Market Forces October 2005 Vol. 1 No. 3

HYPERVELOCITY MISSILES FOR DEFENCE

Presented by

Faqir Minhas
College of Engineering
PAF-Karachi Institute of Economics & Technology

April 6, 2005

Table of contents

Note: This 34-page paper is abridged description of the presentation. It is condensed from the original paper of 150 pages, which contains detailed information on propulsion systems and hypersonic aerodynamics.

Copies of this paper or the original paper can be obtained the Royal Aeronautical Society, Pakistan Division on demand.

Abstract

The paper reviews the history of technical development in the field of hypervelocity missiles. It highlights the fact that the development of anti-ballistic systems in USA, Russia, France, UK, Sweden, and Israel is moving toward the final deployment stage; that USA and Israel are trying to sell PAC 2 and Arrow 2 to India; and that India's Agni and Prithvi missiles have improved their accuracy, with assistance from Russia. Consequently, the paper proposes enhanced effort for development in Pakistan of a basic hypersonic tactical missile, with 300 KM range, 500 KG payload, and multi-role capability. The author argues that a system, developed within the country, at the existing or upgraded facilities, will not violate MTCR restrictions, and would greatly enhance the country's defense capability. Furthermore, it would provide high technology jobs to Pakistani citizens. The paper reinforces the idea by suggesting that evolution in the field of aviation and electronics favors the development of ballistic, cruise and guided missile technologies; and that flight time of short and intermediate range missiles is so short that its interception is virtually impossible.

PROLOGUE

Ten years after the birth of Pakistan; in October 1957, the USSR launched Sputnik I. It was a great feat in the history of aviation. On October 4, 1957, the Canadian CF-105 Arrow, the then state of the art fighter flew at Mach 2.5. The then Canadian government cancelled the project and ordered all the prototypes and drawings to be destroyed.

Khuruschev said, "the fighter can go to the museum, now".

The fighter has not gone to the museum, yet, but its role has changed significantly a considerable due to the of emergence of synergetic technologies.

I. Piloted aircraft & Tactical Missiles:

The pattern of present and future offensive action against small nations may be construed from the recent wars against Iraq, Yugoslavia, and Afghanistan. The attacking countries were very powerful and technologically superior in all respects. The attacking forces had complete control of the air, the sea, and the adjoining ground territory. The outcome was obvious, even before the conflicts began.

The offensive systems, used in the above-mentioned wars, consisted of standoff plat-forms of ships, submarines, and penetrating stealthy aircraft, capable of launching precision-guided munitions and cruise missiles. Spaced based and overhead loitering unmanned combat air vehicles (UCAVs) monitored and relayed the target information to command and control centers.

The piloted aircraft is both a defensive and an offensive weapon. Man is expected to continue to play a dominant role in a future offensive or defensive aircraft-system; however the g-limitation on the human body is of paramount importance. F-16, M-2000, Rafale-A, Mig-29 can sustain a maximum 9g. F/A-18 is limited to 7.5g. Present day's missile g-level is more than four times that of a fighter aircraft.

In the U.S.A., considerable research and development activities are devoted to the perfection of J-UCASs (Joint Unmanned Combat Air Systems). In 2004 experiments on mid-air refueling of a J-UCAS were conducted. A ground operator was able to communicate with two J-UCASs on two different missions. A J-UCAS transferred data to a T-33 airplane via a "secured" data link. In February 2003, Northrop Grumann X-47A Pegasus UAV made a precision landing on a US Navy carrier, using the shipboard relative GPS system. The X-47 program is a test-bed for the development of unmanned combat aerial vehicles (UCAV). Boeing's X-45A UCAV has undergone ground and flight tests on command, distributed control, and 4D navigation (space / time) (Ref-2).

Not in the distant future, the standoff platforms would be able to launch hypersonic (speed exceeding M 5) missiles. There is a considerable interest in scramjet propulsion, in all technologically advanced countries. The scramjet is an engine for propulsion at hypersonic missiles, which are considered suitable to hit time critical targets, such as mobile launchers and ballistic missiles. The X-43 Hyper-X program of the USA is concerned with the development of scramjet engines. The X-43 vehicle is carried to an altitude of 20,000 ft in a B-52, from where it is taken to the height of about 100,000 ft by a booster, and from there, the scramjet engine starts and propels the warhead to the intended target. The flight test on March 2004, X-43 has reached a speed of Mach 7. The next series of tests are aimed at flying it at Mach 10. Experiments conducted by the Russian, with rocket boosters have reached the speed mark of Mach 6.

The iSTAR (intelligence, surveillance, target acquisition, and reconnaissance) micro air vehicle (MAV) achieved autonomous flight in May 2003. MAV and organic air vehicle (OAV) are small vehicles, in development, to support ground troops.

Early in the year 2003, the US Air Force Research Laboratory (AFRL), Munitions Directorate tested a Low Cost Autonomous Attack System (LOCAAS) that uses an on-board GPS/INS to navigate it to a designated target. The system was released from an aircraft. It has the capability to identify SAM transport, launch, and radar systems and; it rejects decoys. The system is designed for F-16, F-22, F-35, B-1, and B-2 (Ref.2).

The development times for airplanes are much longer for a country (such as Pakistan) with little aircraft manufacturing experience. India has shortened the development cycle for its indigenous aircraft manufacturing by acquiring the know-how from Britain, Russia, Israel and other sources. Under the "Strategic Partnership" between India and Russia, India is going to manufacture, under license, 149 Sukhoi Su 30 MKI twin seat fighters. HAL (Hindustan Aircraft Limited) will also manufacture, under license, AL-31FP turbofan that has thrust vector control capability. AL-31FP engine, which has the same diameter as the F-100 engine, used in F-15 Eagle, produces far more thrust at less specific fuel consumption (sfc). Su-30MKI is more advanced than Su-27 and Su-30, which are still used by the Russian air force (AW&ST Feb. 5, 2001 pp 51-52). According to the Russian AF Commander General Anatolly Kormkov, the Russian anti-JSF program will be cheap and versatile, with moderately stealthy characteristic aircraft.

It could be a derivative of Sukhoi, Mig and Yakolev. The Russian AF commander estimates that its development could take a decade and the first prototype could be ready in 2005-06.

Mid-air re-fuelling has extended the range of stealthy fighters and bombers. With high T/W, high L/D, high lift flap, thrust vectoring, and fault-tolerant electronic and avionic systems the operational capabilities of aircraft have increased. Chaff and jamming pods, ECM equipment, radar homing and warning indicators that a SAM's radar is active etc., are aiding the capability of fighters.

The most important components of modern weapon systems are computers, which have been integrated with the cockpit. The air launched all weather and precision air-to-air (ATA) and air-to-ground (ATG) missiles and laser guided smart weapons, coupled with stealth capability of bombers and bombing accuracy have increased the power of fighter-bombers.

The advanced integrated command, control, communication, computer, intelligence, surveillance, and reconnaissance (C4ISR) network is on the horizon (expected to be available around year 2010). The radar and electronic sensors for intelligence gathering and reconnaissance are expected to provide near real time and high accuracy locations of time critical targets to the C4ISR network. The C4ISR network is expected to provide the target locations to the fighter, bombers, helicopters, UAVs, ships, submarines, and ground vehicles of the near-future attacking forces of technically advanced countries. The high-speed data links from the launch platforms to the attacking missiles are expected to convey the updated target locations of mobile targets. These links are expected to be able to provide battle damage indication (BDI) to commanders, also.

The spaced based weapon systems are evolving as a part of the future military mussel. The current space based weapon development and sensor technologies are expanding very rapidly. These technologies are being integrated with the fighter aircraft. There has been progress towards the development of chemical oxygen iodine laser (COIL), as a mega-watt weapon class airborne laser (ABL). There are preparations to test the device on a 747-200. The continuous output of all gas phase iodine lasers (AGIL) have exceeded 33 watts. Several solid-state lasers have been tested for tracking targets. Mobile theatre high-energy laser (MTHEL) has proved to be a potential field weapon. It has been tested to destroy artillery shells and rockets in flight. The Israeli Ministry of Defense and the U.S. Army Space and Missile Defense Command are carrying out the MTHEL development jointly.

A stealthy aircraft design makes use of faceted configuration to minimize the normal reflection back to illuminating radar and electro-magnetic properties of airframe materials. In order to achieve stealthy characteristics, design compromises have been made. For example, large horizontal and variable geometry air-intake are needed for aerodynamic efficiency. Shielded inlet and exhaust nozzle, closed coupled layout and thrust vectoring are employed, as a compromise. This can lead to 20 to 35 percent loss in thrust. The use of un-equal leading and trailing edge sweeps and highly loaded wing tips have been used, in order to produce small radar energy spikes. The use of sophisticated electronics, digital control, BVR combat capability, and superior weapon systems is anticipated to compensate for aerodynamic deficiencies in stealthy airplanes.

The use of computers, to gather intelligence and to introduce false information in the enemy's computers, has been considered an effective weapon. This includes getting into the enemy's computer systems and reading of e-mails of officers and civilians.

EFA 2000 Euro-fighter, developed by Britain, Germany, Italy, and Spain an is M 2.2 delta wing fighter. It is equipped with advanced radar, infrared sensors, and a package of advanced avionics.

The power of the piloted aircraft comes from the parallel advancements in weapons, electronics, electro-optical sensors, computers, stealth technology, and electronic counter and counter measures.

Soft civilian targets have been attacked, in most modern wars, under one pretext or another. A passive defense to protect civilian population against biological and nuclear weapons is usually neglected in most defense plans.

This main arguments of this section may be summarized as follows

- The potential of human-piloted airplanes at speeds higher than Mach 2 is limited due to excessive g-forces on the human body during military combat maneuvers, whereas a missile can sustain much greater acceleration.
- Remotely controlled unmanned vehicles are evolving as potential future weapons. The developments in radar and smart active guidance system tend to increase the lethality of aircraft beyond visual range (BVR).
- The technologically advanced countries have strong navies; and ships and submarines form forward mobile stand off platforms, for launching cruise missile and bomber attacks.
- The carriage of guided weapons by aircraft and their guidance via satellites and unmanned aerial vehicles (UAV) have added new dimensions in modern warfare.
- Maneuverability drives T/W, W/S, higher load factors and thrust vector control.
- A less maneuverable fighter with a more maneuverable missiles can do the job, with better training and tactics. Better training and tactics really use one's own strength and exploit the opponent's weaknesses.
- Much more money is needed to build a very maneuverable fighter than a maneuverable missile.
- Missile research to develop hypersonic vehicles to complement the existing or projected fighter aircrafts seems to be a good option for Pakistan's the national air defense.

- But, high caliber trained scientist, engineers, technologists, and organizers are needed to achieve, this objective.

II. Ballistic and cruise missiles:

The emergence of ballistic missiles has completely changed the concept of present day warfare. The first modern ballistic missile was introduced by Germany, in the late stages of World War II. It was called **V-2** (Vergeltung swaffen zwai : Vengeance weapon 2). It was a single stage rocket, weighing about 30,000 lb (12,835 kg) and carrying high explosive warhead 2200 lb (1000 kg). V-2 was propelled by a rocket motor with liquid oxygen and 75% ethyl alcohol and water. It produced a thrust of 25,000 kg. Burn time was 60 seconds and burn out velocity about 6000 ft/sec (1.6 km / sec). The approximate range of V-2 was 230 miles (360 km). It attained a height of 56 miles (90 km) (apogee). Between September 1944 and March 1945, 4300 V-2 missiles were launched against targets continental in Europe and Britain. The first cruise missile, V-1 (Buzz Bomb) was also introduced by Germany during World War II. It carried a warhead of 1000 kg of high explosive. Between June 1944 and June 1945, 21,000 Buzz Bombs were used against targets in Europe. 2340 were launched against London alone.

After the WW II, the U.S.A. employed captured German engineers. From the components, captured during the occupation of Germany, about 100 V-2 were built and tested at White Sands proving grounds, during 1946 - 51. The first copy of the V-2 was the HERMES was built in the first five years with the help of the captured scientist Werner von Braun. The other variants of these efforts were: Redstone (1958) missile and Pershing (1962) missile. In December 1958, Werner von Braun started to design Tomahawk cruise missile for a range of 800 km. The Tomahawk Land Attack Missiles (TLAM), Tomahawk Anti-ship Missiles (TASM), Tomahawk ship and submarine launched are a few of the variants of Tomahawks now in the USA inventory.

The Soviet Union followed the USA development course. With the help of captured German engineers, they experimented with V-1 and V-2. Their first missile was the SS-1 Scud A (1955), with a range of 160 km. The Scud B (1961) had a range of 300 km. The Scud C (1965) has a range of 600 km. Skyster (1956), with a range of 1200 km was a stretched V-2 missile. Thousands of the Scud missiles have been sold to Egypt, Iran, Syria, and North Korea.

The U.S.A., Russia, and other technologically advanced nations have huge inventories of all sorts and types of ballistic and cruise missiles. These are capable of carrying nuclear bombs and biological weapons. The launch weights are greater than 100,000 kg (compared to 10,000 kg of V-2). SS-6 has a range of 10,000 km and launch weight of 500,000 kg. The ballistic missiles (the state of art 2000) have launch weights of 100,000 – 1,000,000 kg and can carry a payload of 10,000 kg. The range can be 1000 – 50,000km. The cruise missiles have launch-weights of 1000 – 10,000 kg and range 5,000 – 50,000 km and can carry a payload of 1000 kg (Ref.1).

These are the real the weapons of mass destruction.

The old missiles, like ICBM Minuteman-2, carried only one warhead, whereas modern missile such as Minuteman-3, Polaris carry multiple warheads and are called MIRV (multiple independently target re-entry vehicles). These vehicles have post-boost control system, which has an additional rocket stage that releases these warheads at re-entry points against pre-selected separate targets. The position and velocity of a warhead, at the time of re-entry in the atmosphere uniquely determines the point of impact on the surface of the earth. The shape of the ballistic trajectory and re-entry point depend upon the guidance and control of the missile during the powered phase of the trajectory. Each Trident nuclear submarine carries 24 ballistic missiles with multiple warheads, over 150 per submarine (Ref.4)

The current development in the ballistic missile field is the AMARV (advanced maneuverable re-entry vehicle). The re-entry vehicles of these missiles have their own guidance system for maneuvers during the terminal phase of the flight to avoid anti-ballistic weapons and to correct atmospheric anomalies to land accurately on targets.

"Russian designers have improved the accuracy of India's 250 km range Prithvi and 2500 km range Agni ballistic missiles, using upgraded Scud B seekers that reduce the CEP from 900-1000m to 20-40m. (Ref.1).

In 1987, 28 nations lead by the U.S.A. have introduced *"Missile Technology Control, Regime (MTCR) Restriction"* to control the transfer of equipment and technology in the area of ballistic missiles and cruise missiles. Under these restrictions, missiles allowed are with 300 km and 500 kg payload only within these restrictions, I believe, a basic hypersonic tactical missile can be developed, that can be adapted as ATS (anti-tank), STA, ATA, or ant-ship weapon system. If, such a missile is developed within Pakistan, by the use of existing and up-graded facilities, this will not violate the MTCR restrictions.

THAAD (Theatre High Altitude Area Defense) system is the defense-shield the United States of America is building to defend America / NATO countries from a possible ballistic missile attack. It is expected to be operational by the year 2007. It, essentially, consists of ground and space based early warning systems, BM / C^3 I system, and surface to air, air to air, ship to air layered interceptors, placed around potential launch sites of long range ballistic missiles. In the ballistic missile defense, reaction times are of the order of a few minutes. The THAAD system consists of three over lapped defense systems. The forward layer is to intercept the ballistic missile during its boost phase and this would comprise of forward bases supported by space base early warning and BM / C^3 I components. BM / C^3 I "comprises of the capabilities, processes, procedures, and information for coordinating and synchronizing, both offensive and defensive measures, during, peace, crises, and wars" (Ref.1).

The upper layer of this defense shield of surface, air, or possibly space based interceptors to destroy the ballistic missiles during their mid-course trajectories. The lower layer of defense is to destroy the missile during the terminal phases of their trajectories. It is a form of local defense shield. It could consist of surface-to-air or air-to-air interception systems. The cost, technologies, forward bases, and control of sea are within the capability of a few western nations only. Nations, who have such a system, would posses a much greater power over smaller counter.

No small or large nation, in Asia, does poses or is likely to pose any threat to the USA or NATO countries, in the foreseeable future,. But, THAAD system would keep the

NATO countries under American hegemony and dominance and would give the USA additional power over smaller nations.

The other antiballistic missile systems are USA Patriot PAC-3, Russian S-300, Israeli Arrow system, French FSAF. Most of these systems emerged in the sixties and are expected to be in final hit to kill stage by the year 2010.

The actual motion of the missile in the atmosphere is quite complicated. Atmospheric conditions change moment by moment and affect the subsequent motion. Both open and closed loop controls are needed to lead the missile to a cut-off point in space. During the boost phase, the missile is in the dense atmosphere and is also in the gravity field. Both gravity and atmospheric drag affect its motion.

Newtonian equations of motions are valid in the inertial frame of reference. Such a system is attached to the centre of the sun. Since the duration of motion of a missile is very short, the motion of the earth around the sun is neglected and a quasi-inertial reference system that is a non-rotating reference system with origin at the center of the earth, is employed. In this system, the X-axis is aligned to the mean vernal equinox (of the date), the first point of Aries γ. The Z-axis is aligned to the north, and the Y-axis lies in the equatorial plane, forming a right-hand orthogonal system of coordinates.

The launch site is related to this system, by a polar coordinate system, in which the coordinates of a launch site are its radial distance, R_l from the center of the earth, its right ascension and declination. The right ascension is comprises of the Greenwich hour angle of the vernal equinox plus (ω_e t_L) and the longitude Λ_l, The declination is the latitude Φ_l of the launch site. "ω_e" is the angular rotation of the earth and "t_L" is the time of launch, Universal Time.

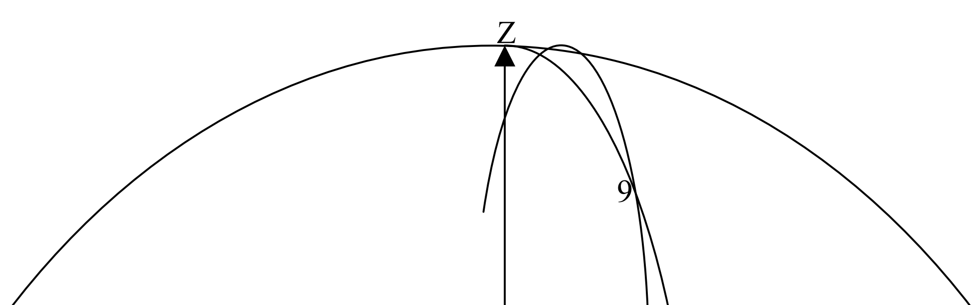
The launch site coordinate system may be chosen as a rectangular Cartesian coordinate system, in which the outward-pointing radial is chosen as a Z-axis, X-axis pointing in the down range direction and the Y-axis in the cross range direction. Both X-axis and the Y-axis lie in a plane normal to the Z-axis, at the point of launch. The down range makes an angle, say, "ψ_L" with the north (heading). The coordinate system forms a right-handed orthogonal system.

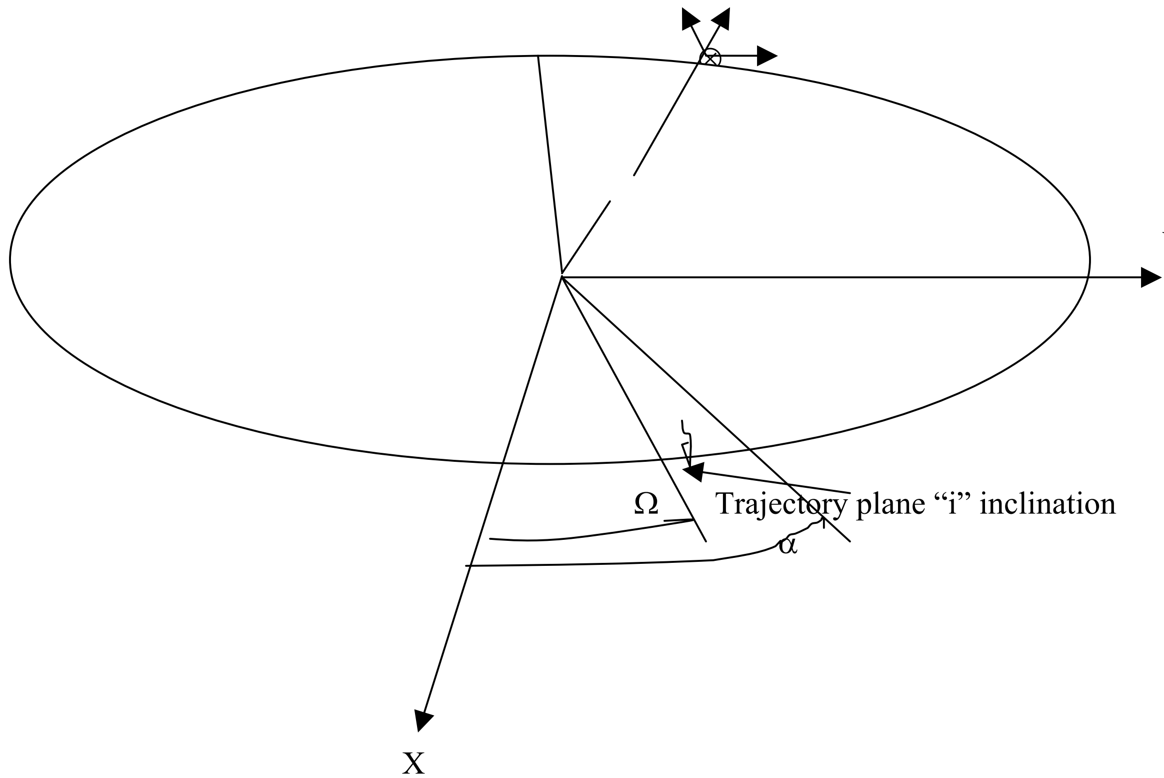
The launch site coordinate system is related to the geocentric equatorial coordinate system, described above, with launch site coordinate system by Euler angles rotations of the Z-axis by (90° + right ascension of launch site), X-axis rotation by (90° - declination), and Z-axis rotation by (90° - the heading), respectively (Ref.4&5).

Ballistic trajectory coordinate system:

Trajectory plane

Launch site coordinates: $r = R$ (the earth radius)
α = the right ascension
δ declination = latitude.



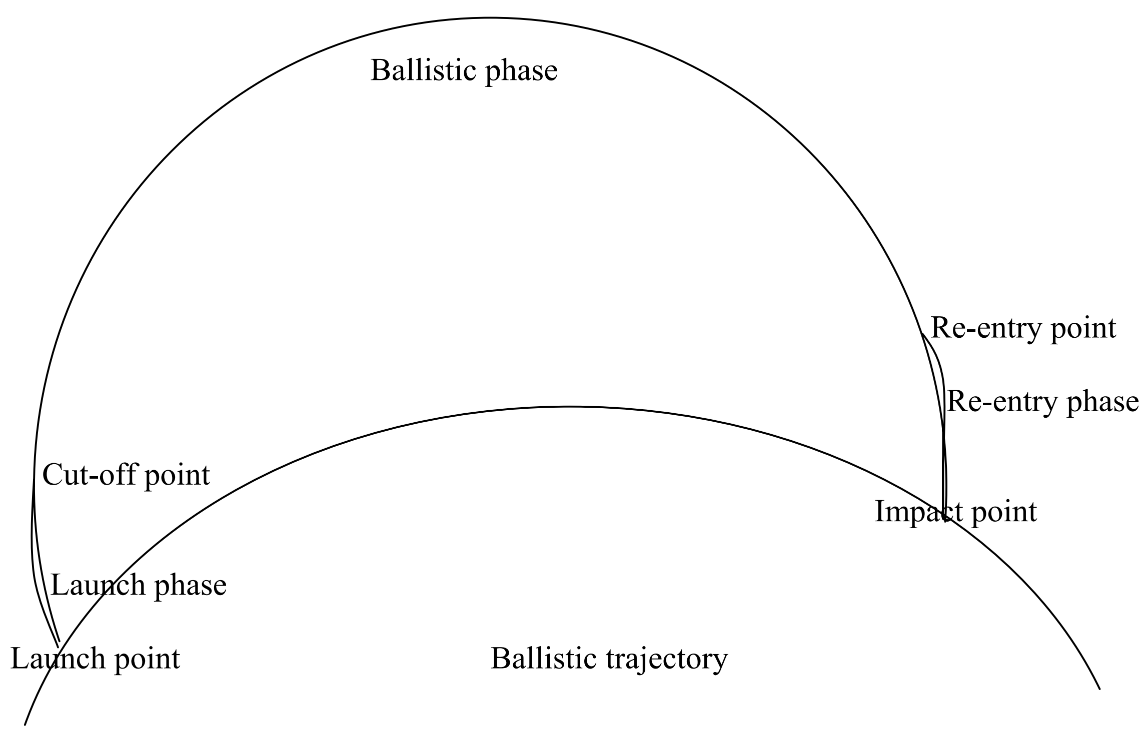


⊗ - Cut-off point: declination = δ_1 , heading = ψ_1

“i” - : $\cos^{-1}[\sin\psi_1 \cos \delta_1]$ $(0 \le I \le 180)$

$V_{xi} = \omega (R+h_1)\cos\delta_1 \sin\psi_1$ = down range

$V_{yi} = \omega (R+h_1)\cos\delta_1 \cos\psi_1$ = cross range



Equations of motion:

For **the short range or tactical missiles**, the acceleration of the missile is expressed as:

$$dV/dt = d^2r/dt^2 = T/W - g_0[R/(R + h)] – (½ C_D \rho S V^2)/W - 2\omega \times V \quad \ldots \quad (1)$$

where, **r**(x, y, z) is the position vector of the missile referred to the Earth centre, which is considered the origin of inertial coordinate system. "**ω**" is the rotation of the Earth (0.000073 radian per second). The last term in the acceleration equation is the Coriolis acceleration. *The above equation is non-linear and can only be integrated, numerically, on a computer*.

Simplified solutions are obtained to gain insight into the characteristics of the ballistic missile:

The thrust vector, '**T**' in the above equation is approximated as:

$$T = I_{sp}\, g\, M_{prop} / t_{bo} = I_{sp}\, W_{prop} / t_{bo}, \quad \ldots \quad (2)$$

Where, I_{sp} is the specific impulse, M_{prop} is the mass of the propellant burnt, and t_{bo} is the time of burn out of the propellants.

The specific impulse for jet engine is in the range of 1000 to 4000 seconds. For rocket propulsion, the specific impulse values lie between 200 and 300 seconds. The SCUD B missile, which uses fuming nitric acid and di-methyl-hydrazine at combustion pressure Pa = N/m^2 = 115, has a specific impulse of 280s. The Saturn rocket, which uses liquid oxygen and liquid hydrogen at the combustion chamber pressure of Pa = 113, has a specific impulse of 335 s. The specific impulse is a complex function of combustion temperature and pressure, Mach number, and specific heats of the combustion products.

On short range missiles the effect of rotation of the earth is small and is neglected in the analysis of the boost phase. It is incorporated as correction to the initial conditions to the coasting phase, that follows the boost phase.

The initial velocity, V_i is zero, if the launch is from the ground; it is equal to the velocity of the aircraft if launched from an aircraft. The burnout speed depends on the value of the specific impulse and fuel fraction. Typically for the rocket propelled missile the specific impulse is between 200 seconds and 300 seconds. For fuel fraction = 0.5 and specific impulse = 250 second, the increase in velocity is about 5600 ft/sec.

In the above analysis the air drag and gravitational effects are neglected. Both the drag and gravitation affect the motion. Simplifications are made in preliminary evaluation.

Neglecting gravitational terms and the rotation of the earth, equation (1), after burnout, in the simplified form becomes:

$$dV/dt = - (g/W)\,(0.5)[\rho V^2 S\, C_D] \quad \ldots \quad (3)$$

The usual expression for the drag, expressed in terms of drag coefficient, has been assumed. It may be noted that the density decreases with the altitude. The equation is usually written as:

$$dV/V^2 = -(1/2)(\rho g)(S\,C_D/W)\,dt$$

$$= -(½)(\rho g/\beta)\,dt$$

where, "β" is called the ballistic coefficient and is equal to $W/(S\,C_D)$.

Assuming "ρg" and "β" as constant, the above equation can be integrated

$$1/V_{t1} - 1/V_{t0} = [(½)(\rho g/\beta)]\,(t_1 - t_0) \qquad \ldots \qquad (4)$$

If the gravity is included in equation (4), the motion can be expressed by two parametric equations:

$$d^2h/dt^2 = (½)(\rho g)(V^2/\beta)\sin\gamma - g$$

$$d^2x/dt^2 = (½)(\rho g)(V^2/\beta)\cos\gamma \qquad \ldots \qquad (5)$$

where, "h" is the altitude measured from the earth, considered flat. "x" is the down range. The exact solution requires the use of a computer. "γ" is the flight path angle. However, if we assume the body is non-lifting (i.e. descends vertically), drag coefficient and "g" are constant, and the density varies with the height, as:

$$\rho = \rho_0\, e^{-c\,h}$$

Where "ρ_0" and "c" are constant.

Equations (5) may be reduced to give the magnitude of deceleration due to drag.:

$$(d^2h/dt^2) = (-\,dV/dt)/g = (½)(\rho_0)(V^2/\beta)e^{-ch} - 1 \qquad (6)$$

Neglecting drag altogether, the equations give parabolic trajectory on flat earth. Neglecting the drag, thrust, and rotation of the earth, equations of motion, in polar coordinates, take the following form:

$$d^2r/dt^2 - r(d\theta)^2 + Mg/r^2 = 0 \qquad \ldots \qquad (7A)$$

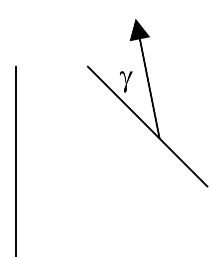
$$(1/r)d[r^2 d\theta/dt]/dt = 0$$

Or, after integration,

$$r^2 d\theta/dt = (R_0 + h)V\cos\gamma \qquad \ldots \qquad (7B)$$

Such equations are used to describe the post boost or coasting trajectory

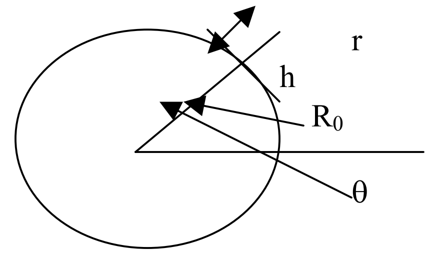
The initial conditions are:



$r(t=0) = (R_0 + h) = r_0$

$\theta(t=0) = 0$

$dr/dt(t=0) = V \sin\gamma$



These equation can be written as follows to represent a conic: (Ref 6)

$$r_0/r = [(gM/r_0)(1 - \cos\theta) / (V^2 \cos 2\gamma)] + [\cos(\theta + \gamma) / \cos\gamma] \quad \ldots \quad (7)$$

"θ" is measured from the initial launch position.. If "Δθ" is the angle subtended between the launch to the impact points on the surface of the earth, considering the earth to be spherical, the down range is given as:

$$R \text{ (range)} = R_0 (\Delta\theta)$$

For a desired range "R", the central angle "Δθ" is:

$$\Delta\theta = R \text{ (range)} / R_0 \text{ (the radius of the earth)}$$

The equation (7) gives:

$$(R_0+h) / R_0 = [gM/(R_0+h)] [1 - \cos(\Delta\theta)]/ [V^2 \cos 2\gamma] + [\cos(\Delta\theta + \gamma) / \cos\gamma]$$

"R_0" is the radius of the earth. "V" is the launch velocity. "γ" is the launch angle. "h" is the launch height from the surface of the earth, if launched from an aircraft.

The launch velocity to cover the down range, "R" is obtained from the above equation as:

$$V=\sqrt{\{ gM(1 - \cos(\Delta\theta) / \mathbf{[}(R_0 + h)\cos\gamma \,\mathbf{\{}(R_0 + h) \cos\gamma / R_0 - \cos((\Delta\theta) + \gamma\mathbf{\}]} \}}$$

At apogee (maximum height) $dr/dt = 0$, or assuming a symmetrical ascent and descent trajectory, the apogee (h_{max}) is obtained from the following equation:

$$r_0/(R_0 + h_{max}) = (gM/r_0)[1 - \cos\theta]] / [V^2 \cos 2\gamma] + [\cos(\theta + \gamma) / \cos\gamma]$$

or

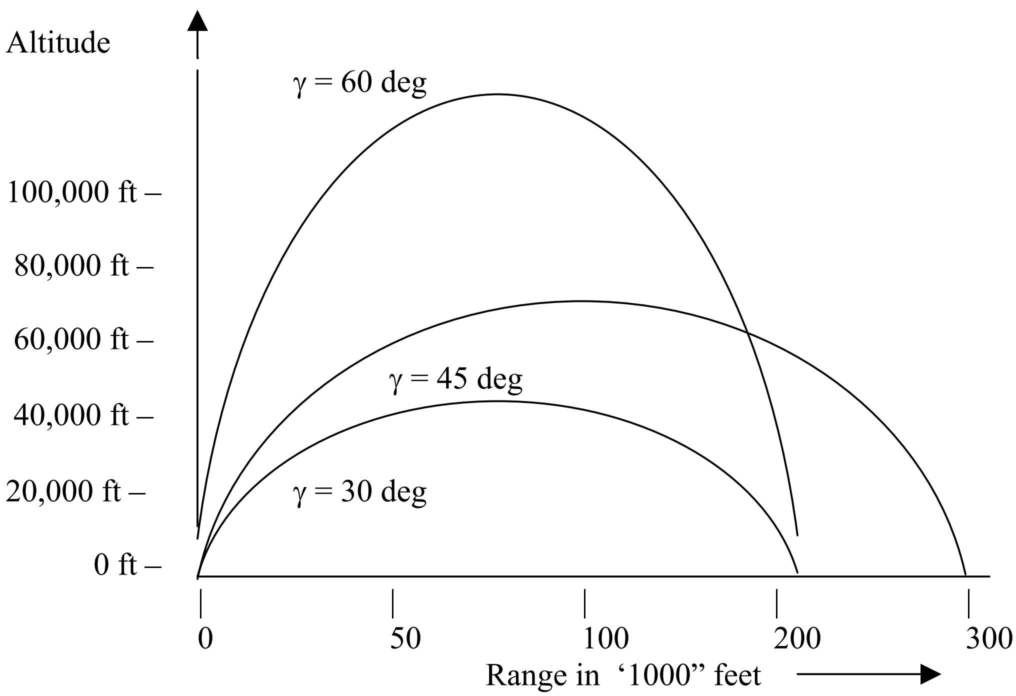
$$h_{max} = [(r_0^2V^2)/ gM)] \cos^2\gamma] / \{1 - \cos(\Delta\theta/2) +$$
$$+ (r_0 V^2/gM)\cos[(\Delta\theta/2 + \gamma)] \cos\gamma] - R_0$$

The time for the flight to cover range "R" may be obtained from the integrated equation (7B):

$$t_F = \int [r^2\, d\theta] / [r_0 V \cos\gamma] \quad \text{from "0" to "}\Delta\theta\text{"}$$

The closed form solution of the above integral is available (Ref.5).

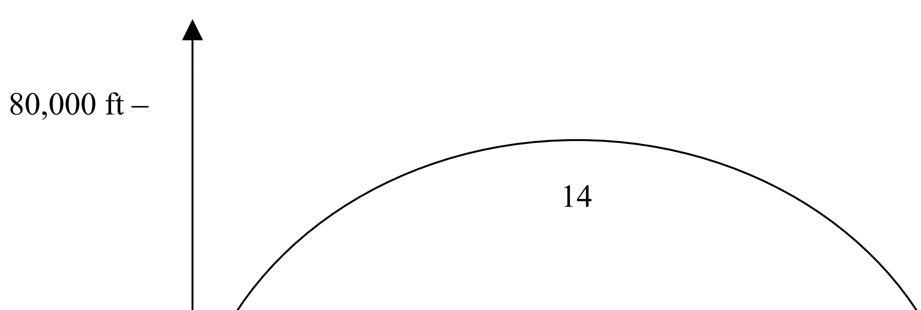
The following data is obtained, using the simplified analyses, to explain some of the characteristics of the ballistic missiles:

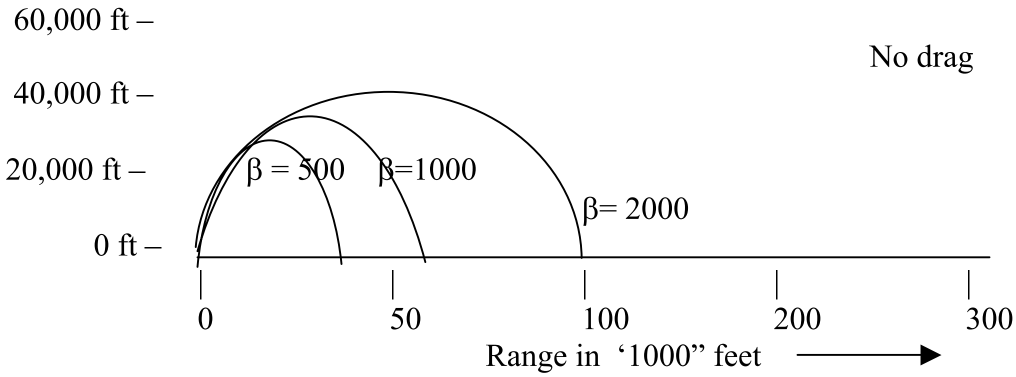


Effect of launch angle on range

Initial velocity 3000 ft/sec

No drag, gravity only, launch angle = γ

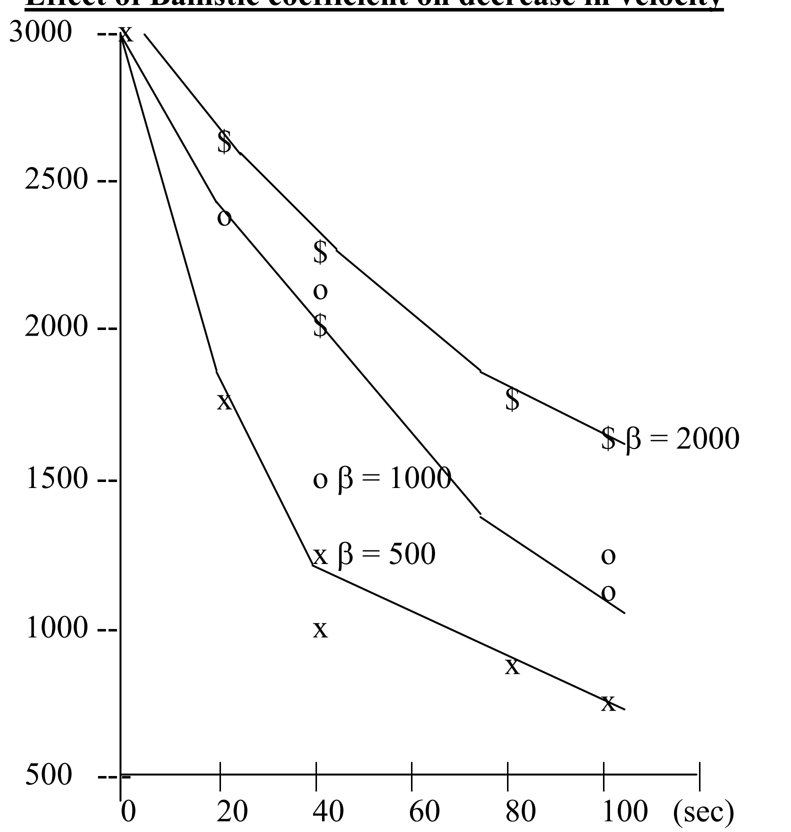




Initial velocity 3000 ft/sec
β = Ballistic coefficient lb/ft^2
Drag, gravity, and γ = Launch angle = 60 deg
<u>Effect of drag on range</u>

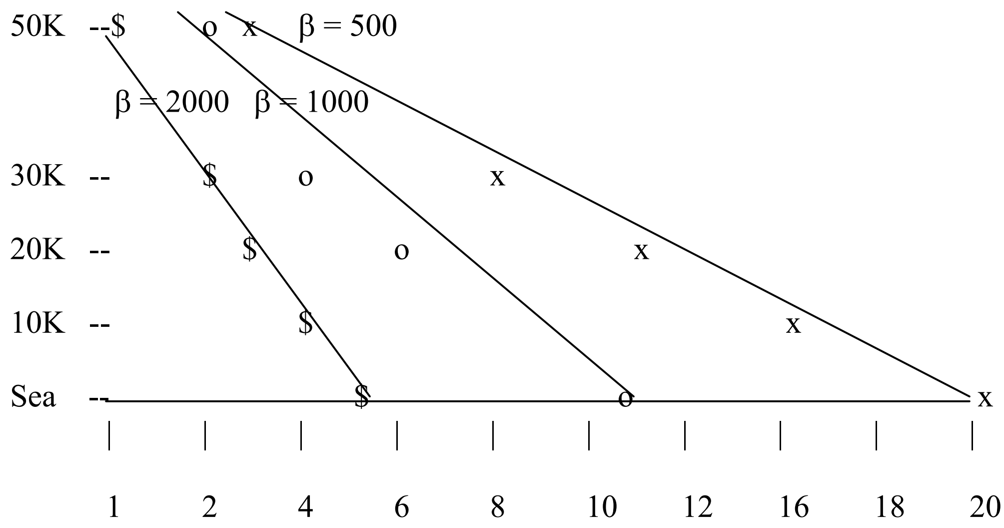
Initial missile velocity =3000 ft / sec: Altitude = 50,000 ft

<u>Effect of Ballistic coefficient on decrease in velocity</u>



<u>Initial missile velocity = 3000ft / sec</u>

Height



Deceleration due to drag (g)

Effect of altitude on deceleration due to drag

From the simplified analysis the following data are obtained:

Apogee (km)	**24**	**60**	**100**	**200**	**300**	**400**
Maximum range (km):	**120**	**300**	**500**	**1000**	**1500**	**2000**
Total time of flight (minutes):	***2.6***	***4.0***	***5.70***	***8.23***	***10.00***	***11.48***

It may be noted that the flight times for short-range missiles are very short. Need for space-based early warning system, identification of the incoming missile, and calculations to devise intercept trajectory, and decision to launch an interceptor from the appropriate launch location, make the interception of ballistic missile very difficult, if not impossible. It is certainly not within the capability of small nations. The interceptor needs to be a highly maneuvering hypersonic missile capable of flying above Mach 7.
The worst part of the state of affairs is that a ballistic missile can carry nuclear and biological weapons. The technologically advanced western nations have stockpiles of these weapons.

A credible deterrence, if the people are willing to pay the high cost in investment in science and technology, is strategic offensive capability of limited magnitude, as the President of Pakistan has stated on several occasions. Regardless of the claims on avoidance of co-lateral damages, population centers have been attacked in wars, through out historical times. What a willing nation can always do is to build an early warning defense system. Properly trained local civil defense organizations can help to reduce the damage to civilian population and to keep communication channels, food supplies, and the necessities of life available to people.

In summary, the times of flight for short and medium range missiles are very small. Only an autonomous system preferably based in space, with full authority to act without delay, can hope to intercept intermediate and short-range ballistic missiles. For the inter-continental missiles, the time is about 30 minutes. The best chance is to hit to kill during the early boost phase, when the missile velocity is not high. Or perhaps to hit the launch sites as pre-empt measures. Surprise attacks without warning are, therefore, highly probable, in the future.

However, in spite of the helplessness of defense against a ballistic missile attack, the quest to build anti-tactical ballistic missile (ATBM) is on. There is progress in the development and perfection of PAC-3 (Patriot Advanced Capability –3) and Theatre high altitude area defense (THAAD) systems, US-Europe MEADS (medium extended defense system), and SS-20 theatre ballistic missile system.

Israel is the first small nation that has built and tested "Arrow" anti-ballistic system successfully, using U.S. technologies and funds. India has bought SA-10 batteries from Russia that are capable of anti-ballistic missile defense (Ref.3).
India is likely to purchase Patriot-2 system from the USA

In future wars, the offensive threat is comprises of ballistic missiles, stand off platforms, like ship, submarines, long-range bombers, fighter aircraft, overhead loitering UCAVs, with the capability of launching hypersonic missiles, precision guided missiles, cruise missiles and directed energy weapons. The supporting systems are expected to be on and off board sensors, tactical satellites, overhead UCAVs to relay accurate target information to the command and control centers.

A partial existing defense system can be upgraded by investing in science and technologies related to defensive missiles and synergic technologies.

The major subsystems of a tactical hypersonic missile are:

Airframe
Guidance
Warhead
Fuse
Data link
Telemetry
Propulsion system
Aerodynamics and test facilities
Stability and flight controls

These sub system are not considered in this paper. Some simple mathematical concepts, related to *missile trajectories*,_propulsion, and hypersonic test facilities are briefly discussed in the rest of the paper.

III. Missile Trajectory Propulsion and Hypersonic Test Facilitate

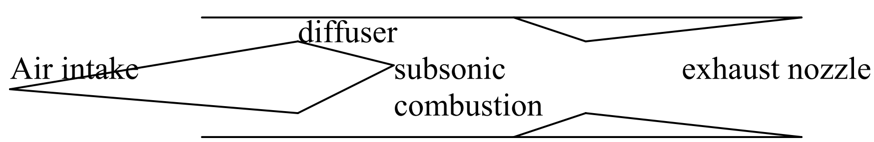
To make a missile a weapon system additional subsystems are needed. These include

Launchers
Communication, Command, and Control
Radar and laser
Battlefield management
Logistic facilities.

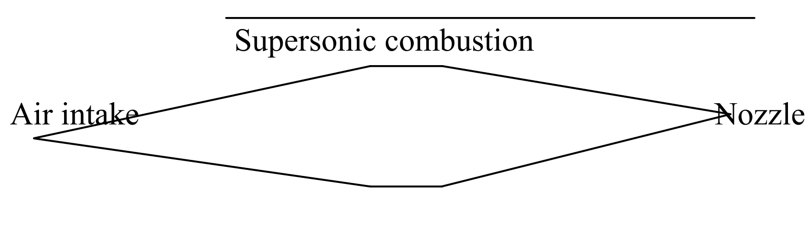
Hypersonic propulsion:

The engines that are suitable for hypersonic propulsion are called the ramjet and the scramjet. Both ramjet and scramjet need to be integrated with a turbojet or a rocket engine to propel the vehicles at lower Mach numbers (less than M = 3).

Ramjets and scramjets are under active investigation for applications to hypersonic flights. In a ramjet the air is compressed in a diffuser to a subsonic speed and the combustion takes place as in a normal turbojet engine. In scramjet the flow is slowed to supersonic speeds and fuel is injected into supersonic air streams and the combustion takes place at supersonic speeds. In concept both type of engines are simple and are sketched below:



Schematic of ramjet



Schematic of scramjet

Above Mach numbers 6, there is a great pressure loss and increase in temperature when the flow is decelerated to subsonic speeds. For example, if the free stream flow at Mach number equal to10 and at temperature 300 deg K is slowed down in front of the combustor, adiabatic ally, the stagnation temperature would reach up to 6000° K. At this temperature, the fuel injected would simply decompose, rather than burn. This would produce pressure drag rather than thrust. It is, therefore, necessary to have the flow slow down to a lower supersonic velocity and have the combustion take place at supersonic speeds. Since 1950, a great deal of efforts has been directed to develop scramjet. Component behaviors, operation limits, heat transfer and cooling are being tested in free-jet hypersonic wind tunnels.

The concept of ramjet is not new. Rene Lorin of France recognized the potential of ram pressure in propulsion, in 1913. A German patent for a hypersonic device was issued to Albert Fono of Hungary, in 1928. Rene Leduc of France was issued a patent for a piloted airplane propelled by a ramjet, in 1935. This patent resulted in an experimental airplane, Leduc 010. On April 21, 1949, Leduc 010 was launched from a Languedoc airplane. This plane reached M 0.84 at altitude 26,000ft (7.9 km). Subsequent models Leduc 016 and 021 reached M 0.9. Nord Aviation of France started work on ramjets to develop a practical airplane (Griffon II) in which a turbojet (SNECMA Atar 101 E-3) was integrated with a ramjet for subsonic and supersonic speeds respectively. Both engines used the same inlet and exhaust ducts. The ramjet engine generated 80% of the thrust at M 2.1 at 61000ft (18.6 km) altitude. This airplane established a speed record of 1024 mph (1640 km/hr) and flew 100 km on February 24, 1959.

The potential of ramjet-powered missile has been widely recognized as compared to rocket-powered missile. It attracts the military for it can achieve greater range for the same amount of propellant weight. Since a ramjet produces no static thrust, it has to be combined with another power plant, such as a turbojet or a rocket. The ramjet takes over when the ram pressure is sufficient to propel it.

In the USA, by 1946, work had begun to develop ramjet missile for the defense of ships. A ramjet engine (20 in diameter (51 cm)) was mounted on the tip of a Lockheed F-80 fighter and tested. During the period 1951–60, X-7 and X-7A pilot-less rocket-boosted ramjets were released from bomber airplanes and tested. The ramjet engine started when “takeover velocities” were reached. These vehicles reached velocity of 2881 mph (4636 km/h). Bomarc-A rocket-boosted ramjet powered missiles, surface to air (STA), (built by Boeing and Michigan Aeronautical Research Center,) were deployed for the defense of the USA against bombers, in 1955. After separation from the booster, the ramjet engines with a total thrust of 28,000lbf (124,000 N) could propel these missile for 435 miles (700 km) at altitude of 69,00 ft (21 km) at speed of M 3. Talos was another STA ramjet missile, ship launched, that was deployed in 1959 to protect naval fleets. This is 31.3 ft (9.5 m) high, boosted by solid a propellant rocket. The liquid propellant ramjet propelled it for 75 miles (120 km) at an altitude of 87000 ft (27 km) at M 2.5. Around 1980, it was replaced by Aegis. By 1990, several ramjet missiles were operational, such as, Bloodhound, Sea Dart (British), NY-3/C101 (China), SA-4, SA-6 (USSR), ASMP (Air-Sol-Moyenne-Portee, France). ASMP is ATS, a third generation, French missile that has the highest performance for its size and weight. It has a range of 155miles (250 km) at M 3 (Ref.9).

Hypersonic manned vehicles:

Among the applications of hypersonic flights, faster intercontinental travel is often mentioned. For example X-30 was expected to fly from New York to Tokyo in about 1 hour. The transport of satellite to low earth orbits (LEO) are likely to be another motive in the research and development of manned hypersonic aircraft.

At hypersonic speeds, heat is generated by the shock waves and skin friction drag. At hypersonic speed, very few materials have the sufficient heat capacity to be used as structural materials. Designers of hypersonic vehicles have to take steps to deal with the heating problem (Ref. 8)

The German Sanger Space Transportation System is a conceptual hypersonic vehicle for orbital payload. It is a two-stage wing/body, designed to take off and land from conventional runways. The first stage is piloted and is common to European Hypersonic Transport M 6.8 Vehicle (EHTV). Its take-off mass is 807000, lb (366,000 kg), with a payload of 247,000lb (112,00kg). It is 277 ft (84.5 m) long and has a wing span 136 ft (41.4 m). EHTV is propelled by hydrogen fuel turbojet. The first stage separates at M 6.8. There are two identical upper stages, which are powered by hydrogen oxygen rockets. Hypersonic Orbital Re-usable stage (HORUS) is a piloted vehicle, intended for space station support and has a nominal payload of 6600 lb (300 kg) to a 280 miles (450 km) Earth Orbit. The un-piloted re-usable vehicle is intended for delivery and retrieval of cargo payload of 18700 lb (8500 kg) to 124 miles (200 km) at LEO. This system is expected to be operational during the first quarter of 21st century, may be under the European Space Agency (ESA)(Ref.10).

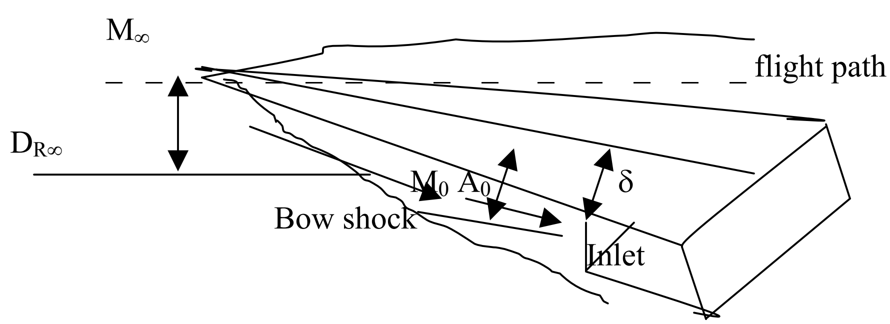
In the rocket-based propulsion system, a large fraction of oxygen is required to be carried to propel the vehicle to the earth orbits. The cost per lb of payload runs up to \$300 – \$ 10,000. In hypersonic propulsion system cryogenic hydrogen would be substituted for liquid hydrocarbon fuels to reduce the take off weight and use liquid hydrogen for cooling of the vehicle.

National Aerospace Plane (NASP) program of the USA (classified) was started in 1986. It aims to study the feasibility of a single stage piloted aircraft to achieve hypersonic speeds into orbit and deliver useful load in space and return to the earth, like a conventional airplane. The experimental reusable vehicle was designated X-30. It is powered by H_2 fuel air breathing ramjet / scramjet engine. It is to be actively cooled with liquid hydrogen. Such an aircraft needs low density, high temperature performance materials, such as carbon-carbon composites, titanium based metal matrix composites, ceramic matrix composites, and beryllium alloys (Ref.9).

The conventional synthetic aviation hydrocarbon fuel is adequate for speeds up to M 4. Liquid methane may be used up to M 6. The other fuels, such as ethyl alcohol, methyl alcohol, ammonia etc are not sufficiently energetic. With the present day available materials, the use of hydrogen fuel, in hypersonic aircraft, for speed above M 7, becomes necessary. The hydrogen has high heat of combustion, high specific heat and has necessary cooling capacity (Ref 8). But, the liquid hydrogen needs heavy cryogenic tanks, airtight insulation, and special fuel feed system and vents, and constant tank pressure to carry aboard the aircraft.

The US Air Force investigated the potential of scramjet-powered very high-speed military aircraft (M 5 – 14), during 1965 – 68, and conceptual studies were made (Ref.8), using boron slurries and special fuels. Lockheed, North American/Rockwell and General Dynamics Corporation were involved in these studies. Composite propulsion systems, for the advanced launch vehicle applications, were studied, at NASA. Out of the 36 composite engines, supercharged ramjet and scram LACE (scramjet liquid air cycle engine) were preferred, based upon the maximum payload that can be placed by the second stage of the vehicle. The configuration was the lifting body. In 1978, NASA gave a contract to Lockheed to study a dual fuel hypersonic aircraft. At low speed operation, jet fuel was to be used; and at high speed liquid hydrogen was to be used. The hypersonic vehicle configuration, HYCAT-6 (hydrogen cruise aircraft technology has a modified lifting body fuselage. The nacelles under the wing carried two GE 14/JZ8 turbojet/ramjet engines. The liquid hydrogen was carried in the fuselage. Later, engines were changed to Pratt & Whitney SWAT –201B, which were designed for liquid hydrogen. Seven vehicle designs were evaluated. HYCAT-8 design was considered to be promising. (Reference 8.)

The vehicle configuration studies determined the aerodynamic characteristics, propulsion system (weight and installed thrust), estimates of weights of principal equipment, and the optimum design (for maximum range. The wing-and-body configuration, in which fuselage consists of cone (ideal for storage of liquid hydrogen and minimization of drag) and wing generates lift to balance the weight, is one possible option. A combination of a turbojet and scramjet and appropriate inlet system can be formed around the cone. The rear of the cone can be used as a nozzle. The other option is a lifting body configuration, which provides better integration of the components. This provides lower structural weight. The upper contour can be an arc of a circle and with a suitable lower surface forming a two-dimensional body of constant width to depth ratio. The air passing through the downward branch of the bow shock, formed from the upper contour, can be sucked into the inlet and into the scramjet combustion chamber.



Major components of the hypersonic air-breathing engine are:

Compression System (diffuser):

There are two types of diffusers that can be used for the compression of in-coming flow in the inlet, internal compression diffuser and external compression diffuser.

There are several areas involved in the analysis of the flow in a diffuser, such as:

Formation of normal and oblique shock waves
Boundary layers and their interaction with shocks
Pressure recoveries
Influence of heat transfer on compression
Compression efficiency – experimental verification
Air bleeds to match engine mass flow requirements
Pressure at the entry to burner
Starting processes and pressure fluctuations
Variable geometry, etc

Combustion Chamber:

Fuel air mixing: axial fuel injection, normal fuel injection, vortex fuel mixing
Mixing layers: laminar boundary layer, turbulent boundary layer
Gas composition in the mixing layers
Heat release

Combustion chemistry:

Thermodynamic equilibrium of ideal gas mixing
Adiabatic flame temperature
Flame propagation waves, detonation
Aero-thermo-dynamics of combustion system

Expansion Nozzle:

Non-equilibrium chemistry
Thrust coefficient

Integration with a turbojet:

Integration with a rocket:

Ducted rocket and ramjet combination:

Heat Exchange:

Convective heat transfer
Surface roughness
3-dimensional flow
Leading edge shock wave interference
Cooling requirements

Thermal stresses:

Materials:

Major sub-systems:

Power units:
- Electric
- Hydraulic
- Pneumatic
- Mechanical

Integration with airframe:

Testing:

Surface pressure, temperature, heat transfer, skin friction
Surface flow, velocity, chemical constituent, air and fuel flow, combustion instabilities
Thrust

A very brief description of some typical problems associated with the hypersonic propulsion is mentioned below (Ref. 11,12)

Internal and external aerodynamics:

External aerodynamics is closely related to the airframe design.

Internal aero-thermodynamic is used to design and analyze an aero-engine.

Flying at hypersonic speeds puts some additional constraints on the design of the aerospace propulsion system. The dynamic pressure imposes forces on structure. For the present structural materials and construction, the limit is 2000 lbf/ft^2 (90,000N/m^2). As applied to hypersonic vehicles, if the dynamic pressure is too low then larger lifting surfaces will be needed to generate enough lift and control forces to sustain the motion at hypersonic speeds. The lower limit is about 500 lbf/ft^2 (20,000N/m^2). For a fixed dynamic pressure (say 2000 lbf/ft^2), if the Mach number is increased, the static pressure should be decreased. This implies flying at higher altitude. At M = 3, the corresponding altitude is about 11 km. At M = 25, the decrease in static pressure corresponds to an altitude of 42 km.

Hypersonic test facilities:

The critical major areas of hypersonic vehicle are: propulsion, propulsion / airframe integration, aerodynamics, flow physics, materials, structures, thermal protection, guidance, navigation, control, and payloads. All components must be tested in realistic flight conditions, before a flight vehicle can be certified. The flow characteristics, in the hypersonic regime, are quite different from those at lower supersonic Mach numbers. The differences pose challenges to the hypersonic vehicle designers.

The hypersonic theories, linear hypersonic flow equations and small disturbance equations are adequate to obtain preliminary design and conceptual information for a hypersonic design, but are inadequate for the design of a prototype.

The design of a hypersonic vehicle requires ground test facilities that can duplicate the flight conditions on a full-scale vehicle. Large pressures and temperatures are required to produce hyper-velocities in the test facilities. It is not an easy task to design and operate test facilities to test full-scale prototypes. The high temperatures and pressures at which the test facilities operate require construction materials, with high temperature melting points.

Additionally, some physical phenomena, at hypersonic speeds, become important; and these can no longer be neglected. At Mach numbers > 9 (velocities greater than 9,850 ft/s) (3km/s), oxygen molecules start dissociation. At higher velocities, chemical reactions between the molecules of oxygen and hydrogen take place and ionization occurs. For velocities greater than about 13,000 ft/s (4 km/s) and altitude less than

130,000 ft (40 km) the chemical equilibrium exists because of high free stream density. At higher altitudes, the gas molecules travel a distance comparable to the length of the vehicle and the flow is no longer in equilibrium. At altitudes greater than about 296,000 ft (90 km), the atmosphere becomes rarefied and the flow cannot be considered a continuum. During an operation, a hypersonic vehicle is likely to encounter a range of flight conditions.

The high pressure of the order of 10,000 atmospheres and temperature of the order of 9000 ° Kelvin are required to duplicate the scaling parameters. Chemical rate coefficients, physical species concentrations, and diffusivities measurements, aerodynamic, aero-thermal, chemical-turbulent interaction are challenges for the experimentalists.

The ground test facilities do provide design information for low hypersonic regimes (M 5 – 12), where the perfect gas assumptions are adequate. But, for hyper-velocities, where thermal, chemical, ablative, and radiation effects are important, real gas effects should be taken into consideration.

All conditions of hypersonic flights are difficult to be obtained from the ground based test facilities. The wind tunnel tests and numerical simulations and flight tests on prototype models, are used in the design process.

High enthalpy flows can be produced in arc-heated or combustion heated wind tunnels. High enthalpy can be achieved by raising the temperature and pressure of the test gas. Shock compression raises the temperature and pressure of a gas in the shock tunnels. The rapid expansion of high enthalpy stagnation air to hypersonic speeds produces non-equilibrium flow. The non-equilibrium effects can be minimized by addition of energy in steps. There are technological challenges to realize this in practice. Radiation in heated wind tunnels coupled with MHD accelerator may be used. The high stagnation temperature and pressure for generating hypersonic flow poses several challenges in design of test facilities. The hypersonic flow requires a large temperature ratio. The upper limit on temperature is set by non-equilibrium phenomenon and the lower limit is set by liquefaction.

For simulation of actual flight conditions, the non-dimensional parameters should be duplicated. These parameters are the Mach number (M), the Reynolds number (R_e), and Prandlt number (P_r). The replication of these numbers does not match all aspects of hypersonic flow, especially when there are chemical reactions and combustion. At high temperatures, real gas effects are prevalent. In ideal equilibrium flow, vibration time constant, $\tau \approx 0$ and the reaction rates, k_f and $k_{vib} \rightarrow \infty$. In practice, the characteristic flow, τ_f is large compared to vibration relaxation time or characteristic chemical reaction time:

$$\tau_f >> \tau_{vib} , \tau_{chem}$$

If the converse is true, then the flow is frozen. A consequence of this is that aerodynamic parameters, such as pressure, heat transfer, and ablation may be in error. Even if, the flow in the test section is in equilibrium, the flow field around the model may differ from the flow fields around prototype in free flight. The diffusing shock fronts in the test section transform the frozen flow to equilibrium flow. In free flight, this shock is wider from the object. The front should be matched in both free flight and model tests.

The natural time scale, 'L/V_∞', for free flight is much longer than the model in test section. Collision between nitrogen and oxygen molecules, at lower temperature, can form nitric oxide. The rate of dissociation is proportional to ρ and the rate of recombination is proportional to ρ^2. For re-entry type of flow, the dissociation length 'l_d' is comparable to the characteristic length of the vehicle 'L_{char}'. The Damkoler number, $\Omega = L_{char}/ l_d \approx 1$. In many cases, the dissociation behaviour is important and binary scaling (density-length product) must be duplicated. The binary scaling requires high density (or high stagnation pressure) in the test section.

There are three types of hypersonic test facilities used in ground tests:

Wind / shock tunnels,
Ballistic ranges, and
Rocket-sled tracks.

<u>Wind / shock tunnels:</u>

In continuous wind tunnels a compressor system is used to provide the pressure differential and mass flow. Moderate density and Reynolds number can be achieved at moderate hypersonic flows. These tunnels are very well suited for testing of models with six degree-of-freedom and evaluation of preliminary configuration.

For a hypersonic vehicle, to withstand a dynamic pressure of 500 lbf/sq ft., the following table shows the total temperatures and pressures that will be encountered by the vehicles at various heights and Mach numbers.

Dynamic pressure (qbar) = 500 lbf / sq. ft.

Mach	p_s, psia	h, ft	T_s, °R	T_t, °R	p_t, psi
3	0.55	73400	393.7	1102.4	20.2
4	0.31	78750	396.5	1665.3	47.1
5	0.198	95100	406.5	2439.0	104.8
6	0.138	103150	410.0	3362.0	217.9
7	0.101	115400	427.6	4618.1	418.1
8	0.078	125350	447.8	6179.6	761.5
9	0.061	132200	453.4	7798.5	1287.3
10	0.049	137000	460.9	9678.9	2079.5
11	0.041	140700	466.4	11753.3	3293.7
12	0.034	143500	470.7	14026.9	4911.7

To simulate M 6 flight at altitude 103,105 ft, using ideal gas compressible flow, one needs a total pressure and temperature of 218 psi and 3362 °R, respectively. To achieve Mach numbers higher than 8, air needs to be compressed to pressure greater than 3000 psi and temperature greater than 4500 °R. This places engineering limits on the design of a test facility. To mitigate this effect, some facilities use combustors to burn air, and a fuel (hydrogen or methane), which increases the air temperature down stream of pressure vessel. Oxygen is added to the flow to make composition (21%O_2 78%N_2) by volume.

The blow-down tunnels operate from the gas compressed and stored in tanks at high temperature. The gas is expanded into a lower pressure tank via a nozzle to hypersonic Mach numbers. The two tanks are connected via a valve. The test period is an order of a few minutes. High pressure and high Reynolds number numbers can be achieved in these tunnels. These tunnels are useful for simulation of viscous effects. The heating may be provided by electric arcs or combustion. Very high enthalpies to duplicate re-entry heating are possible in arc jet tunnels. A limited amount of mass flow can be heated in an arc jet. These facilities are used for re-entry, ablation, and materials. Combustion heating has a total temperature limitation and can reach Mach numbers up to 7, unless hydrogen is used for heating.

Shock tunnels use a shock moving through high-pressure reservoir. The movement of the shock produces high temperatures and pressures in the nozzle plenum. Up to Mach number 20 can be achieved. The gas is expanded through a nozzle to the test chamber. These types of facilities are limited to a test time of a few milliseconds and are used for testing of chemically reacting flows over Mach numbers 8.

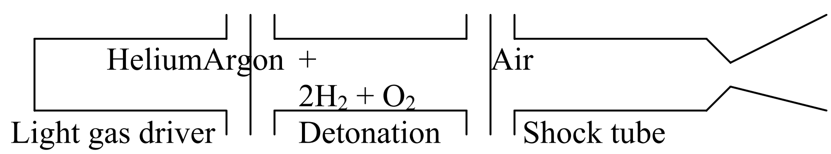
An example of shock-heated tunnel is NASA's HYPULSE dual driver reflected shock and expansion tunnel. It is designed for ground testing of ramjet, scramjet, hypersonic combustion, and hyper-velocity models in the flight regimes of Mach numbers 5 – 25. It is capable of studying real gas effects in re-entry aerodynamics. It achieves 3 – 7 milliseconds steady flow in the test chamber in reflected shock mode. It was initially built in 1960 an as un-heated expansion shock tube for real gas and radiation gas dynamics. It was relocated at GASL in 1989. It has been expanded to conduct research on hypersonic scramjet (X-43A) and re-entry aero-thermodynamic (X-37) research. The addition of a detonation driver mode was implemented to increase the total enthalpy and total pressure. The reflected shock mode was added to develop Hyper – X scramjet engine and test it at lower Mach numbers. The current facility can be operated in the above-mentioned modes.

Another large hypersonic test centre is Calspan, Buffalo, New York, where vehicles up to 3 ft diameters and 14 ft long can be tested to duplicate flight conditions from Mach numbers 4 – 15. Detailed aero-thermal, aero-optical, aero-acoustical measurements have been made at this facility. Two shock tunnels can use helium, hydrogen or nitrogen as driver gases and can be operated at 30,000 psi. They use a common compressor, vacuum, and measurement system. A 25 ft long 11-inch diameter, an electrically heated driver drives a 60 ft long 8-inch diameter tube. Another tunnel has a 24-inch diameter 60 ft long driver and drives a 24-inch diameter and 100 ft long driven tube.

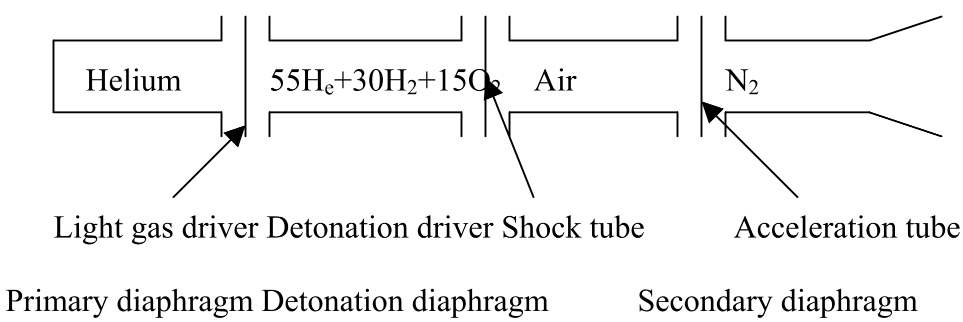
Another large shock tube (U – 12) is located in Moscow. It was established in 1956 to do research on aero-physics and chemical kinetics, shock waves, and aerodynamics. The facility produced flow from Mach numbers 2 – 20. The driver gases were hydrogen, helium, air, and nitrogen.

Other detonation driven or free-piston shock tunnels are at Arlington(USA), Ronkonkoma (USA), Beijing (China), Aachen (Germany), Gottingen (Germany), Kakuda (Japan), and Moscow (Russia).

Shock tunnels are extension of shock tubes and use the shockwaves to heat up the test gas. Previous facilities used heat up to a temperature to avoid condensation in the test section. Only Mach and Reynolds numbers were simulated. In the present day facilities velocity, pressure, and temperatures are also match ed at hyper-velocities or hypersonic conditions. In a shock tunnel, total enthalpy and pressure are achieved by the driving shockwave. The total enthalpy in the shock tunnel is proportional to the square of the shock velocity. The increase in the strength of the incident shockwave depends on the fill pressure in the driver and the increase in the speed of sound of the driver gas, which is obtained by heating the gas or using a lighter gas. Combustion of stoichiometric mixture of hydrogen and oxygen in helium may be used to obtain a hot driver gas. Detonation has higher speed than deflagration combustion waves. Detonation wave can either be generated by a strong ignition or by deflagration to detonation transition (DDT) after weak ignition or by shock induced detonation (SID). There are two types of shock tunnels, reflected shock tunnels and shock expansion tunnels.



Schematic of detonation driven shock tunnel



Schematic of shock expansion tube

To achieve higher performance, hydrogen can be used as a light gas, but it is costly. Heating the driver gas to achieve higher performance is a better alternative. The driver gases are heated by means of internal or external heaters. Combustion heating by detonation is often done at many facilities to achieve velocities up to 6000 ft/sec. The contamination of the test gas influences the tests and reduction in test time. Velocities greater than 8000 ft/sec can be attained with the heated driver gases. The heating may be done by means of electric heaters and shock waves. The use of free piston driver to compress light gas for high enthalpy is done at some facilities. To obtain velocities greater than 20,000 ft/sec needs shock strength that can be achieved in piston driven shock tunnels. The duration of flow is less than a millisecond. The test time depends on diameters and lengths of the driver and driven tubes. Large tubes with multi-diaphragms can provide longer test times.

<u>Ballistic ranges:</u>

Ballistic ranges use guns to fire the test objects to move on a rail or in free flight in chambers of known densities. The test objects are limited in size, weight, and instrumentation. Ballistic ranges are capable of producing high Mach numbers. These facilities are very useful in impact testing.

Light gas guns fire the test model into tunnel sections having controlled environment and instrumentation. These facilities are used to study the free flight scramjet models of a few inches diameter at 1000 per sq. ft dynamic pressure and Mach numbers around eight. The environment in tunnel sections are matched to conditions at different altitude (densities and temperatures), the tests provide realistic data. The test times are of the order of 20 – 30 milliseconds. Non-intrusive techniques of measurement are used to obtain test information. Hypersonic speeds and the test models should be stressed to withstand the launch loads of over 13,000g.

Light gas guns use highly compressed hydrogen or helium to propel the research models. Muzzle velocities from 2km/sec to 6km/sec have been used for slender metallic models. For blunt models, speeds up to 11 km/sec have been achieved. The basic components of these test facilities are:

1. A light gas gun,
2. The instrumented test model,
3. Photographic stations in flight chambers,
4. Accurate records of events in photographic stations, and
5. Stoppage of projectile.

The models in flight can attain very high temperatures. At a speed of 4km/sec, about 4000 deg K can be reached. The bow shock wave temperature may reach up to 10,000 deg K. The gas surrounding the model and the model itself may become luminous. The flight times of the models are a few milliseconds. High frequency response instruments are needed to record data on photographic plates.

Radiometers are used to measure the radiation properties of nitrogen, oxygen, and carbon dioxide. Electron densities, radiation emission and absorption in the wakes of models have been measured by the use of microwaves and interferometers.

Photographic stations in the flight path of the models have point source, high intensity, collimated light (x-rays), mirrors, lenses and prisms to direct the light. Photographic films and cameras are installed to record the transit images of models in flight. Optical, electro-optical, and Kerr cell shutters are used to control the duration of the flight. Trigger systems, to sense the arrival of the model at the photo-station, are used.

Measurements of the position, altitude, and velocity of the model are obtained from the photographic information and the chronographic record of times of the passage of the model. Yaw cards are installed in the way to measure the altitude of the model.

Lasers, flash lamps, carbon arc search lights, self-luminosity of the model and the surrounding field, and explosive light sources are used to obtain the shadowgraph, Scheliern and interferometer pictures of models.

Rocket sled track facilities:

Rocket sleds have been used for full scale testing of defense related equipment, such as warhead, fuses, ammunitions, missile dynamics, space vehicle re-entry, anti-armor, high Reynolds number flight, aero-thermal protection materials, hypersonic heat shield, etc. These tracked sleds can produce aerodynamic forces on full-scale models and are in use for scramjet research. Models are mounted on sleds, which are attached to rails by slippers. The slipper dynamics, vibrations, and wear are the limiting factors on the speeds that can be reached. Sleds are propelled by rocket motors. Sleds are propelled by rockets to slide on monorails at velocities up to 1.5 km or on narrow gauge rails for heavier models with higher drag. There are engineering challenges involved in construction of the sleds. The selection of slipper materials, rail coating, the alignment of rails, roll stability while in motion and the instrumentation of models are important factors for high speed sleds. Velocities greater than 3 km / sec have been achieved. Sleds can be made to pass through a polyethylene tunnel erected around the track filled with helium. Helium is 14% denser than air. A Mach number 6 in air corresponds to Mach number 2 in helium. If, the test item is needed to be recovered, then the sled should be decelerated some where in the middle of the track length, in order to come to a stop at the end of the track.

The slipper track interaction and vibration produce impact with track. To solve this problem, the support of the sled by magnetic levitation has been used. Alternating current levitating linear induction motor is used. The eddy currents are produced in tracks by the alternating electro-magnetic field, without the motion of the sled. For example, when a copper coil, carrying A.C. is brought near a conducting plate, a repulsive force is produced in the surface layers of the conducting plate, which in turn produce a repulsive force on the coil, by the Lenz's law.

The direct current magnets can be used to produce electro-dynamic levitation of the sled. In this case, the eddy currents are induced due to the relative motion of the vehicle by the D.C. magnets on conducting tracks.

In both cases, the vehicle suspension forces are produced between vehicle-borne magnets and the electrically conducting strip track, in which circulating eddy currents are induced. The magnets are attached to the sled which when passed over the conductors on the guide- way generate levitation forces. The sled may be suspended magnets and be propelled by rocket motors.

Rocket sled tracks are used to accelerate large heavy bodies. These are mostly used in weapon testing.

There are difficulties for providing realistic flight conditions in the ground test facilities. It is essential to demonstrate the performance of the engine and its integration with vehicle systems or their models by free-flight tests.

References

1. Mantle. P (2004) The Missile Defense Equation. AIAA Education Series 2004

2. Aerospace America, December 2004
AIAA

3. Ben-Zion N Azriel L (2000)
Theater Ballistic Missile Defense
AIAA **Progress in Astronautics and Aeronautics Volume** 192

4. Deutch 200
Nuclear Posture for Today
Foreign Affairs, Jan / Feb

5. Cornelisse J.V 2003
Rocket Propulsion and flight Dynamics
Londa Pitman.

6. Ball G.F. Osborne (196)
Space Vehicle Dynamics
Oxford, 1967

7. Zarchan P (2003)
Tactical and Strategic Missile Guidance (third edition)
Progress in Astronautics and Aeronautics volume 176

8. Brewer
Hydrogen Aircraft Technology
Florida CRC Press.

9. Heiser, D. T. Pratt (1994)
Hypersonic air-breathing propulsion
AIAA Education Series,

10. Hypersonic Aero-thermodynamics
AIAA Education Series, 1994

11. Oates G.C (1998)
The Aero-thermodynamics of Gas turbine and Rocket Propulsion
AIAA Education Series

12. Mattiningly J., W.H. Heiser, D. T. Pratt (1998)
Aircraft Engine Design, 2nd edition
AIAA Education Series,

13. Lu, F. D. E. Marren (EU) (2002)
Advanced Hypersonic test Facilities
Progress in astronautics and aeronautics volume 198.