Materials, Explosive-Actuated Devices, Pyrotechnic Systems, Reliability and Testing, Explosive Production Methods, and Appendix.

The handbook contains numerous charts, graphs and illustrations as useful aids. Theory, data, and practical applications are explained in detail. Valuable new information is presented in this handbook, as for example data about the effects of extreme environmental conditions on pyrotechnic materials and devices, hints and data for qualification testing, hints for the design and application of pyrotechnic systems, and data for the application of explosive methods in manufacturing processes.

It is recommended to use this handbook together with the book

"Military and Civilian Pyrotechnics" by Dr. Herbert Ellern, published by the Chemical Publishing Company, which contains more detailed information about the properties and production of pyrotechnic materials and an extensive manufacturing formulary.

In writing this handbook, the author made an attempt to cover the whole field of pyrotechnics technology and to present the newest and most complete data and information. The author would appreciate comments from users of this book, which may help to improve the contents of future editions of this handbook.

Thousand Oaks, California
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Part I

Explosive Materials

Explosive materials and compositions which are commonly used in pyrotechnic devices and systems are described in detail in the present Part I, Chapter 1 and 2, to provide the necessary information about the functioning, application, and physical and chemical properties of these materials. Only with the knowledge of the basic characteristics of these materials will it be possible for the user of this handbook to fully understand the functioning of pyrotechnics and to develop new pyrotechnic devices and systems.

1 Explosives and Compositions

Explosive materials and compositions are used in a great variety of pyrotechnic devices and systems mainly as producers of either gas, flame, heat, shock, smoke, light, or sound. Since explosives usually release energy in the form of heat and gas due to chemical disassociation in a way similar to gasoline, kerosene, butane, oil, and coal, they can generally be classified as fuels. The main difference of explosives as compared with conventional fuels is the characteristic that explosives contain oxygen and do not require atmospheric oxygen for combustion, and that the combustion rate of explosives is much faster than that of conventional fuels. The ability of explosives to perform work is based on the release of gas at high temperature and at high pressure. In most explosives, this pressure effect is aided by the quickness of the action which often may produce shock phenomena.

Explosive and pyrotechnic materials and compositions are classified, according to their characteristics, into two major categories:

A. Deflagrating or burning materials and compositions, which undergo combustion,

B. High explosives, which undergo detonation or high-order explosion, to differentiate it from low-order explosion, such as fast combustion of propellant.

All explosives, primers, propellants, and high explosives, are unstable materials by their very nature. While they are safe to handle and to process under controlled conditions, they must be treated and handled with great caution and the respect that their latent power deserves.

It is a not commonly known characteristic of some explosive materials that, the more powerful the explosive, the more difficult it is to initiate. This feature is the main reason for the arrangement of a minimum of two elements of explosive materials in an explosive train, in which the first material is a priming explosive to provide a reliable initiation of the second charge, which is the main charge, often also called base charge, and which has a high power output for performing the required work. The priming explosive is often also called "ignition bead" which, in many pyrotechnic devices, consists of a very small quantity of a highly sensitive explosive material and which is applied to the electric bridgewire in the device to be initiated by heat.

In some devices, a third or intermediate charge is used to aid in the transition to detonation. In these cases, initiating explosive materials are used for the ignition bead and for the intermediate charge, whereas a booster material is used for the main charge.

According to this commonly used arrangement of different explosive elements, high explosive materials can also be classified into the two major groups: Initiating or primary explosives and non-initiating or secondary explosives.

1. Initiating explosive materials which are initiated by an electric current, impact, or friction, are used to initiate the detonation of relatively insensitive explosive materials.
2. Non-initiating explosive materials are detonated by an initiating material which, during the detonation, generates the required shock to accomplish the necessary destruction for the actuation of the pyrotechnic device. Non-initiating explosives can be divided into three types:
   a. Boosters which can easily be initiated and which detonate at a high rate. For this reason, booster materials are not recommended for loading in large masses. A typical booster material is lead azide.
   b. Bursting charges which are initiated by a booster and which are suitable for loading in mass. A typical bursting charge material is TNT.
   c. Explosive materials which can only be used as ingredients in explosive mixtures, because they are either too sensitive or too insensitive to be used alone. A typical example for a too sensitive explosive material is nitroglycerin, and a typical example for a too insensitive explosive is ammonium nitrate.

A. *Priming Materials.*

Priming or "first fire" materials are the first explosive material initiated in an explosive train and are used to initiate the detonation of less sensitive high explosives. Only a few explosives which have a high degree of sensitivity to initiation through shock, friction, electric spark, or high temperature, but which are not too sensitive, are suitable as ideal priming explosives. They must be able to release very high temperature or shock, or both, upon disassociation. A high sensitivity of priming materials is necessary because they are usually initiated either by raising their temperature by means of an electrically heated wire, or by the spit of a powder fuse, or by shock caused by the striking of the explosive by a firing pin in a rifle or pistol cartridge or in a special mechanically-initiated device. It is the main function of primers, which are power producers, to initiate a second, more stable and better power generating explosive which requires the high temperature output from the priming explosive.

Typical commonly used priming explosive materials are:

Lead azide
Lead styphnate (lead trinitroresorcinate)
LMNR (lead mononitroresorcinate)
KDNBF (potassium dinitrobenzofurozan)
Barium styphnate
Zirconium potassium perchlorate

Other priming materials which are not frequently used are mercury azide, potassium chlorate, and mercury fulminate.

B. *Propellants*

Deflagrating material is divided into three groups, according to their physical shape:

1. Loose powders, fine grains, spherical shotgun grains
2. Pressed or extruded grains (size 1/4 inch or larger)
3. Solid propellant billets, as used in gas generators

Deflagrating materials are generally good gas or heat producers. Some of these materials burn in the same manner as solid rocket propellants, but more rapidly. Since deflagrating materials are more stable than primers, they are usually set off by an initiating material. The force exerted by the deflagrating material is produced by the vapors evolved during combustion, in the same manner as in a solid-propellant auxiliary power unit (APU) gas generator. Similar to the conventional solid propellants, they burn evenly over their whole exposed surface area. Their burning rate depends mainly on the physical form of the deflagrating material. The highest burning rate is obtained in a charge consisting of thin flakes. The pressure rise rate decreases with an increase of the grain size of the material, and the burning rate is also affected by temperature and pressure.

Deflagrating powders, or propellant or pyrotechnic powders are used as the main charge in numerous impulse-type pressure cartridges which are utilized for the actuation of valves, thrusters, and guillotine devices. Important factors that influence the selection and sizing of the propellant powder for a certain application are: Maximum energy required, ignitibility, peak pressure, and burning time. The time from ignition of the propellant to its total combustion depends on the chemical composition of the propellant and the shape or form factor, and on the temperature and pressure. Very important for proper sizing of a propellant charge of a given shape for a certain required output and burning time is the ratio between surface area and total volume, since propellant powders burn only on the surface. When a very fast burning rate and a very high peak pressure is required, flake or flat powders are ideally used, whereas spherical or cylindrical powders are best used when a lower pressure for a longer period of time is required.

Rifle-type powders have such a fast burning rate and develop such a high pressure that the total combustion time may be only one millisecond. In applications where burning times of one second or longer are desirable, it is not advisable to use pressure cartridges with rifle-type smokeless powder which has a too fast reaction time, but to use a gas generator propellant instead. The propellant normally used in gas generators, which is similar to the propellant used in rocket engines, has a much slower burning rate than smokeless powder. The propellant used in a typical gas generator may have a burning rate of 0.1 inch per second at a pressure of 2000 psi, whereas the burning rates of smokeless powders are measured in inches per second. For this reason, the gas generator propellant can ideally be used in applications where burning times of many seconds are required. Gas generator propellants are more difficult to ignite than smokeless powders, and some of these propellants require relatively high pressures and temperatures to be maintained in order to sustain combustion.

Other typical burning explosives are $BKNO_3$, double-base powders, Hi-Temp (RDX), and zirconium potassium perchlorate.

C. *High Explosives*

High explosives are chemical compositions, which when initiated by a suitable stimulus, disassociate almost instantaneously into other more stable components. This reaction is known as high-order or low-order detonation. As a result of the explosive decomposition, detonating explosives produce some gas and high temperatures. The detonation is so fast that a shock wave is generated that acts on its surroundings with great brisance, or shattering effect, before the pressure of the exerted gas can take effect. This type of explosive material is used to pulverize rock and to sever steel beams. The most sensitive detonating explosives are so unstable that they can be set off by the slightest vibration, friction, or heating, and for this reason, such type of detonating materials is useless.

A different type of detonating explosive, which is relatively stable, is used in explosive devices and systems. Some of these high explosives are so stable that rifle bullets can be fired through them or they can be set on fire without detonating. They are set off only by the severe shock of an initial detonation, which is usually supplied by the explosion of a more sensitive explosive material. The more stable explosives which detonate at very high velocities of up to 9000 meters per second exert a much greater force during their detonation that the explosive materials used to initiate them.

Typical high explosives which are widely used in explosive devices are Tetryl, TNT, RDX, and PETN. For the initiation of the most commonly used materials, RDX and PETN, a shock impact of 3000 to 5000 meters per second is required which can be obtained only from another explosive material. For this reason, explosive devices in which RDX or PETN is used as a main charge, contain an explosive train consisting of three units: a primer, a booster, and the high explosive main charge. An exception are EBW (explosive bridgewire) devices, where RDX and PETN is directly initiated by the bridgewire.

The following example may explain the tremendous shock generated by a typical high explosive: If an explosive charge of lead azide is set off against one end of a three foot long and one foot diameter cylinder consisting of RDX, the shock from the disassociation of the lead azide is sufficient to cause decomposition of the face of the RDX cylinder which occurs with release of gas, shock, and increase in temperature. This zone of decomposition travels at an enormous speed down the length of the cylinder to the opposite end. This speed is called the detonation rate, which is different for each type of explosive material and depends also to a high degree on the density and confinement. In RDX, for instance, pressed to a density of 1.6 grams per cubic-centimeter, the detonation rate is 8200 meters per second, or over 18,000 miles per hour. This means that the time required for the decomposition to travel from end to end of the three foot long cylinder is about 0.0001 second. At this high decomposition rate, the byproducts of gas and particles cannot escape from the decomposition area, which results in the generation of extremely high shock pressures. The gases and particles follow the detonation wave from one end to the other as it proceeds through the cylinder. As the decomposition zone reaches the far cylinder end, it is not only traveling at a speed of 18,000 miles per hour, but it has also developed a peak shock pressure of about 4,000,000 pounds per square inch. This combination of velocity and shock results in the tremendous shattering effect of high explosives, which is utilized to break bolts, shatter steel parts, and deform sturdy metal structures.

A recently developed new type of high-performance detonating explosives are the Astrolite materials, which were developed from high-performance rocket propellants. The Astrolite explosives are not considered for use in conventional explosive devices, but mainly for special applications. They are explosives in liquid or putty form which combine the advantages of high performance and safety characteristics of solid explosives and the versatility and handling flexibility of liquid explosives. The sensitivity of Astrolite explosives to impact shock or adiabatic compression is considerably less than the sensitivity of RDX. It can be dropped from low-flying aircraft, and it can withstand 30-caliber rifle fire without detonating or burning. A standard military detonator is only required for initiation of Astrolite explosive material.

Astrolite-A which is intended mainly for demolition work and special applications requiring very high performance, is an extremely powerful explosive in liquid or putty form. This explosive will perform up to five times the work of an equal amount of TNT, and it has three to five times the power of commercial dynamite and Composite C-4, as proven in field tests.

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NOMENCLATURE

amp	ampere
Btu	British thermal unit
C	centigrade, Celsius
cc	cubic centimeter
cm^2	square centimeter
cps	cycles per second, (vibration)
cu.in	cubic inch
erg	unit of work
ft	foot
g	gram
G	force equal to earth gravity
Hz	hertz, cycles per second
in	inch
lb	pounds
m	meter
mc	microfarad (=mfd)

mil	1/1000
mm	millimeter
ms	millisecond
mv	millivolt
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gage
rad	radiation dose absorbed
sec	second
torr	mm Hg at 0°C

ABBREVIATIONS

ac	Alternating current
APS	Ascent Propulsion System, Lunar Module
APU	Auxiliary power unit
ASI	Apollo Standard Initiator
CDI	Confined detonating fuse
CM	Command Module, Apollo
CSM	Command and Service Module, Apollo
dc	Direct current
DIPAM	Diamino-hexanitrobiphenol
EBW	Exploding bridgewire
EDNA	Ethylene-dinitramine
FAA	Federal Aviation Agency
FLSC	Flexible linear shaped charge
G	Gravity
He	Helium
HF	High frequency
Hg	Mercury
HNS	Hexanitrostilbene
KDNBI	Potassium dinitrobenzoferoxan
LES	Launch Escape System, Apollo
LM	Lunar Module, Apollo
LMNR	Lead mononitroresorcinate
LSC	Linear shaped charge
MDI	Mild detonating fuse
NASA	National Aeronautics and Space Administration
NESTS	Non-electric stimulus transfer line (trade name)
OAO	Orbiting Astronomical Observatory, satellite

O.D.	Outside diameter
PETN	Pentaerythritol tetranitrate
PNC	Plastisol nitrocellulose
RCS	Reaction Control Subsystem, Apollo
RF	Radio frequency
RDX	Cyclotrimethylene trinitramine
SBASI	Single Bridgewire Apollo Standard Initiator
SCID	Small column insulated delay, (trade name)
SLA	Spacecraft-LM Adapter, Apollo
SM	Service Module, Apollo
SOFAR	Sound-fixing and ranging
TBI	Through-bulkhead initiator
TEGDN	Triethylene glycol dinitrate
TMETN	Trinitrotoluene
UHF	Ultrahigh frequency
v	Velocity
VHF	Very high frequency

GLOSSARY

Abort – Premature termination of the launch or mission of a spacecraft or missile because of equipment failure or other problems.

Actuator – A device that transforms chemical energy into a mechanical motion.

All-fire current – The minimum electric current that will initiate an explosive-actuated device.

Ambient – The normal surrounding environmental conditions, such as pressure and temperature.

Ascent engine – A thrust engine used for ascent of a spacecraft, as for example, the Apollo Lunar Module's upper stage, called "ascent stage", in which the ascent engine is also used for flight adjustments and for prelanding abort.

Ascent stage – The stage of a spacecraft designed to ascend for the return flight after a completed lunar or planetary surface mission, as for example, the upper stage of the Lunar Module, which contains the crew, controls, and ascent engine, and is used to return the crew to the Apollo Command Module in lunar orbit.

Attitude – The position or orientation of a vehicle determined by the inclination of its axes to a certain reference.

Auto-ignition – Self-ignition (of pyrotechnic compositions, for example).

Blasting cap – A device consisting of a small, short cylindrical housing containing an explosive charge, which is detonated by an electric bridgewire or by a safety fuse, and which is used for initiating a high explosive.

Braid – Woven bare wire.

Bridgewire – A fine wire which, depending on the design type, either heats up or explodes when electric current is applied; used to initiate explosive-actuated devices.

Bulkhead – a dome-shaped segment which encloses the end of a propellant tank; also a structural wall of a pressurized aircraft compartment.

Capacitance – the ratio of the electric charge applied to a device to the resultant charge of potential.

Cladding – A method of applying a layer of metal onto another metal by a continuous welded joint of both metals.

Command – A signal or pulse used to initiate a function or a sequence; used in missile and spacecraft operations.

Command Module – The control center of Apollo, used as living quarters for most of the lunar voyage.

Command and Service Module – Combined Command Module and Service Module which during the lunar surface mission of the Lunar Module remain in lunar orbit and are not separated from each other until shortly before re-entry into earth's atmosphere.

Composition – A pyrotechnic or an explosive mixture of several materials.

Crimped joint – A joint of thin metal parts obtained by folding the edges of one part over and around the edges of another part.

Descent stage – The lower portion of the Lunar Module, containing the descent engine, propellant tanks, landing gear and storage sections. For the lift-off from the moon, it serves as launching platform for the ascent stage, and it remains on the lunar surface.

Detonator – An explosive or device which is initiated by a primer and is used to initiate another explosive which can be less sensitive and larger.

Dielectric strength – The maximum potential gradient that an insulating material can withstand without breakdown, expressed as voltage gradient.

Docking – The closing and mating together two spacecraft, following rendezvous.

Docking probe – An extendable device attached to the Docking Ring on the Apollo Command Module for engaging a drogue on the Lunar Module.

Docking tunnel – Cylindrical tunnel through which Apollo crew transfers between Lunar Module and Command Module.

Ejection seat – Aircraft pilot's seat which is ejected by actuating the ejection system in case of emergency.

Exothermic material – Material evolving heat.

Exploding bridgewire – A wire which heats to a high temperature and explodes when subjected to a high-voltage high-energy pulse.

Explosive train – An in-line arrangement of explosive and pyrotechnic elements of different sensitivities and other properties.

Fragmentation – Breaking up into several pieces.

Function time – Time span between the application of initiating energy to a device and completion of its operation, or pressure rise in the device.

Gas generator – A device for producing gas of a predetermined temperature by burning solid propellant.

Gimbal – A mounting arrangement with two or three mutually perpendicular and intersecting axes of rotation on which a rocket engine or other device can be mounted, and which allows it to swivel or move in two or three directions.

Grain – The configuration of solid propellant preformed to a particular geometric shape and size, for use in rocket motors and gas generators.

Guidance system – A system which measures and evaluates flight information, correlates this with target data, converts the results into operations required to achieve the desired flight path, and transmits this data in the form of commands to the flight control system.

Gyroscope – A device using angular momentum of a spinning rotor to sense angular motion of its base about one or two axes at right angles to the spin axis.

Header – A device's insulated end through which electrical connections pass, as typically used in cartridges.

Heat sink – A contrivance for the absorption or transfer of heat away from a critical part or parts.

Helium – Gas used to pressurize propellant tanks and to force propellant into feed lines. Helium is also used in leak tests of explosive-actuated devices.

Hypergolic propellants – Propellants which ignite spontaneously upon contact with an oxidizer. This eliminates the need for an ignition system in liquid-propellant rocket engines.

Igniter – A device consisting of a contained powder charge, with bridgewire and electrical leads, that produces a flame and slight pressure, used to ignite other materials.

Incendiary material – Spontaneously igniting combustible material, used in incendiary destructors and in similar applications.

Initiator – A device consisting of a small explosive charge which is detonated by electric current or impact and, in turn, detonates a larger less sensitive charge.

Insulation resistance – The electrical resistance between the terminals of a device and the exterior body or exposed metal parts.

Ionization – A process making the total electronic charge of a substance unequal to its positive charge.

Jetevator – Ring-shaped rotatable rocket nozzle deflector mounted at the nozzle periphery.

Lanyard – A line used for mechanical initiation of some explosive-actuated devices. A typical application is a lanyard-actuated reefing line cutter, where the firing pin is released by pull of the lanyard.

Lunar Module – The vehicle consisting of the ascent and descent stages, used to transport two astronauts from the Apollo Command Module in lunar orbit, to land on the lunar surface, to provide a base of operation on the moon, and to return the astronauts to the Command Module.

Manifold – A component or device providing multiple connections.

Match – A non-contained powder charge, ususlly formed around two electrical leads, which, when energized, produces a flame for ignition.

Melting point – The temperature level at which a material melts.

Mortar – A device consisting of a short cylindrical tube containing a piston-type sabot and a breech assembly equipped with a pressure cartridge at the aft end, used for deployment of drogue chutes and parachutes.

No-Fire level - The maximum level of electric energy input that will in no case, within a specified time, initiate an explosive-actuated device.

O-Ring A sealing component, usually made from compressible rubber-like material.

Oxidizer Substance that supplies the oxygen necessary for the burning of propellants and other materials.

Parallel redundancy - An arrangement of two components, methods, or systems working at the same time to accomplish the same task, although either one could perform the operation alone.

Pellet -- Propellant in shaped, bound or compressed form.

Percussion primer - A device in form of a small capsule, containing a prime explosive charge which is ignited by the impact of a firing pin.

Pitch Movement of a vehicle from its lateral axis.

Port -- An internal or external terminus of a passage in a device. A typical example are thrust reversers of rocket engines.

Prime explosive -- The ignition material in which the bridgewire is embedded in an initiator.

Purging - Removing residual fluid or gas from a fuel tank or line.

Pyrotechnic Devices - Explosive-actuated devices, specifically, devices that burn rather than produce a shattering effect.

Redundant A second means for accomplishing a given task.

Re-entry The return of a spacecraft into the earth's atmosphere.

Re-entry vehicle - A spacecraft designed to withstand the heating associated with re-entry.

Rendezvous - Meeting of spacecraft in orbit at a planned time and place.

Retrorocket A rocket which produces thrust opposed to the vehicle's forward motion.

Roll The rotation of a vehicle about its length axis, which is usually designated with "Z-axis".

Sabot – A piston-type component in a mortar provided for parachute or drogue chute deployment.

Service Module The compartment of the Apollo spacecraft that contains propellant, navigation equipment, propulsion system and other equipment required for space flight.

Sheath A protective cover as used for flexible linear shaped charges, made from suitable metal.

Solar radiation - Energy radiated from the sun.

Space environment The conditions existing in space, i.e. a vacuum, temperature from -273°C to +540°C, zero gravity state, and radiation, etc.

Spin motor - A small rocket motor arranged tangentially on a spacecraft or stage for providing spin motion about the vehicle's length axis for flight stabilization.

Squib A device consisting of a contained powder charge and a bridgewire for initiation. When energized, a squib produces heat and slight pressure.

Stability The ability of an explosive material to withstand long periods of storage under adverse conditions.

Staging Stage separation, i.e. separation of a vehicle stage, such as an expended booster stage, from a spacecraft or missile.

Sublimation – The transformation of a material from a solid state to a gaseous state without passing through a liquid state.

Thrust – The pushing force developed by a rocket engine, measured by multiplying the propellant mass flow rate by the exhaust velocity relative to the vehicle, expressed in pounds.

Thrust chamber - The combustion chamber of a rocket engine, where by burning propellant in the presence of an oxidizer high-velocity gases are produced which will exit through the nozzle, and thus produce thrust.

Thrust vectoring – An attitude control for rockets wherein one or more rocket engines are gimbal-mounted so that the direction of the thrust force may be changed in relation to the center of gravity of the vehicle to produce a turning movement.

Trajectory – The flight path traced by a vehicle under power or as a result of power.

Ullage – The volume above the surface of the liquid in a tank, partially a function of temperature.

Ullage maneuver – A quick thrust of the vehicle made prior to firing the engine of a spacecraft, resulting in shifting the propellant to the bottom of the tanks, thus providing the necessary conditions for proper feeding.

Umbilical – The connecting service lines for electrical power, liquids and gases between the launch tower and the spacecraft, or between two stages of the vehicle.

Vernier rocket – A small swivel-mounted auxiliary rocket motor used for flight path correction maneuvers.

X-Axis – Spacecraft axis associated with yaw maneuvers in which the spacecraft turns or twists about its Y-axis.

Yaw – Movement of a vehicle from its longitudinal axis.

Y-Axis – Lateral axis running through the spacecraft; associated with pitch maneuvers, in which the spacecraft turns or twists about its Y-axis.

Z-Axis – Fore-aft axis running through the spacecraft; associated with roll maneuvers, in which the spacecraft turns or twists about its Z-axis.

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