PEGASUS SPACECRAFT

BY

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1. Introduction

The main goal is to design a spacecraft that is able to withstand the re-entry phase when entering earth from outer space. After performing several literature surveys, our team has finalized on a design capable of carrying 4 people and cargo which complies with the requirements of this project.

The Pegasus spacecraft, named after the constellation, comprises advanced materials like composites with light weight construction and aerodynamic design is capable of handling the challenges of re-entry.

On finalizing the concept, the modelling was performed in SOLIDWORKS and analysis was performed ANSYS 2020 R2.

2. Detailed design study

The re-entry phase of a spacecraft is the most challenging phase of its journey, here we will be dealing with re-entry to the earth's surface. The main challenges dealing with re-entry are:

1. Deceleration
2. Heating
3. Landing/Impact Accuracy

1) Deceleration:

The vehicle's structure and payload limit the maximum deceleration or "g's" it can withstand. (One "g" is the gravitational acceleration at Earth's surface—9.798 m/s^2.) When subjected to enough g's, even steel and aluminium can crumple like paper. Fortunately, the structural g limits for a well-designed vehicle can be quite high, perhaps hundreds of g's. But a fragile human payload would be crushed to death long before reaching that level. Humans can withstand a maximum deceleration of about 12 g's

But maximum g's aren't the only concern of re-entry designers. Too little deceleration can also cause serious problems. Similar to a rock skipping off a pond, a vehicle that doesn't slow down enough may literally bounce off the atmosphere and back into the cold reaches of space.

2) Heating:

Heating is another major concern, maybe even the most concerning of the three, it can be clearly seen from meteors, almost all meteors burn and disintegrate when entering the earth's atmosphere, this due to the friction between the speeding meteor and the earth's atmosphere. The space shuttle faced intense temperatures of 1700 degree Celsius. This is mainly due to the conversion of the kinetic energy of the orbital velocity and the potential energy of the spacecraft's height to heat energy from the friction of earth's atmosphere. So a compatible heat shield must be designed.

Thermal Protection System: Space vehicles that enter a planetary atmosphere (i.e. earth) like the Space Shuttle Orbiter require the use of a thermal protection system (TPS) to protect them from aerodynamic heating. The aerodynamic heating is generated at the surface of an entering object due to the combination of compression and surface friction of the atmospheric gas. The vehicle's configuration and entry trajectory in combination with the type of thermal protection system used define the temperature distribution on the vehicle.The heat developed from the aerodynamic heating process is thereby radiated back into space by virtue of the high surface temperature. The leading edges of wings and the nose cap are the highest temperature regions.

3) Landing/Impact accuracy:

This can vary due to the vehicles design purpose, an Intercontinental Ballistic missiles (ICBM) re-entry vehicle will have very tight constraints as it must have pinpoint accuracy, a space shuttle after reentry phase will act as a glider to land on a runway just 91m wide, so it must maintain a sufficient glide path to glide safely to the runway, a capsule will have the least constraints as it can land in a larger are be it on water or on land using parachutes.

Finding the right trade-offs for Re-Entry:

We need to design a vehicle that can re-enter in such a way that it enters the atmosphere at an optimum angle, if it enters at a steep angle, it will decelerate too fast, crushing humans inside and heat up too quickly such that it may end up disintegrating in the atmosphere, if it enters too shallow of an angle then, it won't experience enough drag and may literally skip off the atmosphere, back into space. The spacecraft would also need to maintain the same orientation throughout the entire re-entry phase.

3. Concept Designing

Capsule Shape

For the purpose of the project, a space capsule type design has been selected, the capsule must have a certain shape such that it can be able to decelerate rapidly upon re-entry, so a blunt body shape must be implemented, a rounded end shape was found to be the most optimal shape, it was initially discovered from the Brenham main mass meteor, which is the world's largest oriented meteor. Unlike other meteors, this meteor had a rounded end that did not tumble or change its vertical axis as it plunged through Earth’s atmosphere. As a result, it did not end up disintegrating like the other meteors, the Apollo capsules were inspired from this design and are still used in modern capsules, our design will also implement this shape.

What makes this particular blunt shape work is that when a capsule leaves an orbit from space and enters earth's atmosphere, it will have a speed of about 28,000 km/h and on entering the atmosphere at these hypersonic speeds, it will form a layer of shockwave, if the shock wave comes in contact with the capsule, it will cause excess heating around the capsule and would cause local heating at several spots around the capsule, this blunt body shape will prevent shock interaction by creating a bow shock due to the less aerodynamic rounded end of the body, there will be some air molecules between the shock layer and the body of the capsule, this prevents the capsule from getting too hot and maintain a stable orientation when descending the atmosphere.

Heat shield

Although this shape prevents excess heating of the capsule, the end facing the atmosphere will be subjected to extreme heat, so much so that the air around gets ionized, so an appropriate heat shield must be designed in order to withstand these high temperatures. The heat shield will also have ablative layers so that the outermost layer will burn and chip off protecting the underlying layers from getting too hot.

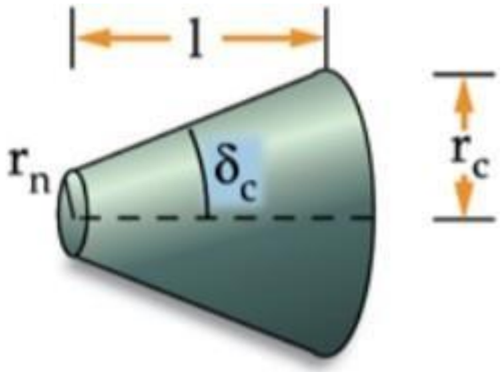
Landing

Even after going through this extreme deceleration phase, the capsule will still fall at about 1000km/h, so special type of parachutes must be deployed in order to slow the capsule even further to an acceptable landing speed. Usually, the landing constraints are not very strict for the space capsules, they are usually designed to land in the ocean.

4. Final concept

The design will have the following basic specifications: -

- Diameter- 4m
- Height-2.5 m
- Passenger weight - 480 kg (all 4 passengers including spacesuits)
- Total return payload- 1500 kg (including passengers)



Coefficient of Drag(Cd):

$$C_D = (1 - sin^4\alpha)\left(\frac{r_n^2}{r_c^2}\right) + 2sin^2\alpha \left[1 - \left(\frac{r_n^2}{r_c^2}\right)cos^2\alpha\right]$$

Using the above formula, coefficient of drag can be calculated. Here, α is the half vertex angle of the capsule. r_n and r_c are the minor and major radii of the cone, respectively.
The coefficient of drag comes out to be **0.169.**

5. Materials used

The materials used for the main parts of the capsule are as follows:

1. Pressure Vessel Structure – Aluminium Lithium (Al-Li) Alloy

Reason - reduced density as well as increased stiffness and strength

2. Joining technique – Friction Stir welding

Reason:

- The finished weld is seamless and aesthetical
- Fully automated process
- No form of flux or shielding agent required
- Low peak temperatures prevent shrinkage and porosity of the cracks

3. Back Shell – Honeycomb with titanium core and aluminium face sheet with Toughened Unipiece Fibrous Insulation (TUFI) coated (AETB) thermal tiles

Reason:

- AETB—Alumina enhanced thermal barrier is a high-temperature tile incorporating alumina fibres; can withstand temperatures up to 2,600°F.
- TUFI- Toughened Unipiece Fibrous Insulation is a toughened tile-coating preparation that provides order of magnitude improvement in damage resistance.
- Titanium honeycomb- Provides good mechanical properties at very high temperatures. Robust and damage tolerant. Lightweight. Large panel sizes. Panel-to-panel overlap minimizes gap seal problems.

4. Heat Shield- Titanium Skeleton and Carbon fibre skin with AVOCAT ablative material

Reason:

- Titanium Skeleton and Carbon fibre skin with AVOCAT – Titanium skeleton provides strength to withstand water impact during splashdown.
- Carbon fibre skin provides additional strength and acts as mounting surface for AVOCAT ablative material.

5. Tile Bonding- The tiles are bonded to the orbiter with a silicone adhesive.

Reason:

- Silicones remain very flexible at low temperatures experienced during the cold part of orbit and retain good bond strength at the high temperatures experienced during re-entry.

6. Parachute – Hybrid of Nylon and Kevlar.

Reason:

- Nylon is very strong and light, that is, it has a very high strength to weight ratio.
- Kevlar will be used in the bridle which are the tethers connecting Pegasus to the nylon parachutes, it is a very strong material, used in bulletproof vests.

6. Manufacturing techniques

The manufacturing of the key parts of the spacecraft are as follows: -

Pressure vessel:

Lithium Aluminium (Li-Al): Aluminium is alloyed with lithium in the following methods

- Displacement:

A lithium atom is lighter than an aluminium atom; each lithium atom then displaces one aluminium atom from the crystal lattice while maintaining the lattice structure.

- Strain Hardening:

Introducing another type of atom into the crystal strains the lattice, which helps block dislocations. The resulting material is thus stronger, which allows less of it to be used.

- Precipitation hardening:

When properly aged, lithium forms a metastable Al_3Li phase (δ') with a coherent crystal structure. These precipitates strengthen the metal by impeding dislocation motion during deformation.

The pressure vessel would be made in several parts which would then be joined together as a single unit using Friction Stir Welding (FSW)

Friction Stir Welding (FSW):

Standard fusion-welding techniques rely on torch-generated heat to melt and join the metal. Friction stir welding does not melt the metal. Instead, it uses a rotating pin and "shoulder" to generate friction, stir the metal together, and forge a bond. This process results in welds with mechanical properties superior to fusion welds

AETB tiles:

A multi-layer tile material produced from layers of alumina enhanced thermal barrier material having different densities. The insulation layers are bound together by a high strength, high temperature alumina or silica binder having a coefficient of thermal expansion similar to that of the insulation layers. Use of the multi-layered tile allows the problems of tile slumping and of insufficient heat management associated with low density alumina enhanced thermal barrier tile to be overcome.

Tile Bonding:

The tiles are first bonded to a strain isolator pad, a needled Nomex felt material, before bonding directly to the aluminium airframe. The purpose of the isolator pad is to allow the tiles to "float" very slightly to limit vibration-induced damage during the ascent to orbit and also to provide a means of compensating for the differences in thermal expansion between the tiles and the airframe.

Tile Gap fillers:

There are typically small gaps left between them to allow for minor structural deflections. In order to prevent hot air intrusion and tile-to-tile contact, gap filler materials are used in areas of large pressure gradients and vibro-acoustic environments. gap filler consisting of a ceramic cloth impregnated with a silicone polymer is used

Heat shield:

The heat shield is composed of a titanium skeleton and carbon fibre skin that gives the crew module its circular shape on the bottom and provided structural support, on top of which a fiberglass-phenolic honeycomb structure was placed. The honeycomb structure had many tiny cells that would be individually filled by hand with an ablative material called Avcoat designed to wear away as the spacecraft returned to Earth through the atmosphere. During the labour-intensive process, each individual cell will be filled by hand as part of a serial process, cured in a large oven, X-rayed and then robotically machined to meet precise thickness requirements.

AVOCAT ablative:

AVOCAT is an epoxy novolac resin with a number of additives to create a substance with a low density of 0.51g/cm^3, it is filled in an empty fibreglass phenolic honeycomb structure attached to the carbon fibre skin.

7. Application Strategy

Pegasus is designed to transport crew of 4 astronauts and cargo to the International Space Station, the overall size of pegasus is smaller than those of dragon and starliner spacecraft, however those crafts are designed to carry upto 7 people compared to the 4 in pegasus.

Pegasus uses the latest space grade materials which are also used in the Orion spacecraft for the Artemis mission, the spacecraft will be mounted on top of a large rocket system for launch from earth and the materials are tried and tested to withstand the G-forces from launch.

Pegasus’s nose cone can open prior to docking to the ISS exposing the hatch which would transfer the crew inside the ISS when docked.

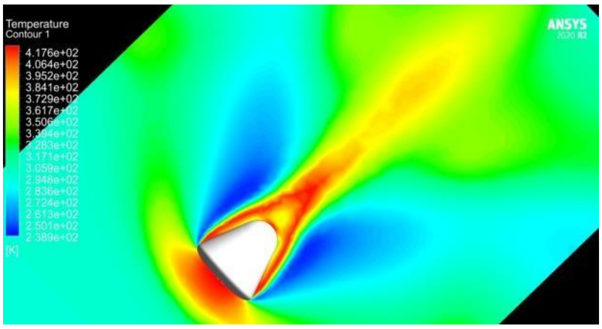
For the re-entry phase, the heat shields will protect the crew inside from the extreme heat and the high G-forces as pegasus decelerates from the orbital velocity of about 28,200km/h at the time of contact to earth’s atmosphere to 1000km/h in 8-10 minutes. The spacecraft will then deploy it’s parachutes which will slow it down even further to a safe landing speed and then will proceed to land in the water.

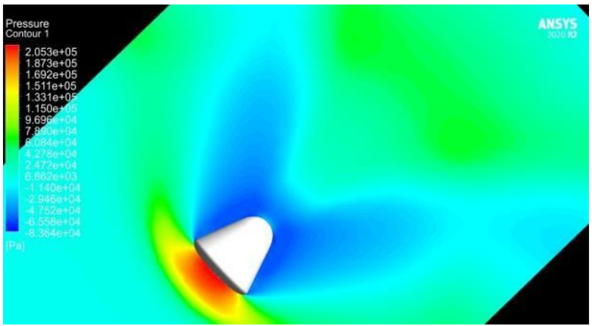
Water landing is ideal as it will cool the spacecraft from the extreme temperatures from re-entry to a safe temperature for the rescue team to open the spacecraft and extract the crew.

8. Result

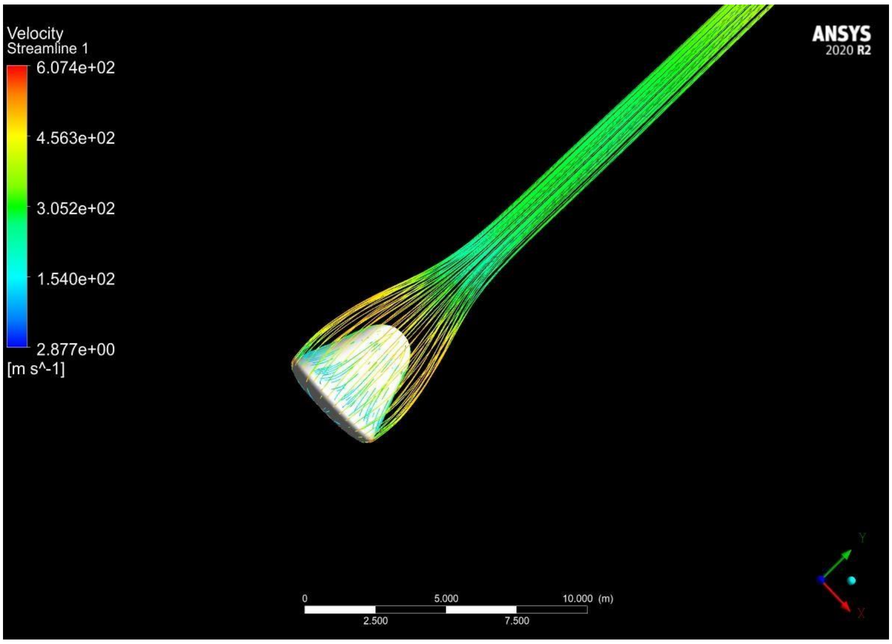
Based on the aerodynamic principles discussed above, the final design of the vehicle was created using SOLIDWORKS.

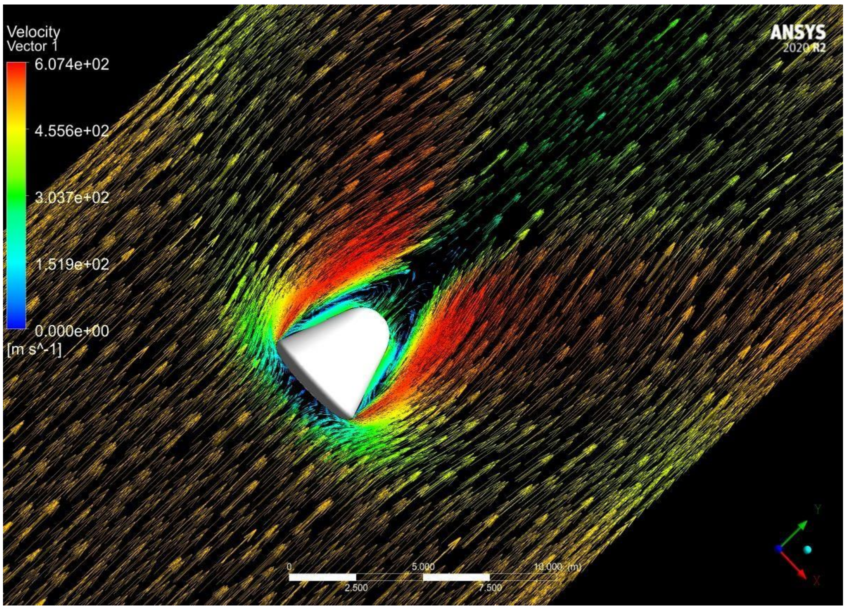
ANSYS CFX was used to perform CFD Analysis on the final design. The RNG k-ε model was used as it provides a good compromise between performance and computer resources. The RNG approach, which is a mathematical technique that can be used to derive a turbulence model similar to the k-epsilon, results in a modified form of the epsilon equation which attempts to account for the different scales of motion through changes to the production term.
The following images show the pressure and temperature contours.





The CFD analysis shows that the temperature is highest(417 K) below the lower heat shield and around the upper heat shield. The pressure is highest(2.053×10^5 Pa) at the lower heat shield.
The following images show the flow of air around the re-entry vehicle.





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