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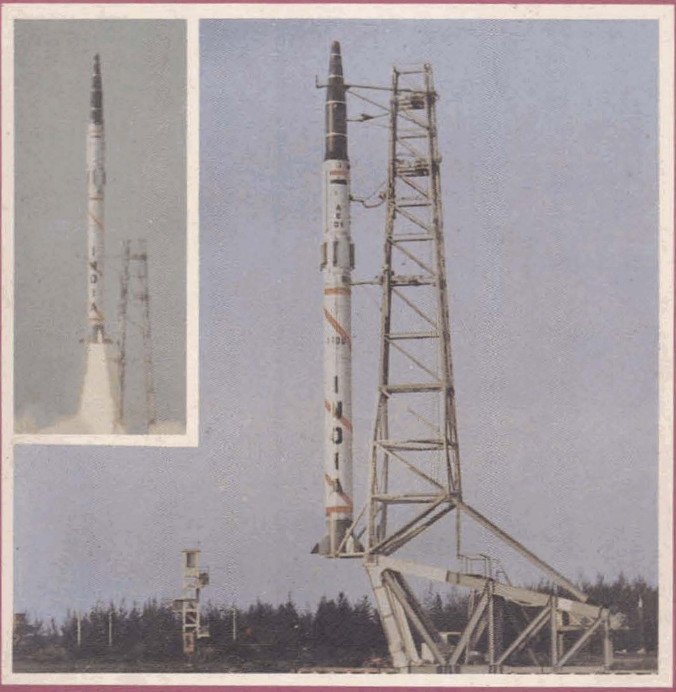
Popular Science & Technology Series

Guided Missiles



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Published 1990

Guided Missiles

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Foreword

I am delighted that Shri TV Karthikeyan and Shri AK Kapoor have brought out a small booklet on guided missiles. Their importance to the Armed Forces has significantly increased. Guided missiles are used for air, land and sea warfare. From the giants of the ICBM class to the midgets such as shoulder-fired weapons, they are used in a multitude of roles. India has been one of the earliest countries to make and use war rockets. Though these were used in the early eighteenth century, it is only in the 1980s that the country entered in a big way the area of guided missile development and production. Several of the country's academic institutions, laboratories, private and public sector industries and user services have come together and are working hand in hand in the development of missile technology in an endeavour to make the country self-sufficient in this vital area. This book 'Guided Missiles' will be valuable in introducing the subject to young readers, and I am hopeful that it will encourage many of them to study the subject in depth and learn in detail the challenge in the area of guided missile technology. I congratulate the authors in bringing out this very useful volume.

Date: 12 Oct 1991

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Preface

Use of modern weapon systems has revolutionised the concept of warfare. Technology as a force multiplier, provides the competitive and cutting edge. The technology of guided missiles encompasses the multiple streams of engineering, technology and applied sciences. A number of factors are responsible for the successful launch of missiles. These involve coordination of a variety of subsystems.

In this book we have attempted to give a bird's-eye view of the interaction of many specialisations—aeronautics; mechanical, chemical and metallurgical engineering; electronics; computers; chemistry, physics and mathematics. An effort has been made to familiarize the reader with some of the oft-used terminologies connected with missiles.

By describing in simple terms, the underlying principles in the building and launching of missile like propulsion, guidance and control, we have provided an introduction to the vast subject. The latest advances in these areas and also the salient features of the Indian missiles currently under development have been covered.

Collection of ideas for this book has been mainly from the unclassified literature and, to the best of our knowledge, only such matters which can be disclosed have been included.

Science has become the order of the day and the assimilation of science in day-to-day life is widespread with businessmen, bankers and lawyers. This book would provide a feeling of scientific awareness and familiarity with missile systems and rocket launchers to the general public.

AK Kapoor
TV Karthikeyan

Acknowledgements

The authors express their gratitude to their Director, Dr APJ Abdul Kalam for providing an opportunity to publish this work, the sensitive know-how notwithstanding.

The authors are also thankful to Shri Anand Parthasarathy and numerous other scientists for their valuable suggestions and clarifications.

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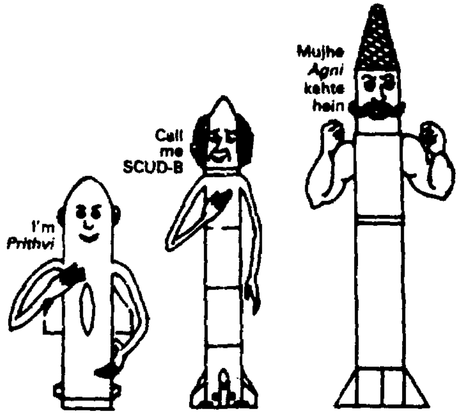


1

Introduction

WHAT IS A MISSILE

Basically any object thrown at a target with the aim of hitting it is a *missile*. Thus, a stone thrown at a bird is a missile. The bird, by using its power of reasoning may evade the missile (the stone) by moving either to the left, right, top or bottom with respect to the flight path (*trajectory*) of the missile. Thus, the missile in this case has been ineffective in its objective of hitting the bird (the *target*) . Now, if the stone too is imparted with some intelligence and quick response to move with respect to the bird, to overcome aiming errors and the bird's evasive actions and hit it accurately, the stone now becomes a *guided missile.*

The incorporation of energy source in a missile to provide the required force for its movement (*propulsion*), intelligence to go in the correct direction (*guidance*) and effective manoeuvring (*control*) are mainly the technologies of guided missiles. They help in making a missile specific to a target, that is, they determine the size, range and state of motion of a missile.

HISTORY OF GUIDED MISSILES

Looking back into the history of rockets and guided missiles, we find that rockets were used in China and India around 1000 AD for fireworks as well as for war purposes. During the 18th century, unguided rocket propelled missiles were used by Hyder Ali and his son Tipu Sultan against the British. There is a reference that two rockets belonging to Tipu's forces were captured during the fourth Mysore war in the siege of Seringapatnam in 1799 by companies of the Bengal and Bombay Artillery of the East India Company.

The current phase in the history of missiles began during the World War II with the use of V1 and V2 missiles by Germany. Since then there has been a tremendous and rapid global advancement in this field. It spawned the growth and pushed the frontiers of many new technologies in the areas of materials science, aeronautics, communications, radars and computers. Huge amounts of prime resources have been channelised into this field resulting in the development of sophisticated missiles. The readers would no doubt be aware of the important role missiles played in the recently concluded Gulf war.

TYPES OF GUIDED MISSILES

Presently, there are many types of guided missiles. They can be broadly classified on the basis of their features such as type of target; range; mode of launching; system adopted for control, propulsion or guidance; aerodynamics; etc. They are also termed in a broad sense as strategic or tactical, defensive or offensive.

On the basis of target they could be called

- Anti-tank/anti-armour,
- Anti-personnel,
- Anti-aircraft/helicopter,
- Anti-ship/anti-submarine,
- Anti-satellite, or
- Anti-missile.

The missile Milan manufactured in India is an anti-tank missile. Roland, Rapier, Crotale, etc., are examples of anti-aircraft missiles and the much talked-about Patriot missile belongs to the anti-missile class.

Another classification of missiles which is very popular is based on the method of launching. The following list will clarify this further as also Fig 1.

- Surface-to-surface-missiles (SSM),
- Surface-to-air missiles (SAM),
- Air-to-air missiles (AAM), and
- Air-to-surface missiles (ASM).

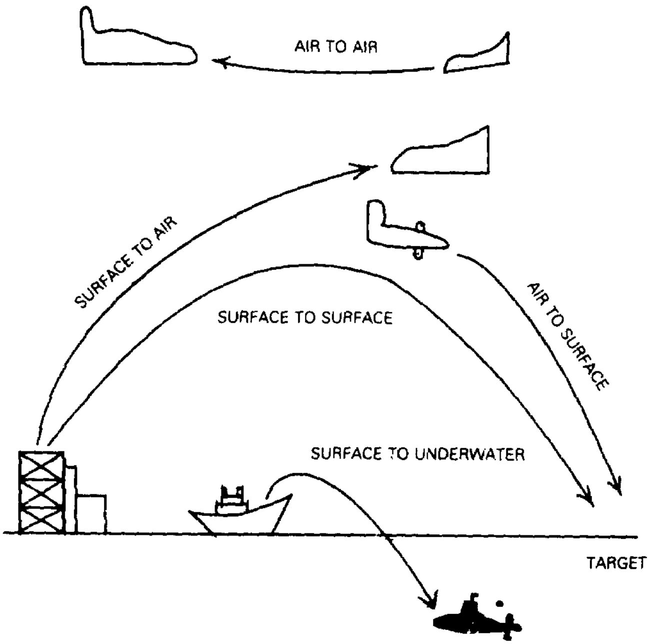


Fig. 1: Missile classification by method of launching

SSMs are common ground-to-ground ones though these may also be launched from a ship to another ship. Underwater weapons which are launched from a submarine also come under this class of missiles. Some examples of SSMs with their respective size and range are shown in Fig. 2.

SAMs are essential complement of modern air defence systems along with anti-aircraft guns which are used against hostile aircraft.

AAMs are for airborne battle among fighter/bomber aircraft. These are usually mounted under

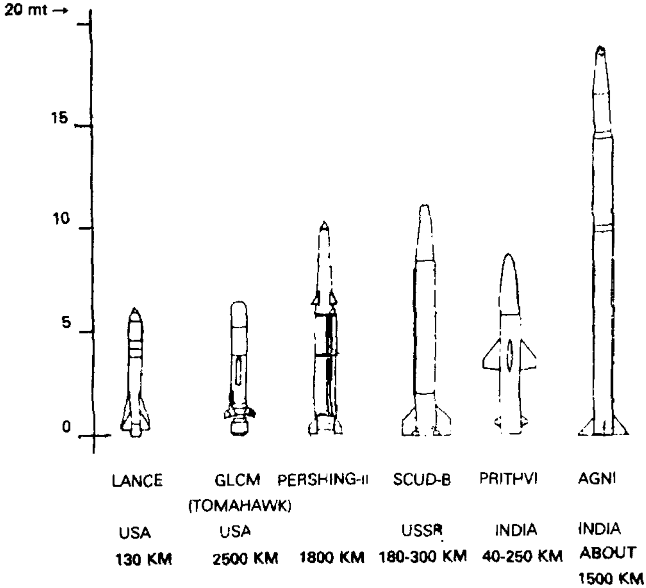


Fig. 2: Some SSMs with their size and range

the wings or fuselage of the aircraft and are fired at enemy airborne targets by the pilot through the press of a button. In his decision to launch a missile at a particular moment, the pilot is aided by a computer and radar network onboard as well as from ground-based data link. The missiles in certain types are ignited before release while in others ignition takes place after release.

On the basis of range, missiles can be broadly classified as

- Short-range missiles;
- Medium-range ballistic missiles (MRBM);
- Intermediate-range ballistic missiles(IRBM);

- Intercontinental or long-range ballistic missiles(ICBM).

This classification is mainly used in the context of SSMs. Missiles which travel a distance of about 50 to 100 km are designated as short-range missiles. Those with a range of 100 to 1500 km are called medium-range missiles and missiles having a range upto 5000 km are said to be intermediate-range missiles. ICBMs belong to the class of long-range missiles which can travel a distance of 12000 km. The Indian technology demonstrator *Agni*, is in IRBM class.

On the basis of launch platform, missiles can be termed as

- Shoulder fired/tripod launched,
- Land/mobile (wheeled vehicle or tracked vehicle),
- Aircraft/helicopter-borne,
- Ship/submarine-launched,
- Silo-based, or
- Space-based (Star Wars concept).

Based on guidance, missiles are broadly classified as

- Command guidance,
- Homing guidance,
- Beam rider guidance, and
- Inertial navigation guidance.

Depending on the aerodynamic control adopted, a missile is called

- Wing controlled,
- Tail controlled, or
- Canard controlled.

One more classification is based on the type of trajectory and a missile is called a ballistic missile or a cruise missile.

By definition a ballistic missile is the one which covers a major part of its range outside the atmosphere where the only external force acting on the missile is the gravitational force of Earth, while the cruise missile is the one which travels its entire range in the atmosphere at a nearly constant height and speed. However, a missile could have a combination of the two also where a missile could cover part of the flight in ballistic mode and later a terminal portion in cruise mode.

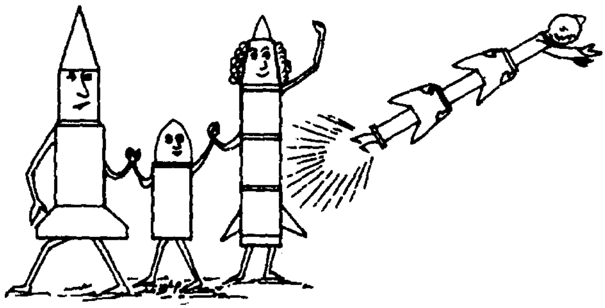
Yet another classification is based on the propulsion system provided in the missile. In rocket propulsion, we have:

- Solid propulsion,
- Liquid propulsion, and
- Hybrid propulsion.

In air-breathing propulsion, we have:

- Gas turbine engine jet or propeller
- Ramjets or ram-rockets

Currently, other types of propulsion like ionic, nuclear, plasma, etc. are under research and development but no known missile uses these.



2

Missile Propulsion

Propulsion is the means of providing power to accelerate the missile body and sustain, if necessary, to reach the required target. The basis for the working of missile propulsion systems are the well-known Newton's laws of motion. In order to aid a quick retrospect, these are stated here again.

First Law

A body continues in its state of rest or in uniform motion in a straight line unless acted upon by an unbalanced force.

Second Law

The rate of change of momentum is proportional to the impressed force and takes place in the direction of the force.

Third Law

Action and reaction are equal and opposite. That is, if a body exerts a force on another body, the other body too exerts a force on the first body of the same magnitude but in the opposite direction.

The propulsion of a missile is achieved with the help of a rocket engine. It produces thrust by ejecting very hot gaseous matter, called propellant. The hot gases are produced in the combustion chamber of the rocket engine by chemical reactions. The propellant is exhausted through a nozzle at a high speed. This exhaust causes the rocket to move in the opposite direction (Newton's third law).

As per the second law, also called the law of momentum, the rate of change of momentum causes a force to be developed. The change in momentum of the missile body including the rocket motor casing, the nozzle and other systems due to the ejected matter creates a force leading to the propulsive action on the missile body.

The missile, propelled into air, would continue to move if there were no other forces acting on it. However, resistance to its forward movement due to air (commonly called the aerodynamic drag) and the force of gravity acting downwards towards the centre of the earth are to be taken into account. By using Newton's first law, also called the law of inertia, compensative forces are imparted to the missile to overcome these negative forces.

PARTS OF PROPULSION SYSTEM

All types of rocket propulsion engines contain a chamber, a nozzle, and an igniter. The chemical reaction of propellant chemicals (usually a fuel and an oxidiser) takes place in the chamber and produces gases. The energy due to this high pressure reaction permits the heating of the product gases to a very high temperature (2000-3500 °C). These gases subsequently are expanded in the nozzle and accelerated to high velocities (2000-4500 m/s). The nozzle design, i.e., its shape and size are critical for the efficient function of the propulsion system. The theoretical model of the thermodynamic processes inside a rocket furnish the analytical data necessary for this.

The nozzle is essentially a conduit of varying cross-section from a maximum area to a section of minimum cross-section (called the throat of the nozzle) and again enlarging to larger cross-section. The nozzle would be subsonic, sonic or supersonic depending upon whether the exhaust velocity is below, equal to or greater than the speed of sound in air. Thus the common shapes of nozzles are convergent type, divergent type, or of the converging-diverging type. There are also conical and bell-shaped nozzles. Bell shaped nozzle or contoured nozzle is also named after its inventor as GVR Rao's nozzle.

The igniter, though a tiny element among the components of the rocket engine or rocket motor, has the function of initiating the proplusion system. The propellant ignition consists of a series of complex rapid events, commencing with the receipt of an electrical pulse and heat generation and heat transfer from the ignition products (hot gases and particles) to the propellant grain surface. Flame spread is achieved to burn the entire surface area to fill the free volume of the chamber. Igniters can be categorized as pyrotechnic, pyrogen, etc. Conventional igniters are made of heat releasing compounds such as black powder, metal oxides and metal powder formulations and initiated by electrical means by passing current through an element (wire) which is imbedded in the pyrotechnic mixture.

There are certain propellant combinations which do not need an igniter and they are called hypergolic. These propellants burn spontaneously when they come in contact in a certain proportion.

PARAMETERS OF PROPULSION PERFORMANCE

The terms relevant for all types of rocket engines and some of which are used as standards for gauging the performance levels of different rocket motors are: thrust, specific impulse, exhaust velocity, specific propellant consumption, mass ratio, factor of safety, etc. The relevant mathematical equations are given in Appendix A.

The success of a rocket design is also governed by a term called *burning rate*. The burning surface of a propellant recedes as combustion proceeds. The rate of regression is called burning rate (r) and is expressed in cm/s. It (r) is a function of propellant composition itself and is manipulated by variation of catalysts, particle size, percentage of oxidiser, heat of combustion of binder and other means. The basic burning laws are shown in Appendix B.

The merit of rocket propulsion design is governed by the impulse delivered per kilogram mass. If this figure is high, it means that we have obtained a better design, i.e., we are delivering the required thrust force to the missile with lesser weight of propulsion system. Since a major portion of the weight of most of the missiles is due to propulsion system and more so for longer range systems (For ICBMs it is >96% of total weight) this parameter is very important. There are multiple stages of propulsion in larger missiles based on the velocity requirements. ICBMs generally have three to four stages and long range surface to air missiles are of two stages.

TYPES OF PROPULSION SYSTEMS

Missile propulsion will be mainly of the following two types:

- Air breathing, and
- Non-air breathing.

The air breathing rocket engines use the surrounding medium of air for the support of their oxidiser. Thus, they can be used only within the Earth's atmosphere whereas in the case of non-air breathing engines the rocket engine itself carries its fuel and oxidiser on board and hence can be used in space above the Earth's atmosphere also and is thus independent of the air medium.

Depending on the physical state of matter of the propellant used, the rocket propulsion system is designated as a solid rocket motor, a liquid propulsion system or a hybrid propulsion system.

Solid Rocket Motor (SRM)

In a solid propellant rocket, the propellant to be burnt is contained within the combustion chamber or case. Figure 3 shows a typical solid rocket motor. The propellant charge or the grain contains the chemical elements for complete burning. Once ignited, it burns at a designed rate till the propellent is completely consumed. Solid rockets are relatively simple as compared to the other systems.

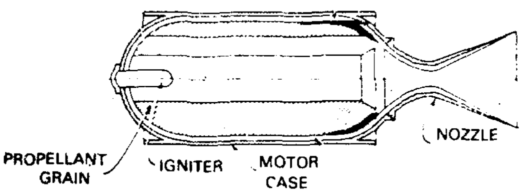


Fig. 3: Sketch of a solid rocket motor

Following are some of the main components of a solid rocket motor.

Casing. In all solid rocket motors, the casing is a pressure vessel designed and fabricated to withstand upto certain internal pressures. It can be made of a composite material such as fibre reinforced plastic (FRP). Such a casing has low weight and high strength. Casings are also made of metallic alloys. For applications in smaller rockets, titanium alloys and aluminium alloys are used and for bigger rockets nickel alloy steels are used. They are fabricated to give cylindrical shells with ends flared for joints. Complex welding and heat treatment fixtures and processes have been specially evolved for specific casing. The casings are subjected to a number of quality assurance tests for strength, toughness, soundness of weld and hydraulic pressure. The casings are provided with thermal insulation on their inner surface to protect them from hot gases. The casing has provisions for end covers, nozzle and handling, etc.

Propellant grain. Solid propellants have fuel and oxidiser mixed together in a suitable proportion. Finished propellant body called grain have rigid shape and form as per design. This shape is obtained by casting or extrusion under pressure. On composition basis there are two types of propellants.

Homogeneous: They are so called because in these oxidiser and fuel are at molecular level. Famous example being 'double base' type which is a mixture of nitrocellulose and nitroglycerine in a certain proportion. They are gelled into a semi-rigid body and extruded. They have a fairly long shelf life of more than twelve years.

Heterogeneous: In this, as the name suggests, the oxidiser and fuel are mixed mechanically in a mixer. They are also called *composite propellants.* Oxidisers are inorganic crystalline salts like perchlorates or nitrates of sodium, potassium or ammonia, while the fuel, which also acts as binder, is an organic resin. Famous resins used belong to the polybutadiene family, like PBAN-Polybutadiene Acrylic Nitrile; HTPB-Hydroxy Terminated Poly Butadiene; CTPB-Carboxy Terminated Poly Butadiene; etc. HTPB has become the single most widely used resin. In addition, fine metallic powders (aluminium) are also added to increase the energetic quality of the composite propellants along with small quantities of catalysts for various properties.

Homogeneous propellants (double base) give specific impulse of about 220 seconds maximum, while composite propellants give 260 seconds and have higher densities but have smaller shelf life. In longer range missiles only composite propellants are used while in smaller tactical missiles, double base propellants are used.

Most of the current ballistic missiles are based on solid propellants because they are storable and ready for use and minimal logistic support is needed. Propellant grains may vary in size depending on application. For example, the smallest grain for an anti-tank missile may be only a few kilograms while the largest is 125 tonnes used in space shuttle boosters where two solid boosters are used. The Indian satellite launch vehicle SLV-3 was also based on solid rocket motors. The processing costs are a large portion of the total cost of a rocket motor.

Igniter. Igniter is the device that helps to start the burning of the main propellant grain of the rocket motor. Its function is for short interval (0.1-2 seconds depending upon size) only but vital. The igniter for small motors will be a few grams of grains while it will be a few hundred kilograms for large boosters. The initiation is done using electrical power by heating a resistance wire and initiating a primary composition. Adequate safety provisions are made through electro-mechanical devices to prevent accidental initiation.

Nozzle. The nozzle is the component through which the hot gaseous mass in the motor case is expelled out. This has to be designed to withstand high temperatures and flow of gases at high velocities. The dimensions of the nozzle are critical for the performance and efficiency of the rocket motor. Nozzles are also used for producing control force for the missile. Such a technique is called *Thrust Vector Control*. It is done by deflecting the flow out of the nozzle or by gimballing of a portion of the nozzle. This nozzle gimballing requires flexible bearing nozzle.

Liquid Propulsion System

Most of the liquid propulsion rockets are used where long duration of operation is required. Here the oxidiser and fuel (both liquid) propellants are stored in separate tanks in the missile. There are basically two types of liquid propellants deployed: cryogenic (with boiling temperature below 120 K like liquid hydrogen, liquid oxygen, etc.) and noncryogenic or storable type (like kerosene, hydrazine, nitrogen tetraoxide, hydrogen peroxide, etc.). In space missions usually both propellants (oxidiser and fuel) used are cryogenic, whereas in missiles the propellants used are storable or non-cryogenic. Sometimes in space missions a combination is used where one propellant is cryogenic while the other is storable.

The engine here is relatively small in size and is designed to withstand hot gases. The engine has an injector through which the propellants are injected at

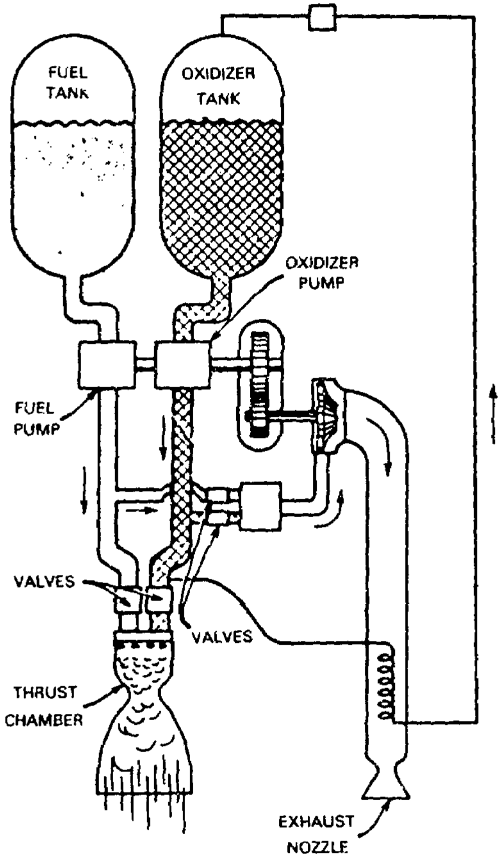


Fig. 4: Diagram of a liquid propellant rocket engine with turbopump feed system

high speeds in the form of fine jets impinging on each other; thrust chamber where the propellants react and produce hot gaseous-products and a nozzle. The propellants are expelled from the tanks under moderate pressures to a turbine-driven system from where they are fed to the injector. Figure 4 shows a liquid porpulsion rocket engine system.

Liquid propellants, especially with cryogenic propellants, give better specific impulse and better stage mass ratio for the same thrust force and duration of burn as compared to solid propellants.

Hybrid Propulsion

In this system one of the propellants is solid while the other is liquid. Usually the oxidiser is in liquid state. This system is very rarely used though it has certain advantages. It has not found much favour with missile designers the world over. Figure 5 shows a simple hybrid motor.

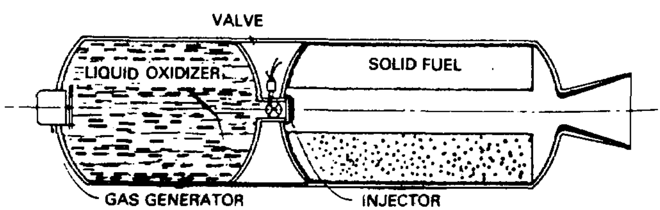


Fig. 5: Diagram of typical hybrid rocket engine

Airbreathing Propulsion

In this case the advantage is taken of the atmospheric oxygen for burning the fuel thereby reducing the quantity of propellants to be carried by a missile. This lowers the weight of the rocket greatly as 75 per cent of the total propellant's weight is due to the oxidiser. This can be used either by using small turbojet engines to power the missile or ramjets. Unlike turbojets which have extensive rotary machinery (and are therefore costly), there is no such system in ramjets. Here the speed of incoming air is utilized, i.e., when we slow it down using the geometry to intake passage, its pressure rises. Then we add fuel to this and through a nozzle obtain the thrust force. Here a conventional rocket motor (normally solid type) called booster is used to provide the velocity initially at which a ramjet engine can start operating in a steady way. Ramjets cannot operate without atmosphere and also at extremely high speeds. They also have constraints of producing high thrust for a given size. They are highly suited for long range, low manoeuvre, steady and level flying missiles. For such missions they result in a lighter missile.

However, advances in ramjets are being made to meet hypersonic propulsion requirements. Theoretical studies have shown promise in providing airbreathing propulsion even at near orbital speeds like twenty to twenty five times the speed of sound. These engines are called scramjets and National Aeronautics and Space Administration (NASA) of USA has evolved a project in which scramjets are used to develop an aerospace vehicle called NASP which will replace the space shuttle eventually in delivering payloads into orbits effeciently. NASP stands for National Aero Space Plane. In scramjet engines the very high airflow is slowed down and combustion is carried out when the speeds are supersonic say between Mach 2 and Mach 5. Liquid hydrogen fuel is the suitable fuel for such engines. These craft are winged and can take off from large conventional runways horizontally unlike rockets. They also land back and can be used many times. However a large effort has to go in to make this realisable.

State-of-art propulsion systems use chemical combustion as energy source though nuclear, solar radiation, electrical, anti-matter, anti-gravity and the like are under varying stages of feasibility studies and research. It would not be surprising if superconductivity which is creating waves in the world of science currently, too is considered as a prospective candidate for missile propulsion systems in the coming decades.

TESTING OF PROPULSION SYSTEM

Before a rocket engine can be put to use, it has to be tested. This is true whether it is in the case of the quality assurance of a rocket engine, R&D of a new or modified rocket engine or evaluation of the suitability of a new or a modified rocket motor to a specific application. Some of the tests are as follows.

- Manufacturing, inspection and fabrication tests (pressure tests, bursts tests, leak tests, electro-mechanical checks).
- Component tests (functional and operational tests on igniters, valves, injectors, structures, etc.)

- Static rocket systems tests (with complete rocket engine on test stand) : (a) simulated rocket operation (for proper function, *calibration, ignition, operation-usually* without establishing full combustion or nuclear reactivity); (b) complete engine tests (under rated conditions, off design conditions with intentional variations in environment or calibration).
- Static vehicle tests (when rocket engine is installed in a restrained non-flying vehicle).
- Flight tests: (a) on a specially instrumented flight test range with special flight test vehicle (b) with production vehicle.

Above all, flight testing of the integrated system is the ultimate in such tests. This is done in conjunction with tests of vehicles and other systems such as guidance, control, ground systems, structures, the details of which are enumerated in the succeeding chapters. These tests are usually conducted at missile or space launch ranges over the oceans. Data from most missile and space flight tests is telemetered to a ground receiving station as the test measurements are made. Some flight tests rely on salvaging some sections or pieces or data capsules. Some form a part of re-entry *technology and recovery systems.*

USES OF PROPULSION SYSTEMS

As stated earlier, the rocket engines are used in all kinds of missiles, satellite launch vehicles, etc. The technology of warhead guidance accuracy determines the lethal capacity of a missile. These technologies are kept a closely guarded secret by all countries. However, rockets with satellite payloads are used in civil applications. They are particularly used in meteorology, weather forecasting data, survey for minerals, satellite communication, mapping, etc.

3

Missile Guidance and Control

MISSILE GUIDANCE

We have already stated that guidance is that aspect of a missile system which helps it to decide the direction in which the missile should move. Generally this decision has to be taken at very short intervals of time (1/50th of a second) during the flight of the missile.

For a specific mission, particular guidance technique is used. A broad classification of various guidance systems is presented in the following pages. The different types of guidance are

- Command guidance,
- Homing or seeker guidance,
- Beam rider guidance,
- Inertial guidance, and
- Stellar guidance.

Some missiles need more than one system of guidance. The requirement depends on the phase of guidance. The various guidance phases are the launch phase, the mid-course phase and the terminal phase as shown in Fig.6.

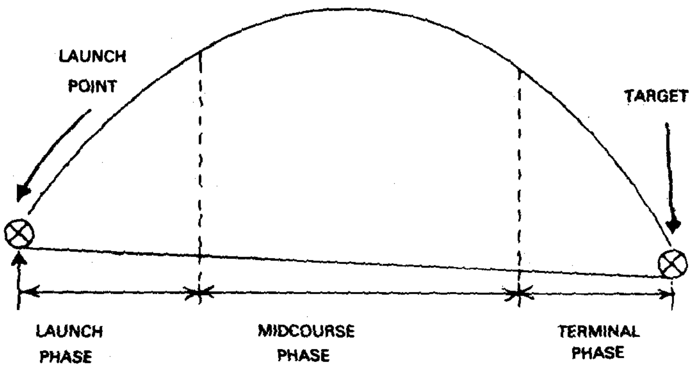


Fig. 6: Guidance phases of a missile

The aerodynamic requirements of the missile are different during the boosted launch phase. The total weight of the missile also varies as the large amount of propellant gets rapidly consumed during the launch phase. Due to this weight reduction and a consequent shift in the centre of gravity, the load, and the various parametric requirements of the missile are altered. During the mid-course phase, a guidance system is required that can hold the missile on course and at required altitude for a long time.

During the terminal phase, another guidance system is needed that can bring the missile accurately to the target and make up for possible inaccuracies or deviations which might have crept in during the flight.

Homing guidance would be a good choice for the terminal phase. The mid-course may have beam rider guidance and during the launch phase, some form of command guidance may be used.

Thus, it is seen that sensing the development status and system integration feasibility, a composite guidance system may be employed.

Command Guidance

In this method, the guidance signal is transmitted from launch site to the missile, giving the missile its deviation from the pathline pointing from launcher to the target, also called the line of sight (LOS). The missile has a logic on board to actuate its control mechanism to turn it towards the LOS. A simplified diagram of command guidance is shown in Fig.7. The signal from the ground is transmitted by different means.

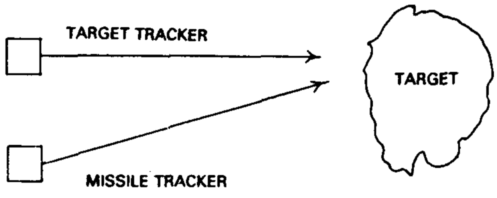


Fig. 7: Command guidance

One method is a wire link between the launcher and the missile and this has been widely applied in surface-to-surface anti-tank missiles upto 4 km range. In this a thin wire is wound on a spool on the missile and is unreeled as the missile travels. Another method is by radio link which is used by relatively faster moving anti-aircraft missiles. The third method and the latest is by fibre optic link. Wire and fibre optic link are used where the velocity of missile is below the speed of sound (Mach 1), say about 300 m/sec. The advantage of fibre optic system is that it is also used sometimes to aim at targets beyond visible line of sight. A TV camera in the nose of the missile transmits the picture through optical fibre link back to the launch site, based on which suitable commands are passed through the same link.

The deviation of the missile from target to launch line of sight is computed on the ground at short intervals (30-50 m/s) and then updated commands are transmitted to the missile. To compute errors, instantaneous positions of missile and target are found out. This is done by means of radar, TV or infrared sensors located on the launcher.

Most of the anti-tank missiles and some of surface-to-air missiles use command guidance. For example, missiles TOW, Milan, HOT, SS-II, etc., are wire guided while SAM-B, Crotale, Rapier, Roland, etc. are radiocommand guided.

An important advantage of command guidance systems is that very little guidance equipment need be carried in the missile itself. Because target tracking and flight path computation are carried out by tracking radars and the associated computers on the ground, the missile need carry only its control system and a receiver to accept the signals. Reduction in the amount of guidance equipment carried in the missile means more room for a larger warhead. Alternatively, a smaller body can be used thereby reducing the overall cost.

The disadvantage of command guidance is that it cannot be used against a situation of multiple targets. The system can guide only a limited number of missiles at one time.

Homing Guidance

Homing guidance is generally used for short-range missiles. In this system the missile receives the signals reflected/emanating from the target and generates the command to direct its motion along the instantaneous LOS formed between the missile and the target. Figure 8 gives a schematic sketch of homing guidance system. Active, semi-active and passive homing are the main types of homing guidance systems.

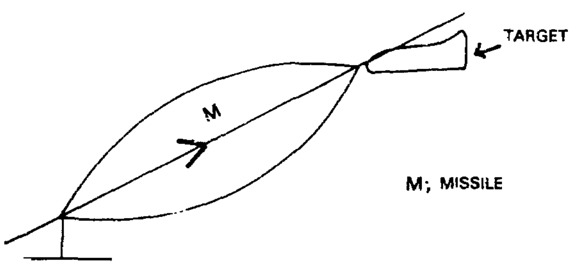


Fig. 8: Homing guidance

In the active homing guidance system, the missile itself carries the transmitter and the receiver. The signal, generally electromagnetic radiation, is transmitted at the target and the reflected signal is received. In this system, the missile is not dependent on the ground launcher. Active homing can be used for guidance in all phases, from launch upto target interception. It can also be used in terminal guidance in conjunction with other modes of guidance for the initial phases.

Where homing guidance is used alone, the range is limited because the system is bulky and needs a lot of force. It has instruments called homing head, also called seeker head, which are locked on to the target in tracking mode before launch. Such a system is also called the 'fire and forget' type of guidance. When used in terminal guidance, the homing head is provided with search capability to locate the target and then lock on to it till interception.

Active homing is used for short-range anti-tank missiles (with <4 km range). It is, however, extensively used as terminal guidance in long range surface-to-air, air-to-air and anti-ship missiles. In such cases, command or inertial guidance is used to bring the missile close to target, say within 15-20 km. Then the homing head is switched on and the search commenced. Once it locates the target, the searcher starts tracking the target and homing guidance commences. In homing guidance, the final accuracy is superior to command guidance.

In semi-active guidance, the source for target illumination is located in the launcher and the missile has only the receiver. The rest of the process is identical to active type. This type helps to have a simple onboard system and can be used for longer ranges (upto 50 to 60 km). Examples of this are the missiles Seahawk, Seadart and Seasparrow.

In passive homing type, the missile has only a receiver and detects signals emanating (not reflected) from the target. The signals could be electromagnetic or infrared or both. The missile has in its homing head detectors sensitive to infrared or electromagnetic radiation. The missile where infrared homing is used are also called heat-seeking missiles. This system can also be used in conjunction with other modes of guidance in the same way as the active system. When it is used as stand-alone method, the range is limited to a maximum of about 7-8 km in case of electromagnetic radiation.

In case of homing guidance, advanced techniques are now being used to overcome the decoys deployed like flares and chaff to distract the missile away from the real target.

Beam Rider Guidance

In this method, the guidance system is to illuminate the target by radiation of a beam of energy from a radar antenna pointed at the target. The missile is fired into this beam and thereafter gets guided over the beam till it hits or misses the target (Fig.9). The sensitivity is lesser at the commencement of the flight and towards the end as the missile approaches the target.

In a beam rider guidance system, equipment in the missile measures the displacement of the missile from the centre of the radar beam then appropriate action by the control system steers the missile back

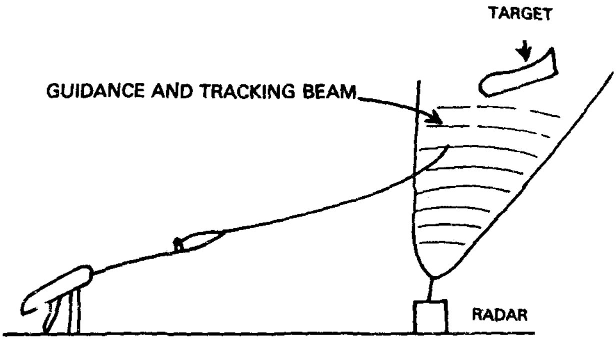


Fig. 9: Beam rider guidance

into the centre of the beam. If the missile is flying in the centre of the beam, no signals are sent to the control system, indicating that no corrective action is necessary.

The guidance beam that guides the missiles is formed by the radar antenna, which sends out electromagnetic energy in the form of lobes, as shown in Fig.10. The antenna is rotated in such a manner that the tips of the lobes describe a circle, resulting in a cone of radiation in space with its origin at the radar antenna. The missile is guided along the axis of this cone.

A few launching considerations are to be taken care of in this system. The missile must be launched in such a manner that it flies as nearly parallel to the beam axis as possible when it first enters the cone of radiation. Otherwise, it might fly right through the beam without being captured by its guidance signals. At this time the missile might not be up to full operational velocity, and its aerodynamic control

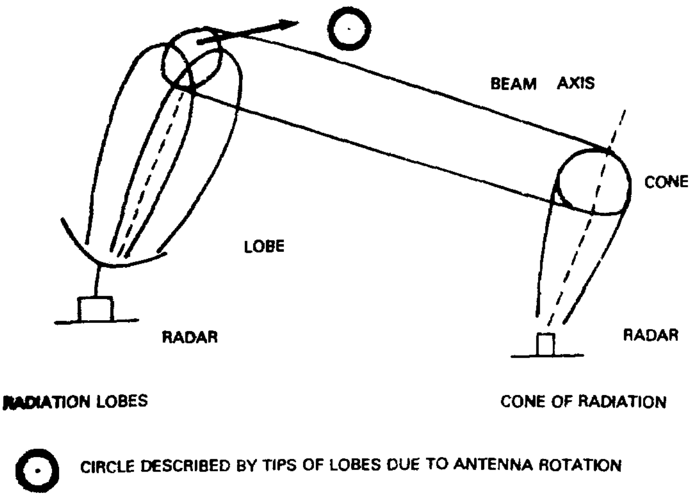


Fig. 10: Movement of guidance beam

system would not be as effective in controlling the missile as it would at the operating speed for which it is designed. Launching the missile as closely as possible to the beam axis eliminates sharp turns and sudden manoeuvres.

This type of guidance system is relatively simple, less complex with increased reliability and lower cost. The limitation is that the trajectory requires high lateral accelerations (latax) during the terminal phase.

Inertial Navigation System

Inertial navigation is another type of guidance which is used for short as well as long ranges. It is a method of dead reckoning.

The measuring instruments in this system are accelerometers which measure translational acceleration. Since acceleration is the rate of change of velocity, it is possible by performing integration to obtain the velocity from the acceleration. A second integration gives the distance travelled. These mathematical integrations are performed by electronic circuits in the inertial guidance system. The accelerometer thus makes it possible to keep track of distance travelled from the launching pad and simultaneously the distance from the target.

There are two basic types of inertial system: stable platform intertial measuring system and strap-down inertial system.

In the first, the accelerometers are mounted on a stabilised platform which maintains its reference axes in flight with the help of gyroscopes. Whereas in the second type, the accelerometers are mounted fixed to the body axes and though measurements are made for acceleration in instantaneous body axes reference they are transformed to the reference axes system using gyroscopes rate data and computational equipment onboard. However for accuracy in long range systems, stable platform system is more suitable.

Gyroscope is a mechanical instrument which uses a rapidly rotating mass to maintain a stable axis. The gyroscopes are mounted on the same platform as accelerometer platform to prevent movement of the accelerometers from the established reference axis. For simplicity it would suffice to state that the gyroscopic properties of rigidity and precision are used in inertial guidance systems to provide space-stabilized platform for the accelerometers, which must measure missile acceleration along a predetermined axis only.

The manner in which accelerometers and gyros operate together in an inertial guidance system is shown in the Fig.11.

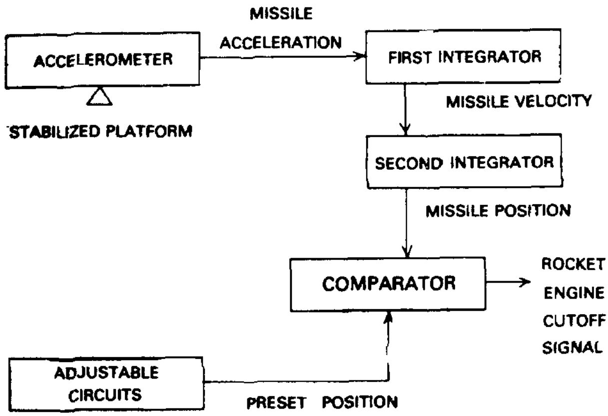


Fig. 11: Block diagram of simplified inertial guidance system

Accelerometers are suitably mounted for measuring the distance travelled along the longitudinal axis and transverse deviations from the preset course. In a ballistic missile such as the Titan or Atlas the values of instantaneous height, velocity and inclination angle are used to calculate the moment of engine's cut off in final phase of propulsion so as to achieve the preset target position. Lateral deviations from the flight due to winds, misalignment errors or changes in rocket motor thrust are sensed by accelerometers; any corrections required are attained by generating guidance commands and implemented through control system.

Thus, unlike other guidance systems, the inertial guidance system does not rely on any outside reference like heat, light or electromagnetic radiation which are susceptible to conditions like weather, atmospheric disturbances, range of the missile from the launching point, low cloud formations, radio-horizon limitations or target position. Therefore this system is self-contained and needs no ground equipment for guidance and cannot be easily detected. Jamming and countermeasures against this are a very far feasibility.

However, the system calls for a high accuracy of the individual components. Certain errors during actual run of gyros which build up with flight time, thereby leading to measurement of erroneous accelerations, are possible.

Thus, inertial guidance system is essentially a dead reckoning system that measures the distance between two points over a period of time. It cannot be used by itself alone against moving targets but only by missiles used to attack a large and fixed target such as a city. All ballistic missiles employ inertial guidance.

One of the most sophisticated inertial guidance systems is used by the Peacekeeper ICBM more commonly known as the MX. It makes it the world's most accurate strategic missile.

The inertial sensors and mounting systems require extreme precision and the MX inertial measuring system is so complex that it has become difficult to produce. It does not use traditional gyroscopes, but inertial reference spheres due to which its guidance system is called Modified Advanced

Inertial Reference Spheres. The same system has been adopted for another advanced US missile, the Midgetman.

Stellar Guidance

These systems are used by some strategic missiles and use star constellations as points of reference for guidance. Stellar guidance is combined with an inertial guidance system on the TRIDENT D-5 (also called TRIDENT II) built by Lockheed Missiles and Space Co of USA.

This thus is a brief pen picture of the various guidance systems adopted. A few other systems without their details are hypergolic guidance, a oustic guidance and optical guidance. Some of these are also used in satellite applications which is a direct outgrowth of missile technology.

MISSILE CONTROL

The reader would have by now seen that a missile gets propelled and guided towards its target destination by the systems explained earlier. In missiles the control function is to ensure stability of the missile and implement the guidance signals received from external sources or generated onboard. The control, after processing the guidance signals, actuates the aerodynamic surfaces on thrust vector to generate turn of the missile speed and direction as required.

The guidance system is to detect whether the missile is flying above or below, to the left or right, of the required path. It obtains these deviations or errors and sends signals to the control system to reduce these errors to zero. The task of the control system therefore is to manoeuvre the missile quickly and efficiently making use of these signals.

In order to appreciate controls we shall briefly describe the motion of the missile as a free body. The missile has a total of six degrees of freedom of movement. Out of this, three degrees are translational or linear about the three axes viz., x, y and z; while the other degrees are rotational movement about three axes termed as pitch, yaw and roll.

Pitch is the turn of missile when it climbs up or down. Yaw is its turn to left or right. The roll is when the missile rotates about its longitudinal axis, which is also called roll axis. The longitudinal axis is the one running from nose to tail. If a missile is resting horizontally then, the pitch axis is the one which is normal to longitudinal axis and parallel to the horizontal axis and pitch axis (Fig.12). Missiles can roll when in motion due to various reasons.

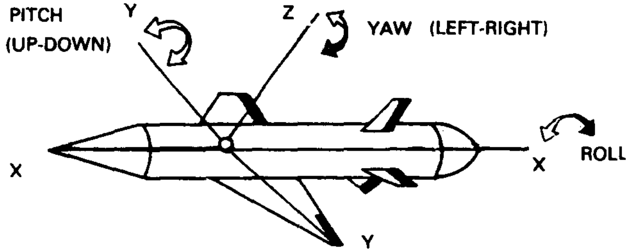


Fig. 12: The six degrees of freedom of movement of a missile—three translational and three rotational

There are missiles in which roll is controlled. Roll can be sensed onboard using a free gyro sensor and eliminated through actuation of controls. Some missiles have roll induced by design to use it for stability. The other axes which are controlled for motion are pitch and yaw axes.

Control Force Generation

The required force to generate the turn in the missile can be produced by many methods like aerodynamic control, thrust vector control and reaction control system or vernier rockets.

Aerodynamic control. This method can be used when the missile is moving in the atmosphere above a certain minimum speed. In this flat aerodynamic surfaces called control surfaces provided on the body of the missile are deflected relatively with respect to the body to generate local differential force leading to a moment acting on the body and resulting in its rotation about a particular axis. Depending on the location of the control surface along the longitudinal axis of the missile, they are termed as canard control (nose end location), moving wing control (middle location), or tail control. Each has specific advantages and application. The control force generated is a function of the dynamic pressure control surface size and shape; angle of deflection, where the dynamic pressure is further a function of velocity of missile; and density of air at the altitude at which the missile is flying. The turning moment will be a function of this control force, location of centre of gravity of missile mass and location of the resultant centre of pressure of the aerodynamic forces acting on the body. The control designer has to reckon with changing velocity, altitude, mass and location of the centre of gravity of the missile during its mission.

Thrust vector control. Here the control force and moment are generated by deflecting the thrust force vector either by gimballing the engine (in case of liquid propellant engines), by rotation of nozzle (used in case of solid rocket motors through a flexible nozzle) or by inserting in or out vanes or blades at the exit of the jet. This system is useful when there is not adequate velocity of missile (immediately after launch) or when the vehicle is in low density atmosphere or space. However, it cannot be used when the engine burning is over.

Reaction control system or vernier rockets. This is also based on chemical propulsion system wherein a number of sets of independent small thrust body fixed engines are provided in addition to the main engine to provide control along various axes. These are generally liquid propellant systems and they can be switched on and off as and when required.

Elements of Control System

The major elements of control system are: autopilot (inertial sensors, altimeter and sensor associated along with electronics) and actuation.

Autopilot. An autopilot regulates the execution of a guidance command. For its function it gets feedback from the inertial sensors like accelerometers and gyroscopes mounted along the pitch and yaw axes. The accelerometers give the feedback of the translational acceleration developed by the missile about pitch and yaw axes while the gyros give the rate of turn of the missile about pitch and yaw axes. These feedbacks are suitably weighted and used along with the incoming guidance signal to determine actuation. The electronic circuit for this is designed to perform this calculation. In missiles where height has to be controlled, an altimeter is also provided as a sensor, and helps generate actuation of controls to maintain the height. Free gyro is also an autopilot sensor which helps in determining the roll of the missile from a reference and helps to control or eliminate the roll by generating actuation controls to develop counter moments in the missile.

Actuation. The means of deflecting the aerodynamic surfaces or thrust vector is called actuation and the force to do this can be from many sources like pneumatic (high pressure air power), hydraulic (high pressure oil power), electrical or turbo-mechanical.

All the four methods are prevalent and used depending upon the size or availability of expertise. Most of the anti-tank missiles and smaller SAMs have electrical actuation, while somewhat bigger missiles have electrical or pnemuatic system. While pneumatic actuation depends upon high pressure air pre-stored onboard, electric type will draw its power from an onboard battery. For the hydraulic type, the power source is electrical and is used in most of the large tactical and all ballistic missiles. For some of the very big missiles and space boosters actuation is realised through turbine mechanical power.

4

Missile Aerodynamics

Study of the movement of a body in the presence of air is called aerodynamics and this study is vitally important for the design of aircraft, missiles and rockets. The atmosphere as we know is densest close to earth's surface at sea level. As we go higher it becomes thinner (i.e., the pressure and density are lower). The sensible atmosphere is upto a height of about 80 kilometers. The temperature also varies with height. The layer of atmosphere nearest to earth is called troposphere. Above that is stratosphere which is further subdivided into lower stratosphere and upper stratosphere. Beyond that, is ionosphere or ozonosphere and the last is exosphere. The very high speed fighter aircraft fly upto altitudes of about 30 km, while transport jets fly upto about 10-11 km.

The aircraft and missiles are bodies that are heavier than air and so can support their weights only if they produce a force to counter it. This force can be either lift force generated by the flow of air over the wings and body or generated by means of an engine in the form of thrust. This is done by helicopters or by aircraft with swing-engines (vertical take off type) where main engines can be swivelled. In missiles (most are launched vertically or with an inclination), a part of the weight is countered by the rocket engine thrust.

When we have a body with wings or without wings moving through air, there are forces generated which act on the body to oppose its motion (drag). In other words, this force must also be countered by the engine's thrust. The drag force depends upon the fineness or bluntness and size of the body. To minimise the drag force one has to choose the aerodynamic shape such that functional requirements are also met. In the missiles aerodynamic surfaces called wings, fins, and control surfaces and body called fuselege (with suitable nose shape conical or ogival followed by cylindrical) are designed to provide the necessary lateral maneouvrability. This is achieved by deflecting control surfaces through actuation mechanism and thereby altering the balance of forces and generating turning moments. This happens at a very rapid rate.

In cruise missiles wings are provided to generate lift force while the missile flies in horizontal level mode. Most of the aerodynamics is studied by mathematical analysis of flow and then further validated by tests on scaled-down models in wind tunnel where forces are measured and correlations generated. An experimental data bank is generated for subsequent designers.

Aerodynamic considerations and structural design factors are intimately related to the propulsion and guidance aspects. Hence the external aerodynamic configuration of the missile is also of primary emphasis. Many aeronautical engineers who were earlier airplane designers transformed themselves from 'airplane to missile' aerodynamicists due to the similar principles involved and the rapid growth in varieties and classes of missiles used in modern warfare. The external missile shape and design is finalised keeping in view the needs of other subsystems and performance criteria. Thus mechanical and electric missile system engineers take equally important part in the overall missile design. This calls for a need to have a good insight and appreciation on the part of these personnel for the overall missile design.

Aerodynamic characteristics of various external components and their configuration aid their selection towards an optimum missile performance with respect to its lift and drag characteristics, aerodynamic stability, manoeuvrability, etc. Comprehensive and accurate data to enable a missile technologist to zero-in on a particular configuration is not readily available since much of the essential data is classified. Moreover, the requirement of stupendous quality of data desirable and sufficient for a fairly efficient design is a deterring factor too. However, an important asset the missile engineer must have in discharging any R&D assignment is a sound understanding and knowledge of the fundamental principles involved in all the subsystems. The fundamentals of many technically specialised areas—aerodynamics, thermodynamics (mainly heat transfer), kinematics, propulsion, structural design—are a necessity though it makes the task of the aeronautical design engineer rather complex. Some of the major considerations the latter should have for an optimisation of design are enumerated here.

- Simplicity in external configuration to reduce development time and cost.
- Efficient aerodynamic control surfaces to simplify control and guidance system circuits and to minimise servo power requirements.
- Missile range, speed and other performance characteristics that satisfy the mission requirements. Adequacy of the airframe from the standpoint of stability, maneouvrability and dynamic responses.
- Simple, efficient and highly reliable power plant.
- Low cost, productability and light weight airframe constructions.
- Accuracy of the control and guidance systems to accomplish the desired mission.
- Reliability of the complete weapon system as well as its individual componets.
- Efficiency in packaging the various major

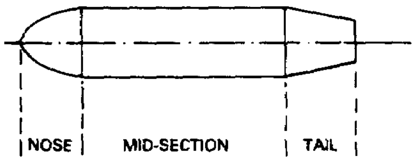


Fig. 13: Sections of a missile

components to facilitate check-out and replacement.

- Degree of complexity in the preparation and delivery of the missile to accomplish its mission.

The body of the missile may be divided into three major sections—the forebody or the nose, the mid-section and the aft or boat-tail section (Fig.13).

Nose Section

Forebodies may have many varieties of shapes, most common of which are conical, ogival, power series or hemispherical. These shapes are used primarily on the missiles of supersonic speeds and are generally selected on the basis of combined aerodynamic, guidance and structural considerations. A hemispherical nose has very high drag from the aerodynamic drag or performance standpoint, but it is excellent from the standpoint of sturctural integrity, resistence to aerodynamic heating and amenability to certain types of guidance like infrared guidance. Since the pressure or wave drag may be several times that due to friction at supersonic speeds, careful selection of the nose shape needs attention to assure satisfactory performance of the overall system.

Conical forebody has given way to other types because of relative disadvantages but the conical one is the basis for the study of aerodynamic characteristics due to its simplicity. Briefly some of the flow chacteristics about which an aero engineer will have to be very familiar are the formation of a shock wave, the shock angle, streamlines or flow direction and air properties between the shock wave and surface of the body. The supersonic flow over a cone has characteristics which are similar in appearance as that of a conical one but are markedly different in nature from those corresponding to two-dimensional flow (i.e., flow over a wedge). The similarity in appearance is that an oblique shock wave is formed at the tip of the wedge and apex of the cone (Fig. 14).

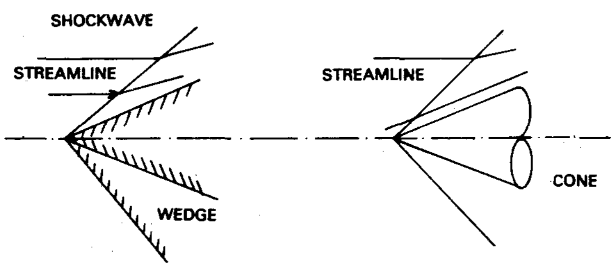


Fig. 14: Flow past a wedge and a cone

An ogive is similar to a cone except that the planform shape is formed by an arc of a circle instead of a straight line as is evident from Fig. 15. The ogival shape has several advantages over the conical section. These are:

- slightly greater volume for a given base and length (e/d ratio).

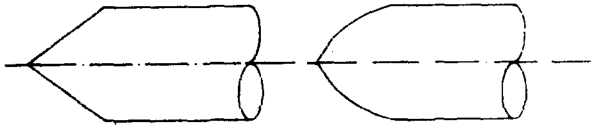


Fig. 15: Conical and ogival nose cone shapes

- a blunter nose providing structural superiority.
- slightly lower drag.

The hemispherical forebody type of nose is more widely used particularly in missiles which use infrared (IR) seekers as their homing head. The ease of manufacture of this shape is one of the major reasons and advantages for its use in spite of its extremely high drag penalty on the missile. This is a measure of the extent to which an aerodynamic engineer must compromise to achieve an optimum and feasible missile system. Many modified ogives are some of the other shapes of noses used in present-day missiles. In some missiles the shape of the nose section may be defined by the 'power series' of the Van Karman type, named after its originator. Other such elaborate expressions derive purely from radar consideration i.e., to minimise refraction and radar beam distortion. The 'parabolic' type and the 'power series' mentioned above are also derived from aerodynamic considerations.

Mid-section

The mid-section in most missile configurations is cylindrical in shape. This shape is advantageous from the standpoint of drag, ease of manufacturing and load carrying capability. From the earlier chapters it is known that the total reaction of the missile at any instant has two components, the lift (components at right angle to the direction of airflow) and drag (those parallel to the direction of airflow). These may be positive or negative. It becomes desirable to have a greater lift than the drag and this can be done by using a curved suface. Angle of attack is the direction of the reaction force with respect to the free stream direction. Even at zero angle of attack, called as the zero-lift drag $(x = 0)$, some lift can be obtained by using what are called as airfoil sections.

The effects of mid-section or afterbody extension on the aerodynamic charcteristics of the conical and ogival nose bodies have been investigatted and it is seen that the effect of afterbody extension is to increase the lift coefficient and move the centre of pressure toward aft end as a result of body carry over and viscous cross-flow effects.

Boat-tail Section

Boat tail is the tapered portion of the aft section of a body. The purpose of the boat-tail is to decrease the drag of a body which has a 'squared off' base. By 'boat-tailing' the rear portion of the body, the base area is reduced and thus a decrease in base drag is realised. However, the decrease in base drag may be partially nullified by the boat tail-drag.

In a nutshell, regarding the aerodynamic characteristics of the complete body the following generalisations may be made:

- The drag of the body at supersonic speeds depends primarily on the nose shape and the amount of boat tailing.
- Base drag is greatly affected by the presence of the jet.
- The majority of the body lift is on the nose section of the body with a small down load on the boat-tail.
- The resultant centre of pressure for a conventional body varies between 15 and 20 per cent of the body length at low angles of attack. At higher angles of attack the centre of pressure of the complete body can move forward or aft of the nominal centre of pressure location depending on the amount of boat-tailing.
- For moderate boat tailing, say seven degree, the centre of pressure tends to shift rearward with angle of attack.
- The nose may be rounded off to lower radii without causing any drag penalty.

WING DESIGN

A major important item in the aerodynamic missile configuration is the wing or the main lifting surface. A great variety of wing planforms or configurations are used. Without going into the detailed analyses for optimisation of the configuration, only the names of a few well-known theories are stated here.

The linearised theory is used in supersoninc flow over wings. This theory is derived from the exact differential equation of steady compressible flow. There are also a few equations of first order and linear equations called 'Ackeret Theory'. The basic assumptions made are: (a) the airfoil is thin, and (b) the flow is two dimensional, to mention a few typical ideal assumptions which one comes across many a time.

A few higher order terms have been derived making use of constants called the 'Busemann constants' owing their name to the man who derived them. This derivation makes use of expansion series which are mainly mathematical.

A straight wing planform is the one which is often used. Two other basic wing planforms used are delta and swept back wings. There are many variations of these basic planforms as shown in Fig. 16 each of which is optimised for its particular application.

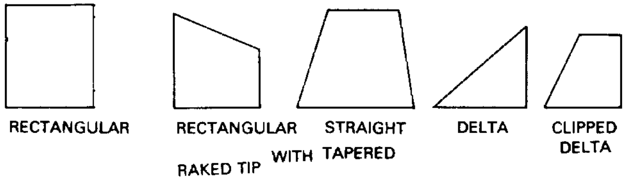


Fig. 16: Typical supersonic wing planforms

Due to the advantages and disadvantages associated with each of the basic planforms used, a thorough study involving their aerodynamic efficiency, structrual weight and cost of manufacturing is often called for.

In the analysis of wings of arbitrary planform it is important to know whether the leading (and trailing) edge is subsonic or supersonic since the pressure distribution is markedly different for each condition. Extensive experimental investigations have been conducted to determine and compare the aerodynamic characteristics (commonly called as chics') of the basic planforms for practical applications. The factors taken into account are Reynold's number, fluid viscosity and such other dimensional properties.

Thus, airfoil is the cross section of a wing which gives a minimum drag and a maximum lift.

The pressure over an airfoil is primarily a function of the angle between the free stream air direction and the surface. The airfoil shape or section for supersonic application is noticeably different from those sections used in the subsonic region. In general, sharp nosed symmetrical airfoil sections of the double wedge, modified double-wedge, or biconvex variety shown in the Fig. 17 result in the most efficient aerodynamic design.

In the final selection of airfoil shape, one must consider also the structrual efficiency and manufacturing cost as well as its aerodynamic efficiency. From the latter standpoint the double wedge has the lowest drag for a given thickness ratio, whereas the biconvex section has the lowest drag per unit strength. From the manufacturing standpoint the modified double wedge is preferred, where solid sections are involved. The sharp leading and trailing

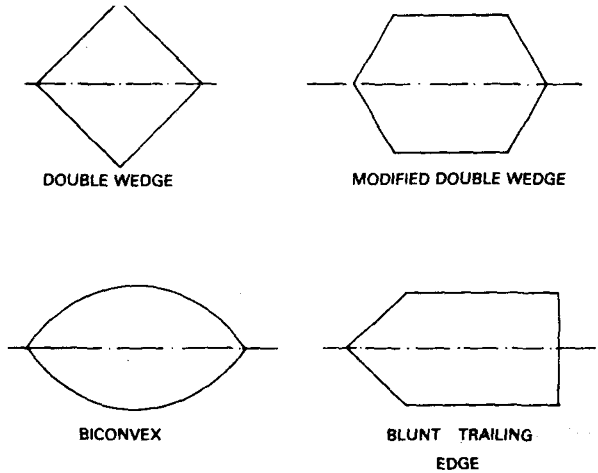


Fig. 17: Typical supersonic airfoil sections

edges may have to be rounded to provide local structural integrity as well as to minimise the aerodynamic heating effects. Generally speaking, the biconvex should be used on large wings which are not solid sections and modified double wedge should be used for smaller sized solid wings.

Finally, the size and area of the wing of a missile may be dictated by considerations of range and manoeuvrability requirements, types of design and compatibility with subsystem operation.

The performance chics of a missile are determined from the magnitude of the pertinent forces (i.e. thrust and drag weight). Drags occur in various forms as friction drag, pressure drag, induced drag and interference drag. Various theoretical methods of evaluation of drag characteristics are available and are used for their corresponding applications and the missile performance determination.

Friction drag is mainly due to the skin friction of the missile and depends on the type of flow (i.e. laminar or turbulent). Pressure or form drag depends on the contour and the pressure distribution over it. The form drag is generally small in the subsonic flow and often neglected. However, in the transonic and supersonic region this constitutes for a good proportion of the total missile drag. This can be determined both by experimental test data and also by computing machines using highly mathematical relations one of which is called the 'transonic area rule'. Induced drag is the drag due to the normal force and is approximated mathematically. The drag of composite configurations (like say the body plus wing, etc.) constitute the interference drag and these are experimentally and also analystically (with some difficulty) are predicted for a general nature of the missile behaviour and performance.

The response characteristics of the complete guidance control and airframe tap determine the effectiveness of a guided missile weapon system, in terms of accuracy and kill probability. The aerodynamicist's or the configuration designer's task is to see that sufficient static and dynamic airframe stability and damping are provided in the air frame system. The two important design requirements are stability and manoeuvrability. Various mathematical graphical, iterative procedures ,using manual computation or by using computers are available to analytically predict these two conflicting needs. These apply equally for forward or aft control.

The momentum equations of motion are applied along the three axes and are used to study the dynamic stability.

Air loads on the missile too are to be systematically analysed. In addition, other loads during flight conditions are to be of interest for the determination of the type and capacity of the servo system used for actuating the aerodynamic movable surfaces. Finally, thermal loading or aerodynamic heating must be estimated in order to determine the best available material and optimum construction for the airframe.

It is beyond the scope of this book to go into the mathematical and detailed analysis of the different aerodynamic loads and aerodynamic heating of the missiles. However, numerous methods exist for their determination some of which are limited to the determination of heat transfer to specified location on the missile under a particular flight condition. Hence an extensive study on the subject of heat tranfer is required before the proper methods are selected for a particular design condition.

Aerodynamic launching problems too surface frequently during firing of missiles. Design of missiles fired from ground launchers (static or mobile), ship board or from a high-speed parent aircraft are some of the few challenging tasks. It is understood that beam-riding missiles have occasionally lost 'beam lock-on' during their boost or launching phase as the result of excessive flight path excursion, resulting in

aborted flights. Detailed analyses of the sources and magnitudes of both internal and external forces acting on the missile during its launching phase are worked out lest these forces should cause undesirable launching dispersion. Also design modifications may be incorporated to assure a satisfactory launch. In the case of an air-launched missile, aircraft-missile compatibility must be realised. Safety of parent aircraft must be assured in addition to satisfying the requirement that the dispersion of the missile during launch must not exceed the limit dictated by guidance considerations. Retro-fitting the missile to the parent aircraft becomes a difficult problem when aircraft and missile designers are working separately as two distinct groups. At such a state of 'frozen' design, modifications cannot be easily made. From the considerations of safety criteria, the following should form a guide for both the missile and aircraft designers.

- The missile should not strike the parent aircraft during boost or jettison.
- The missile structure should not fail under any condition of flight in the immediate vicinity of the parent aircraft.
- The jet blast from the rocket of the missile should not adversely affect the parent aircraft structure and its operating components such as air inlets and control surfaces.

Ground launch problems are of particular interest. These may be categorised into (i) effects of the launching phase on the missile and (ii) effects of the missile on the launcher and surrounding areas. The former effects are studied from the standpoint of missile guidance and missile component operation, while the latter effects are concerned primarily with the safety to the launching crew and surrounding areas.

Excessive missile dispersion at launch should be avoided. These are mainly due to causes like launcher deflection, missile tip-off from the launcher, thrust and fin misalignements and atmospheric disturbances such as tail wind, crosswind and gusts.

The advent of lethal weaponry using atomic and nuclear warhead carrying missiles apart from the explosive warheads poses an extremely serious problem of safety even to the friendly troops, cities and installations. Therefore, a pronounced emphasis on 'range safety' has become a grave but important necessity for clearance of any launch or firing.

The flight path and resultant impact point can be extremely erratic if guidance and control system failures occur. Hence reliability of the components as well as a proper arming system are major requisites in any missile system.

Ideally, it is impossible to achieve 100 per cent reliability for the overall missile performance. Therefore from a realistic standpoint, the problem of range safety is analysed.

Due to any reason, when the missile 'misbehaves' the destruct system is called for which retards the missile's forward movement and prevents any damage to the surrounding. The maximum area surrounding the launch site within which the missile can impact due to malfunctioning, if any, is calculated to determine the various failure modes and their consequences.

As a practical example, India's first indigenous surface-to-surface missile *Prithvi* had a destruct system to be employed in the event of any malfunction. The philosophy consisted of cutting the fuel and oxidiser tanks and allowing the two to mix in the air itself and burn. The explosive propellants would thus get hypergolically consumed (self burnt without the aid of any initiator or igniter), thereby preventing any ground and water pollution. Cutting open the tanks was designed to be achieved by linear shaped charges which are thin rods/tubes filled with explosive material. This Command Destruct System (CDS) is proven for its reliability and safety.

Now, a few words about shipboard and underwater launchers. Space limitation and motions of the ship during both check-out and launching are to be taken care of which launching such missiles in addition to protection to both the ship and personnel from rocket motor blast effects. Little information is available on test results on launching missiles from underwater. The state of the sea should also be looked into in determining the trajectory of the emerging missile. Rocket motor ignition for an underwater launched ballistic missile occures when the missile has cleared from the surface of water to prevent any back pressure. A timer would achieve the ignition of the timer effectively.

Structural design considerations go hand in hand with the finalisation of aerodynamic configuration in the preliminary design. The primary function of the structural design engineer is manifold: (i) to ensure structural adequacy of the missile airframe under its operating environment, (ii) to investigate the most suitable materials to meet the loadings and their associated operating environmental conditions in the missile weapon system and (iii) to analyse and select the optimum type of construction for the type of coniguration from the standpoint of ease of manufacturing, cost per unit and interchangeability of parts.

Adequate factors of safety are applied to the limit or actual flight ground handling loads to assure that all stresses are below the ultimate or yield strength of the material from which the missile structural components are fabricated. Typical values of factors of safety are 1.25, and 1.5 to 2 in some cases. On the whole, the structural design should be realistic and adequate to satisfy the overall mission requirements of the weapon system. The classical equation of bending of beams and related theories for various solid sections are applied during overall structural analysis. Finite element analysis is very widely used in analysing shaped section, propellant tanks, cut outs, etc. on the structure.

FABRICATION MATERIALS

Turning our attention to the materials in general usage, missiles are generally made from aluminium and its alloys, steel, magnesium and titanium. The major concern is the strength-to-weight ratio of the material. Higher this ratio the better. On account of the high tempratures encountered by missiles flying at supersonic speeds and needs for lighter materials, newer materials are coming into usage. Fibre-reinforced plastics (FRP) like the carbon-carbon variety, graphite compounds, molybdenum, beryllium, etc. are some examples. Material for the nose cone for an Indian missile currently being developed by Defence Research Development Laboratory, Hyderabad is proposed to be of the FRP type.

Some of the important factors calling for adequate caution during material selection are as follows:

- Material strength,
- High temperature properties of the material,
- Stiffness or deformation characteristics,
- Corrosion resistance, and
- Ease of fabrication.

Adequate strength with minimum structural weight should be the aim of the designer.

Aerodynamic calculations and flight predictions involve lengthy and numerous calculations and procedures and are more mathematical and theoretical in nature. The aerodynamic engineer is more of a theoretician and requires a powerful imagination to visualize the flight conditions. Hardware oriented engineers may not 'enjoy' such a nature of table and desk work after 'living' with the actual hardwares. However, wind tunnel tests for simulation of flight conditions using missile models or full-scale ones, the experience of which may be comparable to actual flight tests of rockets, ejection mechanisms, separation systems and a score of other components and their behaviour which one can actually 'see' and gain an easier appreciation.

5

Warheads and Fuzes

The only purpose of the missile is to deliver a warhead to the target. The function of the warhead is to damage the target. The warhead is located in the missile. In most of the tactical missiles, the warhead is based on conventional chemical explosives called high explosive. The nuclear based warheads are deployed only in strategic and certain tactical missiles by nuclear club nations, namely USA, USSR, UK, France and China. They are meant for large-scale destructions of areas. The smaller ones carry nuclear material equivalent of 10-15,000 tonnes of TNT (a high explosive) while the larger ones are in terms of tens of million tonnes of TNT. Most of the advanced versions of ballistic missiles carry multiple nuclear bombs in each missile and these are called *MIRVs*

(Multiple Independently-targetted Re-entry Vehicles). Here, we shall discuss the non-nuclear high explosive warheads and kinetic energy warheads. These are specifically designed for different roles:

- Shaped charge warhead (anti-tank or anti-armour) and kinetic energy rod penetrator (against armour),
- Fragment type (anti-aircraft, anti-personnel),
- Blast-cum-earth shock (for damaging built up structures), and
- Incendiary type (against fuel and ammunition dumps, etc.)

Shaped Charge Warhead

Most anti-tank gun projectiles, rockets and guided missiles use this type of warhead. In this on impact or on a signal the warhead is detonated and high velocity finejet (8-9 km/s) of a molten metal like copper or aluminium emerges from the front end of the missile and due to its high velocity, penetrates the thick armour steel plates of tanks or armoured personnel carriers. The high explosive used here is shaped like a hollow cone, the internal surface of which is lined with high purity copper of uniform thickness. On detonation, this copper cone liner melts and forms a focussed jet. They are also used at times against concrete pillboxes, etc.

The armour toughness and thickness have been improving and to match these, the warheads have also been improving in lethality. Latest armour types are reactive armour and composite armour. The characteristic of the shaped charge warhead jet is that it loses its lethality if deflected. This is achieved by having the upper layer of armour filled with explosive which explodes on being hit by the charge and thereby deflects the jet. The same objective is also achieved by having composite (multilayered) armour on the tanks. The former is overcome by providing twin warheads in the missile which detonate sequentially which is a fraction of a millisecond. The first warhead (smaller) wastes the reactive part of the armour and the second warhead (main) pierces the armour.

The composite type of armour is also defeated by the use of kinetic energy warheads which can penetrate the most advanced armours. Here the damage is done through the use of a high velocity, high density rod (about 1400 m/s velocity and tungsten alloy material). These warheads essentially need guidance such that the missile must impact on the target.

Fragmentation Warhead

These warheads are used in missiles against aircraft or missiles, light vehicles or persons. In this case the warhead explodes and a large number of metallic fragments are dispersed at high velocities like 2000 m/s in all directions in a desired spead pattern. The warhead here consists of high explosive chemical with either a metallic casing around with groovings carved in it to facilitate fragmentation of desired size and shape or a large number of small metallic cubes or spheres. The damage or lethal capability of these warheads is measured by the number of fragments hitting the target and the energy content of these fragments (which is a function of mass and velocity of these fragments). These warheads are used when direct hit is difficult because of high velocity of target aircraft and limitations of guidance. The warhead is triggered within close proximity of the target.

Blast-cum-Earth Shock

This type is for damaging radars, buildings and even human beings. The damaging effect is achieved through the creation of a high pressure wave (blast) which spreads around from the point of blast. Upto a certain distance the pressure created is adequate to do the damage. In another type the shock waves are generated and propagated through the ground. This can damage the foundations of buildings and destroy them.

Runway Penetrators

They are also specially designed warheads which first penetrate the runway concrete surface because of their kinetic energy and then blast creating huge craters and upheaval of the runway.

Incendiary Type Fuzes

These types of warheads are carried by surface attack missiles to cause large-scale fire, etc., where the targets could be fuel dumps and ammunition depots.

FUZES

Every warhead must have a fuze. Fuzes are the devices which sense the right moment to detonate the warhead. There are numerous kinds of fuzes which operate on different principles and are suitable for different kinds of missiles, warhead and environment of operation. The most common types of fuzes are impact fuze, altitude fuze, and proximity fuze.

Impact Fuzes

Impact fuzes are used in all anti-tank missiles. Some anti-aircraft and anti-ship missiles also are provided with this fuze in addition to proximity fuze. In impact fuze, an electric pulse develops when it hits another solid object with a certain relative velocity which leads to high deceleration or inertia force. This electric pulse is used to trigger the warhead. The values of impact energy required for this purpose are always much above any impact that the missiles may be subjected to during normal handling and transportation operations.

Altitude Fuze

In this type the warhead detonation is initiated on sensing a preset altitude. This altitude sensing could be based on barometric pressure measurment or radio-altimeter reading.

Proximity Fuze

These are most often used when the impact possibility is less due to unavoidable errors in guidance and control, the missile is expected to pass in proximity if the target above or below, left or right within a certain distance. The proximity fuze can be active or passive system. In the active fuze a very low power and low range radar system transmits radiation only when the target is a small distance away and then when it receives a certain strength of reflected signal it detonates. It can also be an active laser radar system. In a passive system it is generally infrared based proximity fuze.

6

Launchers and Ground Support Systems

All the missiles need certain ground systems to help launch them at the specific targets. Launchers are the most important of these systems. The large ballistic missiles are launched from silos under the ground or submarines or moblile vehicle based launchers. The small missiles are launched from a launch-cum-container tube resting on a human shoulder. The launchers can be very demanding piece of engineering effort with precision in aiming the launcher at a particular target and very high rates of turning in elevation and azimuth in case of anti-aircraft missiles.

In addition, the ground support requires target search and tracking facilities which are normally provided by radar or optical sights, television or infrared detectors. If the missile range is say 50 km, the search radar will have range capabilities of as much as 100 km in good weather to give adequate time for launching the missile and intercepting the target at full range of missile. The ground system is developed to withstand the environment.

For certain surface-to-air homing missiles the ground system will also help illuminate the target for the missile to home-in while command generation and transmission system is needed in command guided missiles.

In addition to these we need communication and intelligence systems also on the ground to coordinate the functions of various missile launching units and have adequate information on targets. We also need to identify between enemy aircraft and friendly aircraft before launching a missile. This system is called IFF (Identification Friend or Foe). In this audio signal at known frequencies is beamed at the suspected target and if the signal is returned by the aircraft (it is automatic without pilot's participation) then it is friendly. In the case of long distance missiles extensive support in the form of ground computers and power supplies and airconditioning, etc., are needed.

CHECKOUT AND SIMULATORS

To certify the missiles worthy of deployment and ready for operation, a periodic health monitoring of its vital subsystems is carried out. This is generally done through an automatic and computerised check procedure on the ground. Similarly, simulators are provided specifically for training the personnel in the operation of the missile. These simulate all the functions of the missile's electrical and microwave components.

TEST RANGES

Extensive testing of missiles proceeds with their deployment. This testing is in two phases, i.e., development testing and user evaluation testing. These tests are done at test ranges which are suitably located keeping in view the safety requirements. The ranges have instrumentation facilities to collect data for evaluation of the missile flight. The safety zones of these regions are very much dependent upon the size and range of the missile and the flight path. Some of the ranges are located close to the sea while some others are located in the desert areas. In India the major range facility is located in Orissa at Balasore. There are two other test ranges equipped with instrumentation for testing launch vehicles, Thumba near Trivandrum and Sriharikota near Madras. These ranges are mainly for the use of Space Department. The instrumentation facilities provide for tracking radars, electro-optic instruments and telemetry receiving stations and meteorological facilities. In the range, flight tests are carried out from the Block House. Real-time data processing facilities and other facilities exist to ensure the range safety for carrying out flight vehicles in case of using telemetry command system.

7

National and International Scenario

The growth in the technological know-how of guided missiles has been spurred by an international race for strategic supremacy and commercial aspects. The launching of a new rocket or a guided missile receives world-wide attention. With the decreasing gap between the launching of missiles and satellites, the military warfare has assumed a new dimension in the form of electronic and push-button warfare.

The successful launch (even as a technology demonstrator) or failure of a missile hits the headlines in the mass media, forms a hot topic for debate in the parliaments, provides inspiration for the columnists, and cake for cartoonists. Above all, it acquires enormous political proportions both nationally as well as internationally. The seven nation embargo termed Missile Technology Control Regime (MTCR) bears a testimony to this. It is a union of seven countries who have decided neither to export items that may have missile applications nor their know-how to the third world countries. With the successive successful launches of Indian missiles (readers can get an idea about the technical and other details of these from Appendix C), neighbourly influences too have sprung in. China being already quite advanced in this field, may not be much affected by India's Guided Missile Development Programme but a lot of heat, light and sound seems to have been developed by the political observers in Pakistan. An excerpt from the statement made by a senior Pakistani diplomat reads thus: 'Defence against missiles is prohibitively expensive, but Pakistan would leave no stone unturned to acquire these systems. We will do it even if we have to eat grass.'

Nation-wide, a few more side effects are surfacing because of the stress being laid on Defence Research & Development. Collaborative ventures related to Space and missile projects have provided a good market for the private sector and industrial entrepreneurs, a field day for the advertising agencies, a major claim for credit by the election campaigners and technical and intellectual satisfaction for the scienctific community. The scientist, on his part, unmindful of some of these pleasant or unpleasant proceedings continues in his quest for new ideas and zeal of translating them into practice.

The emergence of concept of 'Strategic Defence Initiative (SDI)' commonly called as 'Star Wars' is one of the earlier births on account of these.

The Star Wars is a programme using satellite-borne remote detectors and laser-equipped satellites to provide a protective shield for the security of the West in the event of attack by hostile warplanes and missiles. The Space-based defence system would replace existing antiballistic missiles (ABMs) which must be launched quickly if they are to intercept hostile intercontinental ballistic missiles (ICBMs) which reach their targets in less than 30 minutes. Laser or 'beam' weapons are proposed to be used in 'high-ground' space. Space-based 'battle stations' using chemical lasers capable of delivering millions of watts of power and effective over thousands of kilometers, might be operational in the next century. The battle stations would use mirrors to focus the laser beam on fast-climbing ICBMs long enough to explode them. The mirrors would be segmented, each segment computer-controlled to compensate for the distortion caused by heating. One US plan envisions 18 battle stations, each assembled by components taken on three flights of the space shuttle, operating in 1750 km-high polar orbits. Figure 18 shows the concept of the 'Star Wars' programme. The habit of such strategic thought has provided the climate of 'Mutually Assured Destruction' which is being abbreviated as the 'MAD' theory much to the cheer of the anti-nuclear lobby. The popular press adopted the names 'Star Wars' and also the 'MAD' theory for the SDI postulate. The phrase 'Star Wars' was labelled after the title of a popular science fiction film and fitted easily into the headlines.

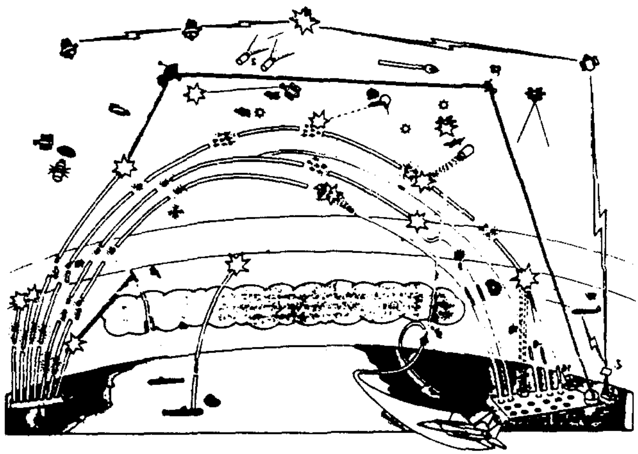


Fig. 18: Concept of 'Star Wars' programme

In short, the treatment meted out to this concept was a mixture of good and bad press. The critics describe it as a cinema-type fantasy referring to the then US President Ronald Reagon's acting background. On upon this programme, liked to call it a vision for the future for world peace by modern technology.

As if not to be outdone for the creative ideas of the Western scientists, their Indian counterparts too have come out with a novel proposal. This somewhat genuine idea may be a 'dream come true' project by the turn of the next century. Referred to as the HYPERPLANE, an acronym for HYPERsonic PLatforms for Airbreathing ascent to Near Earth orbit, describes in a nutshell what it is all about.

The proposal speaks of itself as a safe, reliable low-cost means of transportation to Space that could eventually lead to nuclear waste disposal into the Sun, thus resolving one of mankind's most serious problems.

A single-stage, fully reusable vehicle would takeoff and land from any conventional airport in the world. It is envisaged that such a concept is designable with the help of current aerospace and engineering design practices and the use of current and advanced new materials.

This revolutionary idea would outweigh the high cost of transporting useful payloads to orbit places due to intrinsic limitations in performance of rocket launchers. Effective Space utilisation would be within reach, thus, for most of the less affluent nations of the world. The flight path of the vehicle is such that it takes off from a conventional runway, pulls up like a typical aircraft, then cruises at constant acceleration while collecting air and liquefying oxygen required for the rocket phase of the flight. Finally it accelerates and climbs to orbit employing rocket engines. The flight path can be divided into three phases as shown in Fig.19.

The hyperplane demands a propulsion system that can deliver the highest possible specific impulse in each phase of the trajectory and at the same time lowest possible net weight. The various options of propulsion for each phase are shown as follows.

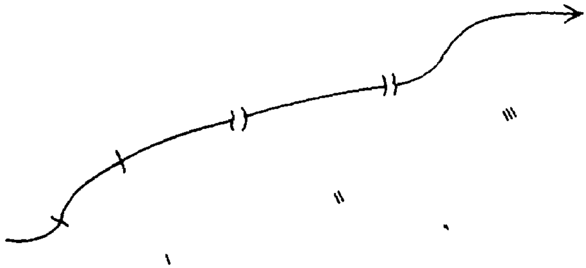


Fig. 19: Flight path of the 'hyperplane'

PROPULSION OPTIONS

Phase

I(a) ROCKET	TURBO JET
(b) AIR BREATHING	FAN RAMJET
	AIR AUGMENTED
	ROCKET RAMJET
II(a) RAM JET	
(b) SCRAM JET	
(c) ROCKET	

Other technical feasibility studies are already under progress.

With the present advancement of Indian technology, the possibility of 'offsetting' the 'monopoly' of the Western countries in the arms trade appears not too distant when the poorer Third world nations would turn to countries like India in the weapons market which India can gladly afford at reduced prices.

Appendix A

Some Propulsion Terms

The *thrust* (F) of a rocket is the reaction experienced by its structure due to the ejection of high velocity matter.

Impulse (I) often called total impulse, is the integral of the thrust F over the operating duration t.

$$I = \int_0^t F\,dt$$

Specific impulse (I_s) is the thrust that can be obtained from an equivalent rocket which has a propellant weight flow rate of unity.

$$\text{That is } I_s = \frac{F}{W}$$

It is measured in seconds and is often the measuring index of the rocket motor's performance levels.

The *specific propellant consumption* is the reciprocal of the specific impulse. It may be defined as the required propellant flow to produce a unit kilogram of thrust in an equivalent rocket.

$$SPC = \frac{1}{I_s} = \frac{W}{F}$$

It is somewhat akin to the specific fuel consumption term used in internal combustion of petrol and diesel engines *for motor cars*.

The mass ratio (mR) of a vehicle or a particular vehicle stage is defined as the final mass, m_f (after rocket operation) divided by the initial mass, m_0 (before rocket operation).

$$mR = \frac{m_f}{m_0}$$

In the case of multistage vehicles, the overall mass ratio is the product of the individual vehicle stage mass ratios. The specific power P_s is a parameter indicating the utilisation of mass in the propulsion system in producing kinetic gas power of the ejected matter.

It is defined as

$$Ps = \frac{\frac{1}{2} mv^2}{W_o} = \frac{F.I_s g}{2W_o}$$

Appendix B

Burning Rate

The following two relations are often used for burning rate r. The second equation is also called the Summerfield criterion.

(i) $r = aP_c^n$

where r and P_c are the burning rate and combustion chamber pressure repectively.

(ii) $\frac{P}{r} = a + bP_c^{2/3}$

a, b and n are constants for a particular grain design. Propellant grains are also programmed as regressive, neutral or progressive for achieving desirable variation of pressure over a period of burning time.

Appendix C

Indian Missiles Programme at a Glance

Name & Type	First test flight	Propulsion	Guidance	Range	Other features
Trishul SAM	1985	Solid HTPB composite dual thrust motor	Command to Line of Sight	500m-9km	Radar LOS guided weapon. Can be used against aircraft as well as helicopters. Has sea-skimming capability when used from ships.
Prithvi SSM	25.2.'88	Twin gimballed engines using storable liquid propellants	Strap-down inertial navigation	40-250 km	Comparable in propulsion and range to Scud missile, but more accurate. Controlled and guided all the way.

contd....

Name & Type	First test flight	Propulsion	Guidance	Range	Other features
Agni Reentry technology demonstrator	2.5.'89	Three stage vehicle (two propulsion stages and payload	Strap-down inertial navigation	Long range capability	The flight demonstrated the capability of reentry vehicle. Only reentry vehicle based on totally composite materials.
Nag ATM	7.2.'90	Smokeless, high energy solid propulsion stages	Imaging infrared & millimetric wave radar	4 km	Third generation fire-and-forget type. Can defeat any known armour of the day.
Akash SAM	14.8.'90	Integrated rocket solid propellant system	Command guidance followed by active homing	30 km	Has phased array radar for multitarget acquisition, tracking and guidance. Mounted on tracked vehicles.

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