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A BRIEF DISCUSSION ABOUT REENTRY VEHICLES

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Abstract: A re-entry vehicle is the segment of spacecraft that returns back to earth surface through its atmosphere. During its reentry, the vehicle is greatly affected by Earth's gravity which makes it prone to hypersonic speeds. Such high speed descent heats up the vehicle to a limit that the material associated with it starts to erode. For their safety, the reentry vehicles need thermal coating which is commonly known as Thermal Protection System (TPS). Since metals are highly susceptible to corrosion, heating and wear, Thermal Barrier Coating (TBC) is applied to withstand large temperature gradients. Apparently, we make use of phenolics and composites like Silica, Ceramics etc. In this module we will be discussing about the challenges faced during reentry, desirable vehicle shapes, materials used to prevent aerodynamic heating, types of reentry vehicles and their analysis in brief.
Keywords: Reentry, Atmospheric Drag, Aerodynamic Heating, Hypersonic Flight, Shockwaves, Uncontrolled and Controlled Reentry, The Space Shuttle, IXV, Inflatable Heat Shield Reentry, CFD Analysis.

INTRODUCTION

Atmospheric entry is the reentry of artificial objects passing through the Earth's atmosphere or the atmosphere of any other planet. It could be ballistic or non ballistic in nature. Early missions used ballistic reentry which is proven to be fatal. It's basically a capsule that returns to Earth following a space flight. It's aerodynamically stable which falls facing its blunt end. Soyuz, Apollo, Orion are certain space capsules used before lifting body with wings and control surfaces came into existence. The latter is comparatively safer than the former since the lifting force acts against the aerodynamic drag and thereby slowing down the descent speed. The modification carried out by adding the lifting technology is a remarkable revolution in reentry vehicles.

HISTORY

Fatal accidents during reentry are mentioned in the table below:

Date	Incident	Mission	Fatalities	Cause
1967-04-24	Parachute failure	Soyuz1	Vladimir Komarov	During reentry due to improper opening of parachute, the capsule at hypersonic speed hit the ground.
1967-11-15	Control failure	X-15 Flight 3-65-97	Michael J. Adams	Due to the electrical problem with the plane, it was difficult to control when it was spinning and diving inverted at about hypersonic speed (Mach 5). This led to excessive loading and structural breakup at about 19.8km.
2003-02-01	Vehicle disintegration on reentry	Space Shuttle Columbia STS-107	Rick D. Husband William McCod Michael P. Anderson David M. Brown Kalpana Chawla Laurel B. Clark Ilan Ramon	The heat shield used in Space Shuttle Columbia are heat resistant tiles. Due to the damage caused in its TPS, during reentry it led to structural failure of the Shuttle's left wing and the spacecraft broke apart.

CHALLENGES FACED DURING REENTRY

Two important factors that cause atmospheric breakup and hence complete disintegration of the reentry vehicle are:
Atmospheric Drag
Aerodynamic Heating

Atmospheric Drag:

It acts on the reentry vehicle due to frequent collisions of gas molecules with the spacecraft when it approaches Earth's atmosphere.

The drag force depends on- The size of reentry vehicle (the cross-sectional area exposed to wind)
- Its drag coefficient (how streamlined it is)
- Its velocity
- The density of air

$$F_{drag} = \frac{1}{2}\rho V^2 C_D A$$

where
F_{drag} = drag force on a vehicle (N)
C_D = drag coefficient (unitless)
A = vehicle's cross-sectional area (m^2)
ρ = atmospheric density (kg/m^3)
V = vehicle's velocity (m/s)

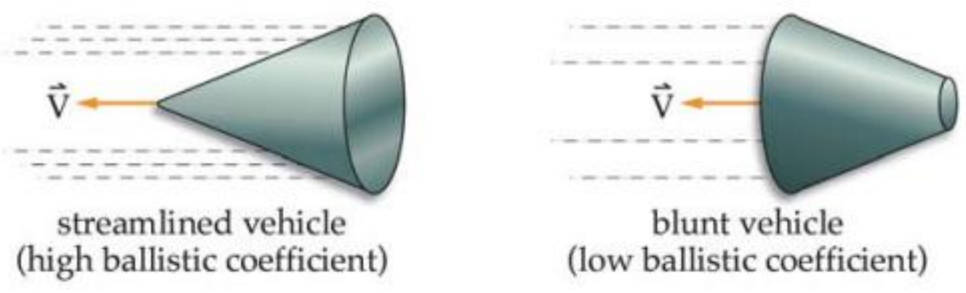
Since, the drag force pushes the vehicle backwards, decelerates its motion.
Ballistic coefficient (BC) by convention can be expressed as:

$$BC = \frac{m}{C_D A}$$

where
BC = vehicle's ballistic coefficient (kg/m^2)
m = vehicle's mass (kg)
C_D = vehicle's drag coefficient (unitless)
A = vehicle's cross-sectional area (m^2)

An object with a low BC slows down much quicker than an object with a high BC.

A blunt vehicle with light weight has lower BC and slows down much more quickly than a heavy, streamlined vehicle having a higher BC.



Aerodynamic Heating:

When the vehicle begins to enter Earth's atmosphere, it has a large amount of kinetic energy due to its

high velocity as it's now under the influence of gravitational pull of the planet.
This kinetic energy eventually gets converted to heat by skin friction on the surface of the vehicle. Also while reentry, near the outer edge of the atmosphere, the vehicle acquires a large amount of potential energy because of its high altitude. Ultimately, as the vehicle touches the surface of the earth, its velocity becomes comparatively small and its altitude becomes zero.

In accordance with the law of conservation of energy, all the energy that was acquired by the vehicle before touching the surface is dissipated in two ways:

(I) The body is being heated up
(II) The airflow around the body is also heated up.

The rate of aerodynamic heating depends upon its viscosity and the speed of air surrounding the body. Viscous dissipation takes place from the neighbouring sub-layers through a non-isentropic process, which reduces the rate of boundary layer formation.

The heat interaction between the atmosphere and the vehicle takes place in three ways: Conduction, Convection and Radiation.

Heat is conducted into the surface material from higher temperature air. Now the gas that have cooled after transferring heat to the material of the vehicle undergo forced convection for continuation of the process. In addition to this, there's also thermal radiation takes place from the flow to body and vice versa.

In lower atmosphere, high density increases the friction over the vehicle and since the vehicle speeds up at lower altitudes, increases the aerodynamic heating to a greater amount.

Effect of Aerodynamic Heating:-

It has a minimal effect when the vehicle is travelling at subsonic speeds but at supersonic (beyond M1.2) and hypersonic (beyond M5) speeds it has a serious effect on the design, material of the vehicle structure and the incorporated systems.
But in actual scenario, the spacecraft reenters at very high speeds(Mach number exceeding 20) which is sufficient to destroy the vehicle, if safety measures are not taken.

Though the vehicle heats up to a high stabilized temperature, still the heating effect reaches the peak value at the leading edges.

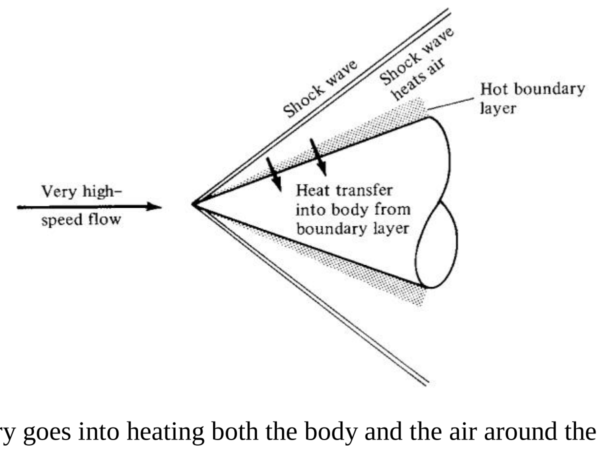
Safety Measures:-

Aerodynamic heating can be minimized to certain extent and to a safety limit by the use of high temperature metal alloys and the exterior of the vehicle has to be insulated by the use of ablative material.

HYPERSONIC FLIGHT AND SHOCK WAVE FORMATION

Shock waves are formed when the speed of the airflow changes by more than the speed of sound. The region at which it occurs, sound waves travelling against the flow reach a point where they cannot travel any further upstream and the pressure progressively builds in that region and subsequently a high pressure shock wave rapidly forms.

The shock wave from the nose of the vehicle heats the airflow around the vehicle. The vehicle is also heated by the intense frictional dissipation within the boundary layer on the surface.

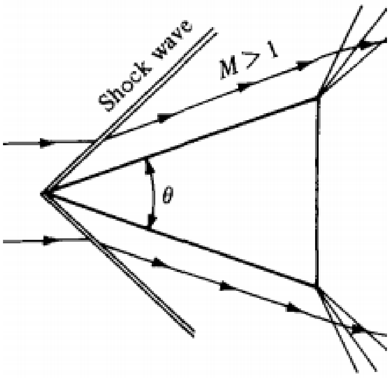


Energy of the reentry goes into heating both the body and the air around the body.

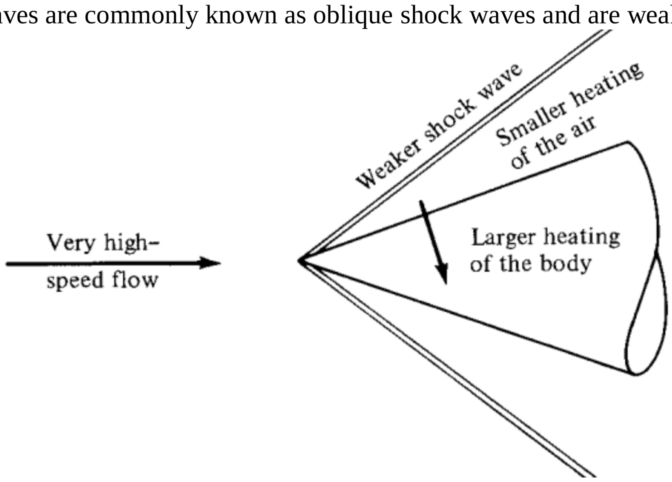
The primary focus should be on preventing the vehicle from heating. One way to achieve this is by dumping more of the total reentry energy into the airflow, i.e., heating the airflow. This can be achieved by creating a stronger shock wave at the nose.

Attached Shock:

- When a slender or sharp body like wedges and cones with small apex angle is moving at supersonic speeds in a compressible flow, these shocks appear to be attached to its tip.



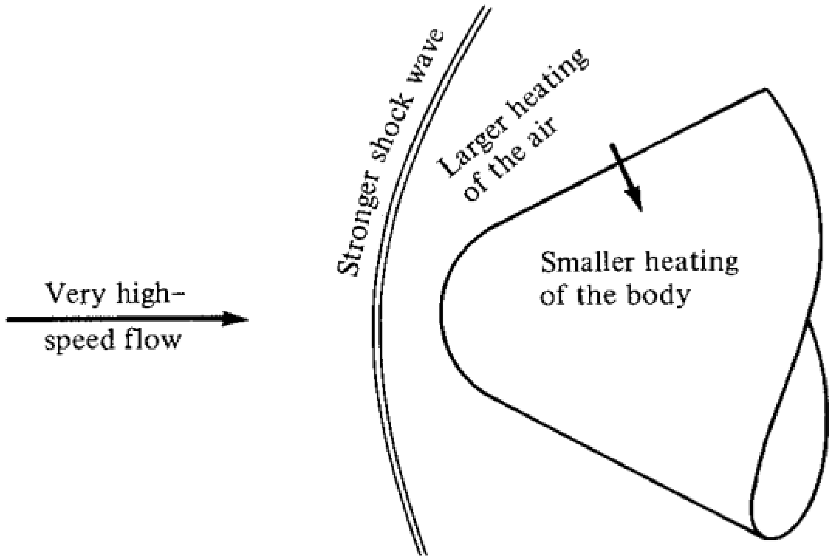
- The upstream streamlines are uniformly deflected after the shock wave.
- These shock waves are commonly known as oblique shock waves and are weaker in nature.



- They cause large heating of the body rather than the airflow.

Detached Shock:

- These shock waves are curved and are formed at a small distance in front of the body.
- If the maximum deflection angle is exceeded (blunt bodies), the shock remains no more oblique and will detach from the tip of the wedge.
- Shock wave stands at 90 degrees to the incoming flow and then curves around the body.
- These shock waves are very strong in nature and commonly known as bow shocks because of their shape.
- The region just behind the wave is a substantial region of subsonic flow.
- Since these shock waves cause smaller heating of the vehicle than the airflow, the nose of reentry vehicles are made blunt.



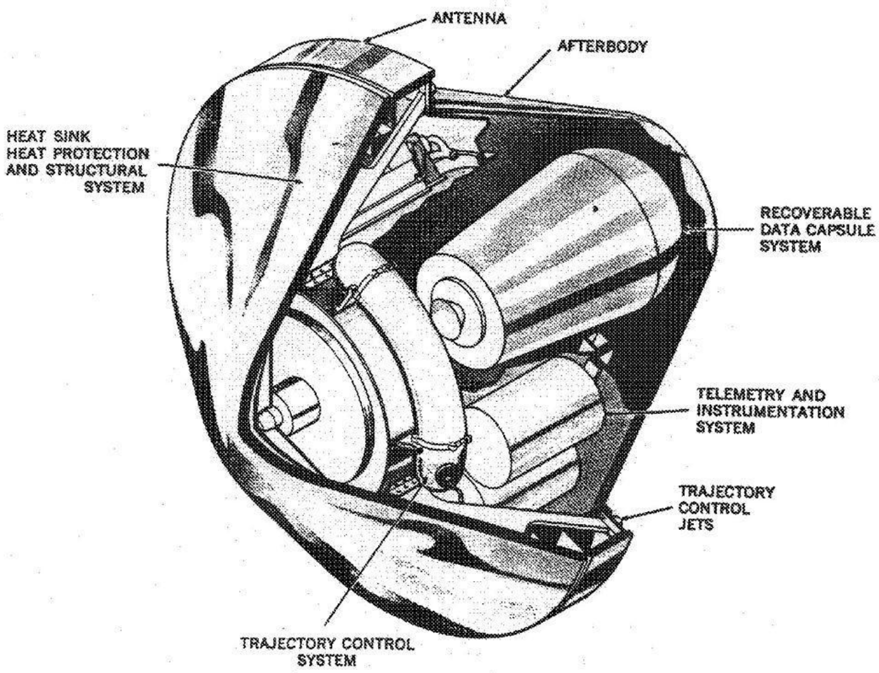
- This causes most of the heat dissipated to surrounding air without transferring through the vehicle structure.

ENTRY VEHICLE SHAPES

(I) Spherical Section:

- The shape of this entry vehicle can be a complete sphere with an afterbody which is converging and conical and hence sphere is the simplest axisymmetric shape.
- Newtonian impact theory can be used to determine the aerodynamics of a spherical section.
- A pure sphere doesn't have any lift but if flown by an angle of attack, it has considerable aerodynamic lift.
- These entry vehicles were used in the Vostok(Early Soviet), Soviet mars and venera descent vehicles.
- Soyuz, Gemini and Mercury are the other examples of spherical section geometry in manned capsules.

(II) Sphere-cone:



Mk-2 RV

- It has a dynamic stability better than that of a spherical section. A sphere cone is spherical section with frustum attached.

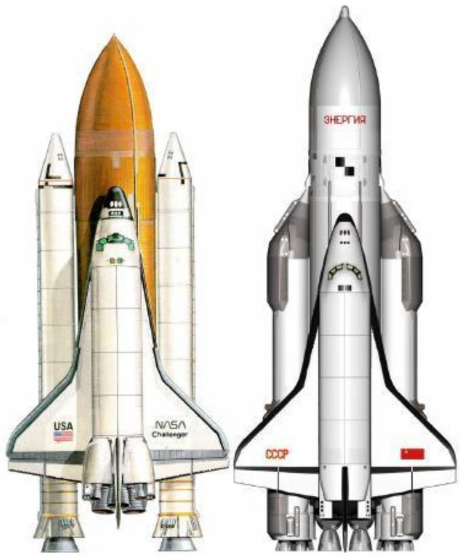
- MK2-RV(Re-Entry vehicle) is an example for sphere cone shaped vehicle and its design was obtained from blunt body theory.
- Sphere cone entry vehicles that are meant for space exploration have landed on the surface of Mars,Venus, Jupiter and Titan.
- The MK-6 re-entry vehicle is an advancement of its predecessor(MK-2) as it had a newer thermal protection system(TPS) and also it overcame the significant defects of MK-2 as it loitered too long in the atmosphere due to its lower ballistic coefficient.

(III) Biconic:

The McDonnell Douglas DC-X

- A Biconic shape similar to AMaRV.
- The biconic re-entry vehicle is a sphere cone with an additional frustum attached and it thus it offers an improved L/D ratio.
- Due to the lower peak deceleration, the higher L/D ratio makes a biconic shape suitable for transporting people to mars.
- The advanced Maneuverable re-entry vehicle(AMaRV) is an example of the biconic shaped RV ever flown.
- The attitude of AMaRV was controlled through a split body flap along with two yaw flaps.

(IV) Non-Axisymmetric shapes:



Concept of Winged Orbit Vehicle(American Space Shuttle)

- Concept of Winged Orbit Vehicle(American Space Shuttle).

- These have been used for manned entry vehicles.
- Eg:Winged orbit vehicle.It uses a delta wing for maneuvering during descent.A similar concept is applicable to the American Space Shuttle.

THERMAL PROTECTION SYSTEM (TPS)

(I) Reinforced Carbon-Carbon(RCC):

- It protects wing’s leading edge and nose cap.
- It is a laminated composite material made from graphite Rayon cloth and impregnated with phenolic resin. It is used at high temperatures by autoclave technique.
- To protect carbon-carbon from oxidation, SiC is used.
- To enhance mechanical, thermal and electrical properties, nanoscale reinforcement such as carbon nanotubes can be used.
- Structural Characteristic of RCC:-
  -By adding CNT, it will accommodate weak points in the reinforcement such as interlaminar regions and fibre bundles.
  -These materials can withstand temperatures above 1260 Centigrade approximately.
  -The SiC coating is produced by changing the outermost layer of C-C material which gIves high strength coating-to-substrate interlaminar strength.
  -RCC is mostly used because it rejects heat by external radiation and cross radiation which means radiating heat from the lower surface to the cooler surface of the material which prevents high temperatures.

(II) Ultra High Temperature Ceramics(UHTC's):-

- UHTC's constitutes borides, carbides, nitrides and oxides.These materials exhibits good overall properties at temperatures more than 2000 Centigrade.
- UHTC's such as zirconium and titanium diborides are used on the sharp edges of the re-entry vehicles which uses concept of "Positioning Massive Thermal Protection System".
- These materials have high hardness, chemical inertness and good resistance to oxidation in critical situations.
- The thermal shock stability of ZrB2-SiCp-AIN(ZSA) can be improved by healing the cracks generated in its structure which can be done by cooling it from 1450 centigrade and ZrB2-SiCp-Graphite(ZSG) can be improved by water quenching test which will provide new surface cracks.
- Zirconium Diboride(ZrB2) when subjected to high thermal loads improves performances having high heat fluxes which are typical in atmospheric re-entry.

(III) Ablatives:

- These materials provide heat shielding to the any propulsion device or protect the nose cap of any reentry vehicle.
- They may be non-polymer materials or polymer ablatives(PA's).
- PA's are better than non-polymer ablatives because of its heat-shock resistance, lower cost and tunable density.
- These ablatives lift the shock layer gas away from the heat shield outer wall creating a cooler boundary layer.

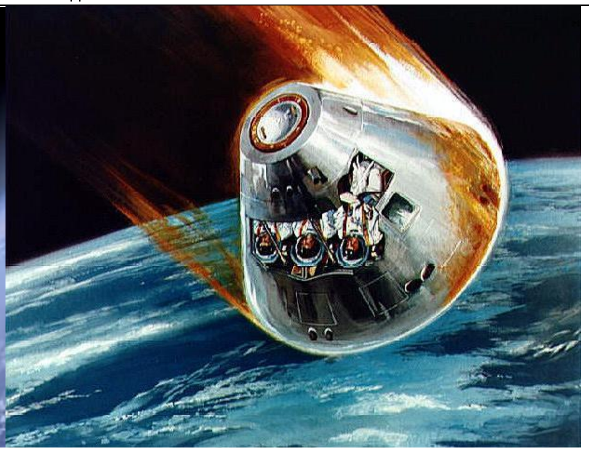
TYPES OF REENTRY VEHICLES

Reentry can be primarily divided into two basic classes:
(I) Uncontrolled Reentry: Launcher upper stage, manned and unmanned capsules etc.
(II) Controlled Reentry: Lifting body or control surfaces.

Uncontrolled Reentry:

- When the vehicles accelerate through the atmosphere at extreme velocities under the influence of Earth’s gravity.
- Such reentries are ballistic in nature.
- Examples include capsules like Orion, Apollo, Soyuz etc.
- Reentry occurs due to increase in atmospheric drag
- Thermal and deceleration loads cause fragmentation and destruction of the spacecraft.

Orion

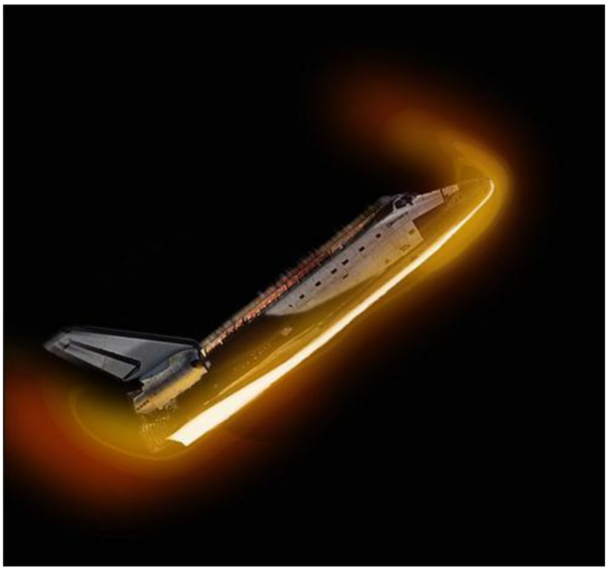


Apollo

Controlled Reentry:

- When atmospheric drag is not the only force acting on the spacecraft while reentry, then it is called controlled reentry.
- With controlled reentry the impact location can be chosen to minimize the hazard to crew and vehicle at lower altitudes.
- The spacecraft is controlled by adding wings to produce lift and ultimately slow down during descent. Vehicle's angle of attack can be changed to improve lift. The space shuttle is a perfect example for lifting reentry.
- It makes the phenomenon of aerobraking happen by using aerodynamic forces (drag and lift).
- Apart from using a wing, controlling surfaces such as flaps are used for better maneuverability, directional control and sticking to the desired trajectory. Examples include ESA's IXV and EXPERT.

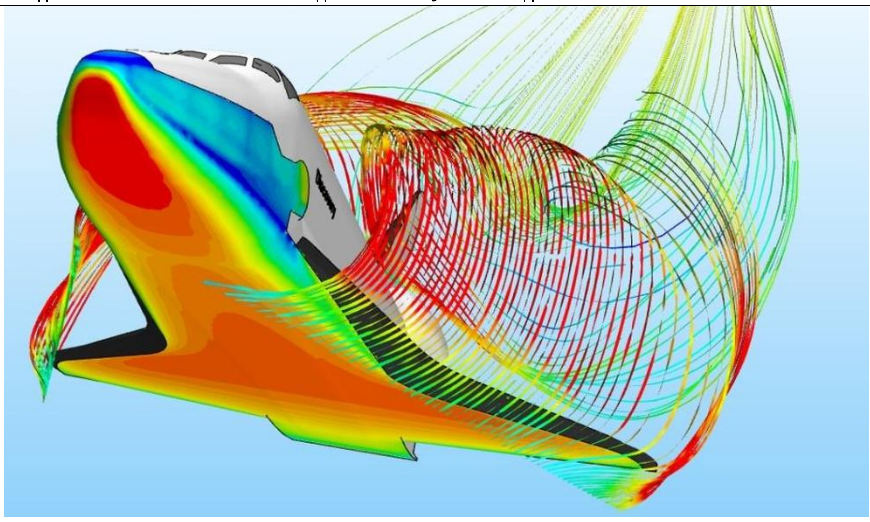
LIFTING REENTRY: THE SPACE SHUTTLE



Reentry of The Space Shuttle with high angle of attack

- It is a winged reusable spacecraft.
- It is designed to achieve large atmospheric maneuverability.
- It reenters horizontally on a runway.
- It has a low aspect ratio wing, vertical stabilizer, body flaps with landing parachute.

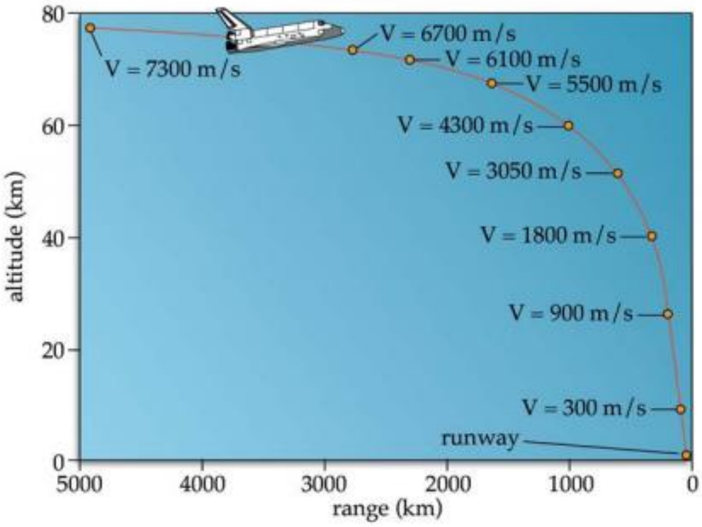
Materials include:



CFD analysis shows that the concentration of heat is highest on the belly of The Space Shuttle.

- Reinforced Carbon-Carbon (RCC) on the wing surface and at the belly of the space shuttle.
- High temperature black surface insulation tiles on the upper forward fuselage and around the windows.
- White nome blankets on the upper payload bay doors, portions of upper wing and mid/aft fuselage.
- Low temperature white surface tiles on the remaining area.

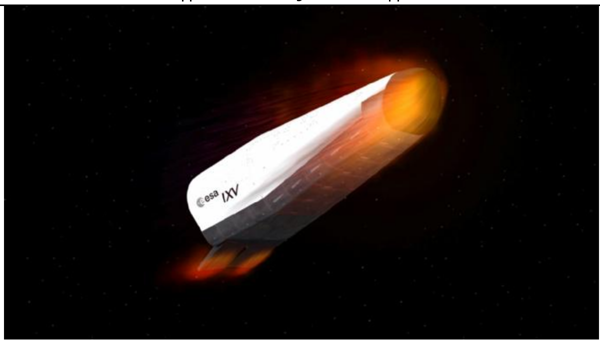
Manoeuvring during reentry:



Re-entry Profile for the Space Shuttle. This graph shows the Space Shuttle's altitude and velocity profile for a typical re-entry.

- The orbiter reenters atmosphere at a high angle of attack about 30 to 40 degrees by the help of aft steering jets.
- Such high angle of attack is used to direct most of the aerodynamic heating to the belly of the vehicle which is in turn protected by the heat resistant tiles.
- The hot ionised gases surrounding the orbiter prevent radio communication with the ground for about 12 minutes which is termed as ionisation blackout.
- After successful reentry, the orbiter flies like an airplane in the main air of the atmosphere.
- At this point, the orbiter is flied by flight computers.
- When the orbiter begins to approach the runway, it makes a series of banking turns to slow down.

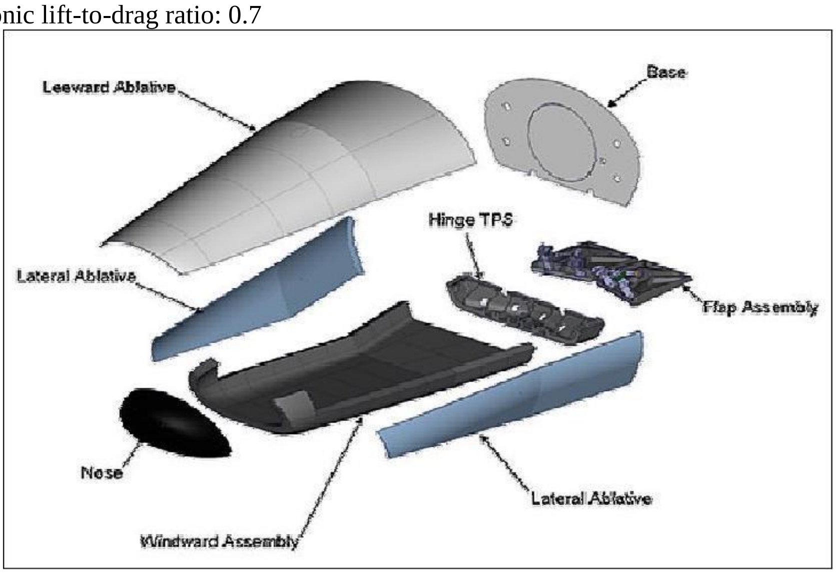
MODERN REENTRY VEHICLE: IXV



IXV reentry

- ESA's IXV, the Intermediate eXperimental falls under controlled reentry having a lifting body conic shape. This makes it highly aerodynamic and easy to manoeuvre.

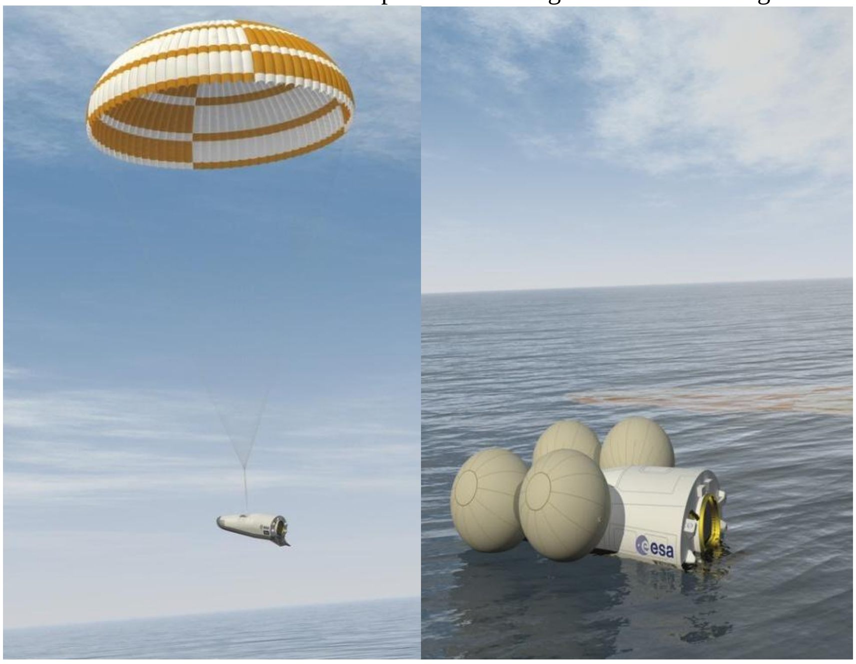
- Dimensions: 5 meters long, 1.5 meters high and 2.2 meters wide.
- Weight: nearly 2 tonnes.
- It has its own high performance diving, navigation and control system which uses mobile, automatically controlled aerodynamic surfaces.
- Heat shield material: Ceramic
- It has a combination of flaps and thrusters for flight control.
- Hypersonic lift-to-drag ratio: 0.7



Components of IXV

- Components: An inner body assembly with a number of inner bays, a base assembly, a lateral assembly, a leeward assembly, a windward assembly, a nose assembly and a pair of flaps assembly.

- The outer surface consists of advanced ceramic and ablative thermal protection materials that can withstand the severe reentry environment and protect the structural integrity.
- Inner elements are built around carbon reinforced polymer structural panels, which provide the strength and stiffness to resist the extreme forces experienced during launch and landing.



- The components house the avionic components for power, data handling and telemetry, the parachute and floatation devices for the flaps and thrusters.
- IXV travels at 27,000km/h while descending into Earth's atmosphere.
- IXV's sophisticated GNC (Guidance Navigation and Control) system uses the vehicle's lifting shape, two flaps and four thrusters to navigate through the atmosphere in such a way that it withstands the pressures and friction while approaching the landing point through 'reentry corridor'.
- Its thrusters and flaps operate together to change the vehicle's flight altitude.

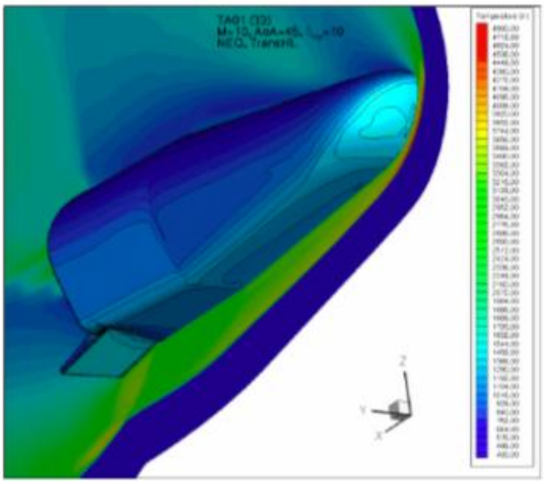
These black coloured tiles on the belly and the flaps are thermal protection panels.

- The thermal protection panels shield Ixv from temperatures reaching around 1700 degree celsius on reentry. The black panels cover the belly of IXV which are made of high performance carbon fibres woven into a ceramic matrix pattern.

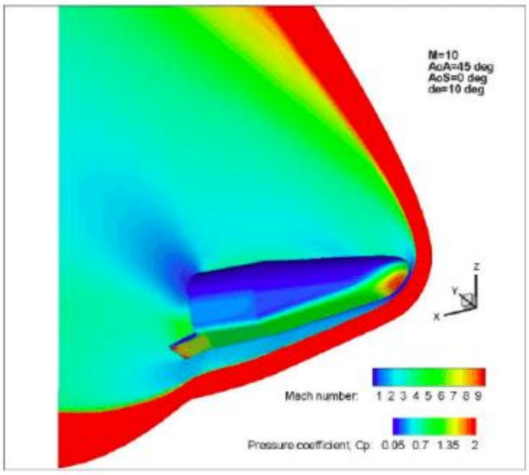
- The flow of heat is mapped across these panels by an infrared camera and 300 sensors integrated from nose to flaps of IXV.
- Four pressure sensors are placed upstream the flaps to provide data on the extent of the shock separation.
- The key technologies demonstrated by IXV include Thermal Protection Systems (TPS), operation in Aerothermodynamic environments (ATD), and Guidance, Navigation and Control (GNC).
- The Flush Air Data System derives precise vehicle altitude as a function of angle of attack, angle of sideslip and atmospheric properties from pressure and temperature measurements taken at the nose of vehicle.
- The flight of IXV was successful on 11th February 2015.

CFD Analysis:

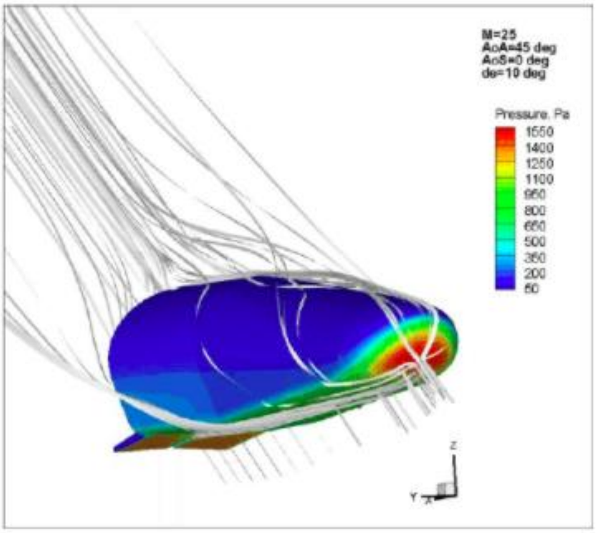
Computational Fluid Dynamics (CFD) solutions needed for the development of the tool have been provided by ESA-ESTEC (with the CFD code LORE) and CIRA (with the CFD code H3NS).



Temperature distribution



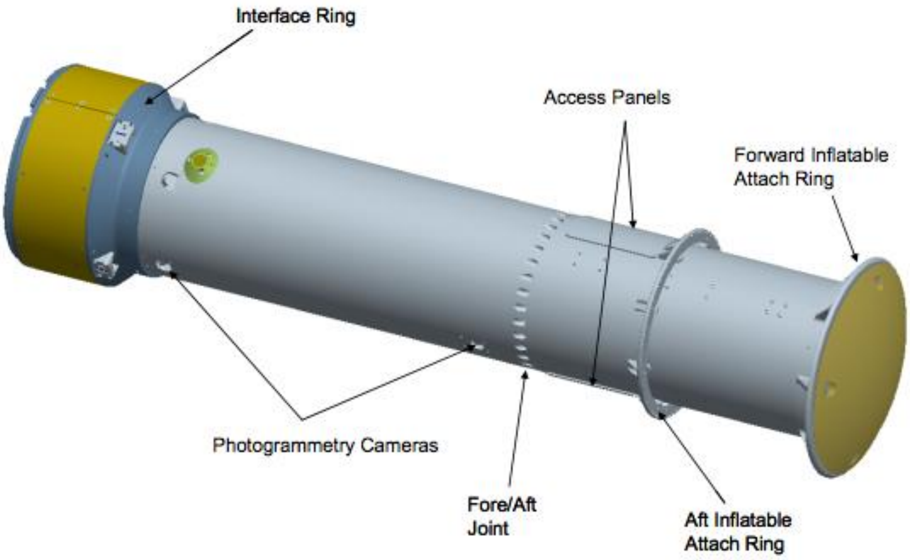
Mach contours at M10



Pressure contours on the vehicle surface with streamtraces at Mach 25

INFLATABLE HEAT SHIELD REENTRY

- For deceleration during atmospheric entry it is beneficial to increase the drag area of the entry system.
- An inflatable aeroshell diameter is not constrained by the launch vehicle shroud.
- It enlarges the drag area with a low mass design which helps it carry higher payload.
- The inflatable fabric surrounds a central instrument core like a folded umbrella.



Centre body structure

- The centre body structure has two segments; in the front half instrumentation is located and the aft segment holds the inflammation system.

CONCLUSION

From above discussion we can clearly get to know that the most crucial part of space mechanics is the reentry of the spacecraft which is the interaction of planet's atmosphere with the vehicle. So for better performance of the spacecraft at the entry, it is permissible to have a good aerodynamic frontal surface that is exposed to the planet's atmospheric layer and also the surface should be made of a high resistance and high strength materials such as ceramics, SiC etc. Recent invention and ideas on increasing the efficiency of reentry used in rockets such as Black Armadillo which has a foam insulation protecting the aluminium nose section from heating, also Parachute braking in which space shuttle velocity is decreased from 8km/s to 1km/s and also heat flow by 3-4 times. It uses high temperature fibers and whiskers.

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