# SPACE

## THE FINAL FRONTIER

### SAMPLE MISSION REPORT

# CREW DRAGON - RESILIENCE

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# MISSION REPORT

## SpaceX Crew Dragon: RESILIENCE

# SPACEX Crew Dragon - Resilience

Sample Mission Report, Group 3

## 1. INTRODUCTION

The Space Crew-Dragon 1 was launched on November 16th on Falcon 9 to the orbit from NASA's Kennedy Space Center, Florida. The mission was a part of NASA's Commercial Crew Program.

The crew included Mike Hopkins (Commander), Victor Glover (Pilot), Shanon Walker and JAXA astronaut Soichi Noguchi (Mission Specialists). Duration of the mission was approximately 6 months. The crew returned back on earth on May 2nd 2021. The spacecraft *Resilience* splashed down in the Atlantic ocean off the coast of Florida.

Falcon 9 is a reusable double stage rocket. A double-stage-to-orbit launch vehicle is a spacecraft premised on the concept of a reusable launch system using two rocket stages, each containing its own engines and propellant - provide propulsion consecutively to achieve orbital velocity. The two stages are designed so that the first stage is reusable while the second is expendable.

The objective of the mission was to reduce the cost of production, transport of 500 pounds of cargo and crew to the ISS and for further scientific research like food physiology of the crew, effect on gene and how it affects the brain functionality of the crew while they are in space, how microgravity affects the the structure and functionality of organs, growth of plants in space in various types of soils and varying light and temperature, to improve the design of spacesuit, and many more.


Fig-1: Overview

## 2. Payload

The payload system of a rocket depends on the rocket's mission. The earliest payloads on rockets were fireworks for celebrating holidays. The payload of the German V2, was several thousand pounds of explosives. Following World War II, many countries developed guided ballistic missiles armed with nuclear warheads for payloads. The same rockets were modified to launch satellites with a wide range of missions; communications, weather monitoring, spying, planetary exploration, and observatories, like the Hubble Space Telescope. Special rockets were developed to launch people into earth orbit and onto the surface of the Moon.

For this mission, the *Resilience* was able to carry a payload of 6,000 kilograms (13,000lb) to the orbit, which can be all pressurized, all depressurized or anywhere between. It can return to Earth 3,000 kilograms (6,600lb) of return pressurized cargo and 800kg (1,800lb) disposed cargo. The spacecraft also delivered over 500 pounds of cargo, science hardware and experiments to the ISS.

Falcon 9 can lift payloads of up to 22,800 kilograms (50,300 lb) to low Earth orbit (LEO), 8,300 kg (18,300 lb) to geostationary transfer orbit (GTO) when expended, and 5,500 kg (12,100 lb) to GTO when the first stage is recovered, in a cargo shroud offering 145 cubic meters of volume.

## 3. Fairing

The fairing is a protective cover that surrounds the payload on the launch vehicle as it ascends through Earth's atmosphere on its way to space.A payload fairing is a nose cone used to protect a spacecraft payload against the impact of dynamic pressure, biospheric contamination and aerodynamic heating during launch through an atmosphere. An additional function on some flights is to maintain the cleanroom environment for precision instruments. Once outside the atmosphere the fairing is released, exposing the payload to outer space.

Payload fairings usually burns up in the atmosphere or destroyed upon impacting the ocean. SpaceX has managed to successfully catch the fairings – catching both halves of the fairing used on one of its Falcon 9 rocket launches. It attempts to reduce the cost of its launches by building In as much reusability as it can. SpaceX estimates that it can save as much as $6 million per launch by recovering and reusing the fairing halves.

The fairing halves don't have any propellant systems to control their landing like the Falcon 9 first stages do – instead, they're slowed via parachutes, meaning there's a bigger reliance on the ships to actually be positioned correctly to anticipate their fall, since it's not specifically programmed.

Falcon 9 fairing measures as 13 m (43 ft) long, 5.2 m (17 ft) in diameter, weighs approximately 1900 kg, and is constructed of carbon fiber skin overlaid on an aluminum honeycomb core. The Falcon 9 fairing can accommodate a combination of up to three access doors or radio frequency (RF) windows in the cylindrical portion. The standard payload fairing door is a maximum of 24 inches (61 cm) in size. Combinations of acoustic surfaces are used inside the payload fairing to help achieve the acoustic environment.

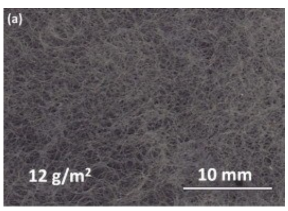



Fig-2a: Material Texture

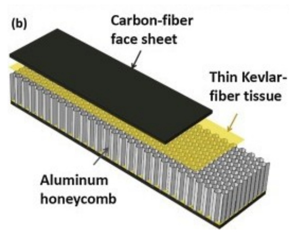



Fig-2b: Faring Material

The Falcon 9 was described as capable of launching approximately 9,500 kilograms (20,900 lb) to low Earth orbit, and was projected to be priced at US $27 million per flight with a 3.7 metres (12 ft) payload fairing and US $35 million with a 5.2 metres (17 ft) fairing.

## 4. Design

SpaceX's Dragon space capsule design is a gumdrop-shaped spacecraft built for spaceflights into and from low-Earth orbit. The spacecraft was initially designed as an unmanned spacecraft, but is being scaled up to launch astronauts into space as well.

Crew Dragon was developed in collaboration with NASA's Commercial Crew Program. In 2014, NASA awarded Commercial Crew Transportation Capability (CCtCap) contracts to Boeing and SpaceX to each safely and cost-effectively transport astronauts to the International Space Station from the United States. Crew Dragon is capable of carrying up to seven passengers but will carry up to four astronauts for NASA missions, and is designed for water landings. Crew Dragon's displays will provide real-time information on the state of the spacecraft's capabilities—anything from the spacecraft's position in space, to possible destinations, to the environment on board. Crew Dragon is a fully autonomous spacecraft that can be monitored and controlled by onboard astronauts and SpaceX mission control in Hawthorne, California.

1. Dragon is composed of two main elements: the capsule, which is designed to carry crew and critical, pressurized cargo, and the trunk, which is an unpressurized service module. The capsule is subdivided into the pressurized section, the service section and the nose cone, which is opened once on orbit and stowed prior to re-entry.Above the seats, there is a three-screen control panel, a toilet (with privacy curtain), and the docking hatch. . Near the base of the capsule, but outside the pressurized structure, are the Draco thrusters, which allow for orbital maneuvering. Additional Draco thrusters are housed under the nose cone, along with Dragon's Guidance Navigation and Control (GNC) sensors . Ocean landings are accomplished with four main parachutes in both variants. The parachute system was fully redesigned from the one used in the prior Dragon capsule, due to the need to deploy the parachutes under a variety of launch abort scenarios.
2. Crew Dragon has an Environmental Control and Life Support System (ECLSS) that provides a comfortable and safe environment for crew members. During their trip, astronauts on board can set the spacecraft's interior temperature to between 65 and 80 degrees Fahrenheit.
3. Crew Dragon has eight side-mounted SuperDraco engines, clustered in redundant pairs in four engine pods, with each engine able to produce 71 kN (16,000 lbf) of thrust to be used for launch aborts. Each pod also contains four Draco thrusters that can be used for attitude control and orbital maneuvers. The SuperDraco engine combustion chamber is printed of Inconel, an alloy of nickel and iron, using a process of direct metal laser sintering. Engines are contained in a protective nacelle to prevent fault propagation if an engine fails *(to be discussed further in engines and propellant section)*.
4. Once in orbit, Dragon 2 is able to autonomously dock to the ISS *(to be discussed further in rocket equations section)*. Dragon 1 was berthed using the Canadarm2 robotic arm, requiring substantially more involvement from ISS crew. Pilots of Crew Dragon retain the ability to dock the spacecraft using manual controls interfaced with a static tablet-like computer. The spacecraft can be operated in full vacuum, and "the crew will wear SpaceX-designed space suits to protect them from a rapid cabin depressurization emergency event". Also, the spacecraft will be able to return safely if a leak occurs "of up to an equivalent orifice of 6.35 mm [0.25 in] in diameter".
5. Propellant and helium pressurant for both launch aborts and on-orbit maneuvering is contained in composite-carbon-overwrap titanium spherical tanks *(to be discussed further in engines and propellant section)*. A PICA-X heat shield protects the capsule during re-entry, while a movable ballast sled allows more precise attitude control of the spacecraft during the atmospheric entry phase of the return to Earth and more accurate control of the landing ellipse location. A reusable nose cone "protects the vessel and the docking adaptor during ascent and re-entry", pivoting on a hinge to enable in-space docking and returning to the covered position for re-entry and future launched *(to be discussed further in re-entry section)*.
6. Dragon's trunk provides the mating interface for the capsule to Falcon 9 on its ascent to space. On orbit, half of the trunk contains a solar array, which powers Dragon, and the other half contains a radiator, which rejects heat. Both the radiator and solar array are mounted to the exterior of the trunk, which remains attached to Dragon until shortly before re-entry when the trunk is jettisoned.
7. The technical definition of a Fin is: A surface used to give directional stability to any object moving through a fluid such as water or air. In short, fins provide maneuverability and stability to the rocket in the upper atmosphere. Falcon 9 is equipped with four hypersonic grid fins positioned at the base of the interstage. They orient the rocket during reentry by moving the center of pressure.

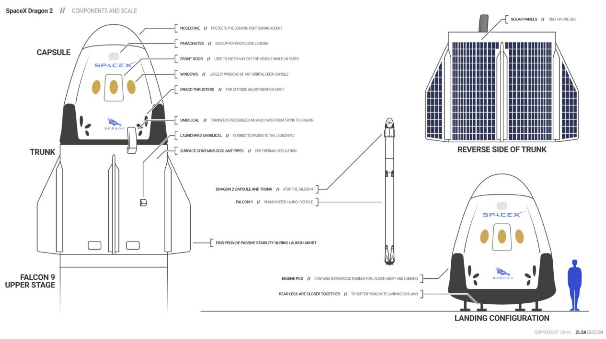


Fig-3: RESILIENCE Information

### *4.1. System Overview of Falcon 9*

1. Height: 70 meters or 229.6 feet
2. Mass: 549,054 kilograms or 1,207,920 pounds
3. Diameter: 3.7 meters or 12 feet

## 5. Boosters

A booster rocket is either the first stage of a multistage launch vehicle, or else a shorter-burning rocket used in parallel with longer-burning sustainer rockets to augment the space vehicle's takeoff thrust and payload capability.

A Falcon 9 first-stage booster is a reusable rocket booster used on the Falcon 9 and Falcon Heavy orbital launch vehicles manufactured by SpaceX. The manufacture of first-stage booster constitutes about 60% of the launch price of a single Falcon 9 and three of them over 80% of the launch price of a Falcon Heavy, which led SpaceX to develop a program dedicated to recovery and reuse of these boosters for a significant decrease in launch costs.

The booster used in this mission is Booster 1061. Falcon 9 B1061 first launched Crew-1 to the ISS in November 2020, the first operational flight of Crew Dragon. Following landing on drone ship following the Crew-1 flight, this first stage has completed three flights by June 2021. B1061 is a Falcon 9 Block 5 core *(to be discussed further in aerodynamics section)*.

## 6. Abort System

A launch escape system (LES) or launch abort system (LAS) is a crew-safety system connected to a space capsule that can be used to quickly separate the capsule from its launch vehicle in case of an emergency requiring the abort of the launch, such as an impending explosion.

The abort system of the spacecraft can be activated by three ways:

1. The crew can pull a handle inside the spacecraft.
2. Mission control can send a remote command to the spacecraft.
3. Or the craft itself can automatically start the sequence if it detects a problem in the rocket.

This will cause the eight small SuperDraco rocket engines on the capsule to fire and lift it away from the rocket.

During the abort, the astronauts experience extreme forces, stronger than gravity, ascending about approximately a kilometer and a half before the capsule splashes down in the Atlantic Ocean under parachute. It's an extreme maneuver for extreme emergencies.

There are four compartments ( Quads ) that integrate a total of eight SuperDraco engines (four pairs, two per Quad ) with a thrust of 73 kN per unit. SuperDraco, high-performance hypergolic propellant engines, serve the dual role of abort thrusters on emergency launch and braking retro rockets on descent. Each of the eight SuperDraco engine generates 15,000 pounds of thrust and burns about six seconds. The test began at 9 a.m. After the engines shut down, the Dragon spacecraft's trunk, will separate when it reaches peak altitude.

The most dicey part of the launch occurs in the second abort stage. This is the point of peak aerodynamic stress known as "max q," which occurs about a minute and a half after launch. The rocket is moving at about 1,500 mph and all the aerodynamic pressure experienced by the capsule during max q makes it the worst possible time to abort. But it's also the period during a launch when things are most likely to go wrong.

During the Crew Dragon launch abort test as the rocket entered max q, SpaceX mission control killed its engines. The capsule automatically registered that something was wrong, fired its SuperDraco engines, and pulled away from the Falcon 9 rocket as it exploded in the air. The capsule kept coasting into the stratosphere before beginning its descent to Earth and splashing down in the Atlantic Ocean under parachute. When it comes to human spaceflight, the best abort scenario is the one that never happens *(to be discussed further in engine and propellant section)*.

## 7. Engine and Propellants

Here our goal is to take astronauts to ISS(international space station) which is revolving at 7.66 km/s around earth.so we need to keep the astronauts in the orbit with nearly same velocity so they can reach ISS without any major impulse which kills them.So we need to apply force(human bearable acceleration$<9$g) which does work against gravity to reach required altitude and accelerates the astronauts to the required velocity.

Till now the best feasible way to apply force on an object that is going to far distances in vacuum(where there is no other significant energy source that can apply force in our desired direction) is expelling out mass carrying with us in the direction opposite to our desired direction of motion.So by Law of conservation of momentum our velocity will increase in desired direction.To apply more force we need to eject more mass as fast as possible with more velocity.

But our desired velocity is so huge that we need to carry a lot of mass with us to expel it out with some low velocity.So we can save money and resources by ejecting less amount of mass with very high velocity so that we can reach our desired velocity.' But how can we expel the mass with such huge velocities? Is there any such machine that can expel the mass with such high velocity? From where can we give energy to such a machine to work? The best method to do this is to use energy from expelling mass itself to throw it with high velocity.So the expelling mass will be storing the energy to use while expelling it out. So we are extracting the energy from the expelling mass by chemical reactions.(forget about nuclear fission and fusion for now,take it for granted that they are not feasible in this mission)

The mass that is using its own chemical energy to expel out with higher velocity is called FUEL.Combustion is the most common chemical reaction that gives out huge amounts of energy. But we need oxygen for combustion,but in most of the points of trajectory of our rocket we don't have required concentration of oxygen to carry out combustion.So we will be carrying OXYGEN with us along with fuel to meet the oxygen demand. Here the machine that expels out the mass as fast as possible is called ENGINE.

## 8. Falcon 9 Specifications

### *8.1. Engine*

Merlin - gas generator powered open cycle engine(both above sea level and vacuum optimized engines exist)

### *8.2. Propellant*

Keralox(RP-1 + liquid oxygen), where RP-1 is the rocket grade kerosene

## 9. Gas Generator Powered Open Cycle Engine

This is the simplest combustion engine.First of all fuel and oxidizer is stored in different tanks.These two undergo combustion in the combustion chamber so that the end products eject out with high velocities by absorbing the energy from combustion reaction.Thus we are able to eject the mass with higher velocities. But the pressure and temperature is very high in the combustion chamber compared to pressure in fuel and oxidizer tanks.So propellant cannot move from high pressure to low pressure.So we want a higher pressure region in the propellant's side than in the combustion chamber such that propellent moves from fuel tank to combustion chamber. But if we increase the pressure in the tank such that it is greater than in the combustion chamber,we need to make tanks with very thick and costly material so it can withstand such pressures.And also the fuel tanks become very heavy so most of the fuel is consumed to accelerate them.So increasing pressure in the fuel tank is a bad idea.

### *9.1. Turbo Pump*

Instead we will be using turbo pumps to increase the pressure such that it is greater than that in the combustion chamber.But we need to power the turbo pumps.As we already have a energy source from propellant,we will be using it to power the turbo pump instead of other sources.Some part of fuel and oxidizer mixture is diverted to the pre-burner where that fuel undergoes combustion and the products evolve out from the pre-burner with higher velocities,these gases are sent through the turbine,where they rotates the turbine and finally ejected out.The turbine is is connected to other two turbo pumps with same shaft thus powering them.

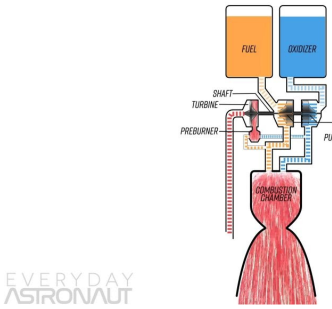



Fig-4: Turbo Pump

### *9.2. Fuel Rich Combustion*

But there is a problem here.The combustion temperature is very high( 3000k) such that the pre-burner and combustion chamber are made with high melting point materials and also very thick.But the turbine is needed to be made with very thin and lightweight material(which generally will not have high melting points) so it will be rotated fast by gases.Thus the turbine melts off with such high temperatures,so we need to decrease the temperature.So we are making an inefficient combustion by keeping incorrect fuel oxidizer mixture(fuel rich or oxidizer rich) in the pre-burner,so that partial combustion occurs and temperature stays low.

In the Merlin engine we are using a fuel rich pre-burner,where all the fuel is not involved in combustion,so remaining fuel absorbs that excess heat and decreases the temperature.Thus the partially burnt propellant comes out as soot (black colour).

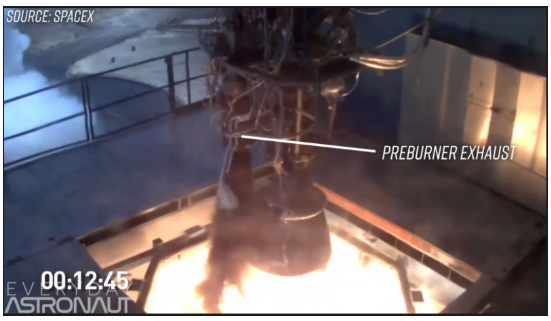



Fig-5: Exhaust

### *9.3. Pintle Injector*

Fuel and oxidizer should be mixed thoroughly in the combustion chamber for the combustion to be efficient.So the fuel and oxidizer are atomized(gaseous bubbles) so that they mix thoroughly.

Fig-6: Pintile Injector atomizing Water

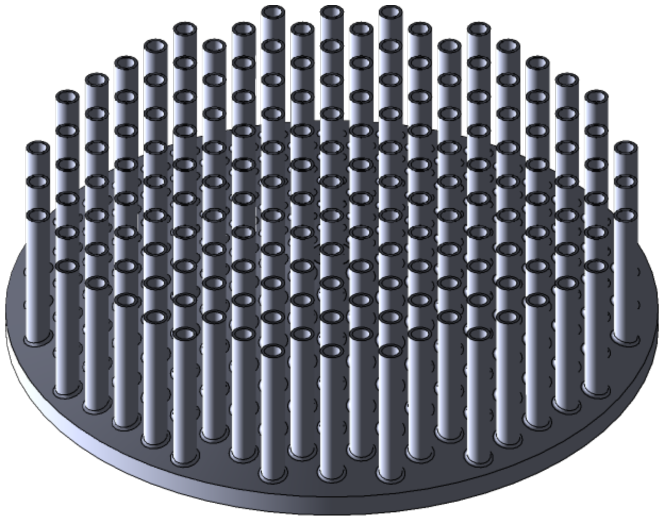


Fig-7: Pintile Injector Visualization

### *9.4. Nozzle*

After combustion of RP-1 and oxygen,carbon dioxide($CO_2$) and water vapour($H_2O$) are formed and they get kinetic energy by absorbing the energy released from combustion.But their velocities are in different directions and also small due to high pressure.We need to direct these gases in one direction and increase their velocity,so that we will be getting maximum thrust.

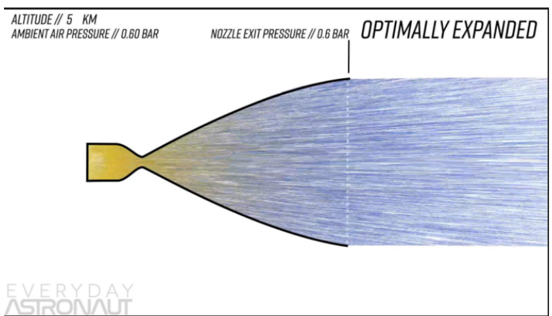



Fig-8: Optimally Expaned thrust

First of all we direct the gases in one direction by decreasing the area of cross section,thus velocity increases and pressure decreases.As the pressure decreases when we are moving from higher to lower cross section,we are able to direct the gases in one direction.As we move to lower cross-section the velocity keeps on increasing and finally we reach speed of sound at that point(at that particular temperature). If we increase the velocity furthermore,then shock waves form and choking occurs.From now we will stop decreasing cross section area and start decreasing the pressure by increasing the cross section in a particular format as shown in the top figure. As the pressure is decreasing the velocity keeps on increasing.But we need to stop expanding the nozzle exactly when the pressure equals the external pressure.If we don't do it then it will cause gas to diverge or converge leading to decrease in thrust.

## 10. Merlin Engine

### 10.1. Max Thrust

Sea level engine: 854 KN
Vacuum optimized engine: 981 KN

There are 9 engines per booster and there are 3 boosters(27 engines) in the 1 st stage. There is only one upper stage vacuum optimized engine with burn time of 397 s. At the time of liftoff engines are throttled down such that the thrust at liftoff is 7686 KN

### 10.2. Thrust to Weight Ratio

198 $m/sec^2$
The Merlin engine has the highest thrust to weight ratio of all other rocket engines.

### 10.3. Chamber Pressure

97 bar

### 10.4. $I_{sp}$

Above sea level(ASL): 282 s Vacuum(VAC): 346 s

## 11. RP-1 Fuel

1. Density: 813 g/l
2. Boiling point: 490K
3. Boiling point: 490K
4. Boiling point: 490K
5. Boiling point: 490K

## 12. Other Engine Information

1. Price of one engine: $ 1M
2. Price of one engine: $ 1M
3. cost/Thrust: 1170 $KN
4. Cost per KN per Flight: 117 $KN
5. Success rate of engine(for 71 flights till now): 99.9%

## 13. Rocket Equation

Lets now derive the rocket equation and apply it in this case. Just to make things simpler, we will be considering the ideal case in which the drag force due to air and the force of gravity are neglected. In doing so we will be saving a lot of unnecessary calculations and easily discuss the main concepts.

The two major considerations for ideal rocket equation taken are:-

- Conservation of mass
- Conservation of momentum

thus we get,

$$M.(\frac{dv}{dt}) = \frac{dM}{dt}.(-v_{ex}) \tag{1}$$

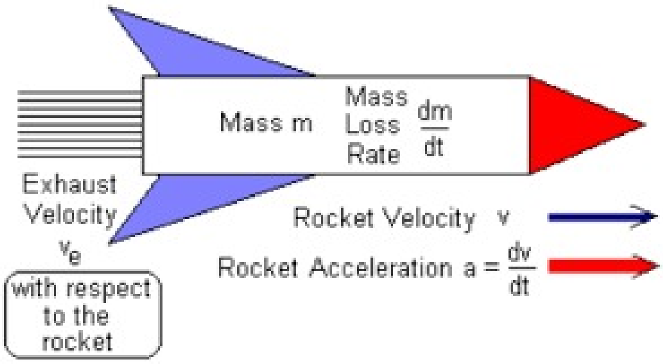



Fig-9: Diagramatic Representation

*where M is the* ***mass of the rocket*** *and $v_{ex}$ is the velocity of the dm mass of the propellant i.e.* ***exhaust velocity****.*

On further solving equation (i),we get,

$$\Delta V = V_{ex}.ln(\frac{M_o}{M_f}) \tag{2}$$

[$v_{ex}$ is somewhat constant at steady state arrival]

here, $M_o$**–initial mass of rocket**, $M_f$**-final mass of rocket** and $v$ is the destination velocity i.e, orbital velocity where the rocket is supposed to land.

We can also get the **mass of the propellant**, $\Delta M$ required for the entire journey by the formula below:-

$$\frac{\Delta M}{M} = 1 - e^{(\frac{-\Delta v}{v_{exhaust}})} \tag{3}$$

### 13.1. Specific impulse

In the language of ROCKET SCIENCE, specific impulse, $I_{sp}$ can be defined as "the efficient use of propellants in rockets/spacecrafts and fuels in jet engines". It is thus the measure of how proficiently a reaction mass creates thrust.

$$I_{sp} = lim_{\Delta t \to 0} \frac{F_{thrust}.\Delta t}{M_p.g_o} \tag{4}$$

*$M_p$ is the mass of propellant and $F_{thrust}$ is the thrust.*

The above formula could be used to get the destination velocity $V$ as well which is given by:-

$$\Delta V = I_{sp}.g_o.ln(\frac{M_o}{M_f}) \tag{5}$$

## 14. Trajectory to the ISS

The International Space Station is orbiting the earth at an altitude of approximately 408 km with an orbital velocity of 7660 m/s. We need to reach the same orbit with our mission, so that the crew dragon capsule is almost stationary with respect to the ISS for easy docking.

You might think based on what has been discussed in the previous section, just by knowing the $\Delta V$ required to reach a specific orbit we can just launch our rocket and give it that $\Delta V$ and we are done! And you are partially correct to assume that as the rocket has to reach that specific $\Delta V$ but it does not happen in one go. There are various burn stages that the rocket goes through:-

- After the launch of the rocket the stage 1 gets separated at an altitude of about about 90 km. The first stage flies off, following a ballistic trajectory and actually crosses the karman line at its apoapsis,then goes on to land safely on a floating pad in the ocean,which had been placed based on precise calculations of its trajectory.
- Then the rocket goes into a stable orbit of about 200 km, where the rocket is brought in phase with the ISS. The frequency of the inner orbit is higher than that of the outer one so there is scope for some correction(if required).
- Now the final orbit transfer burn occurs from 200 km to 408 km through the Hohmann transfer orbit(it is an elliptical orbit used to transfer between two circular orbits of different radii around a central body in the same plane. The Hohmann transfer often uses the lowest possible amount of propellant in traveling between these orbits)

**REFERENCE:** Figure 10 represented below, gives us a detailed view of orbital dynamics implementation in the Crew Dragon - Resilience mission

## 15. Trajectory Optimization

Rockets are defined by many variables and constraints, and ultimately deliver a payload to orbit at some cost. These characteristics provide the basis for an optimization problem. Maximize $J_1$ = Payload Mass (metric tons) and Minimize $J_2$ = Cost. The trajectory subsystem takes in several inputs and calculates the fuel usage and final altitude via the shooting method. It uses the ODE with a state vector composed of radial position, radial velocity, longitude, angular velocity, and mass. The model calculates the changes in velocity using the thrust, gravity, and drag applied at the correct angles. So, in overall define state vector being :

$$\mathbf{X} = [\ \mathbf{r}\ \theta\ v_r\ v_t\ \mathbf{m}\ ]$$

where, $\mathbf{r}$ = geocentric distance, $\theta$ = right ascension (Angular Displacement from launch pads initial position), $\mathbf{v}\ r$ and $\mathbf{v}\ t$ being radial and transverse velocity components. For position vector, we define (**ECI**) $Earth - centredinertial$ coordinate system while velocity vector being in (**LVLH**) $Local - Vertical - Local - Horizontal$ frame.

The resulting equations of motion $\dot{x} = f(x, u, t)$ are:

$$\frac{d}{dt} r = \dot{r} \tag{6}$$

$$\frac{d}{dt} \theta = \dot{\theta} \tag{7}$$

$$\frac{d}{dt} \dot{r} = -\frac{\mu}{r^2} + r\dot{\theta}^2 + \frac{T - D}{m} \cos(\alpha) \tag{8}$$

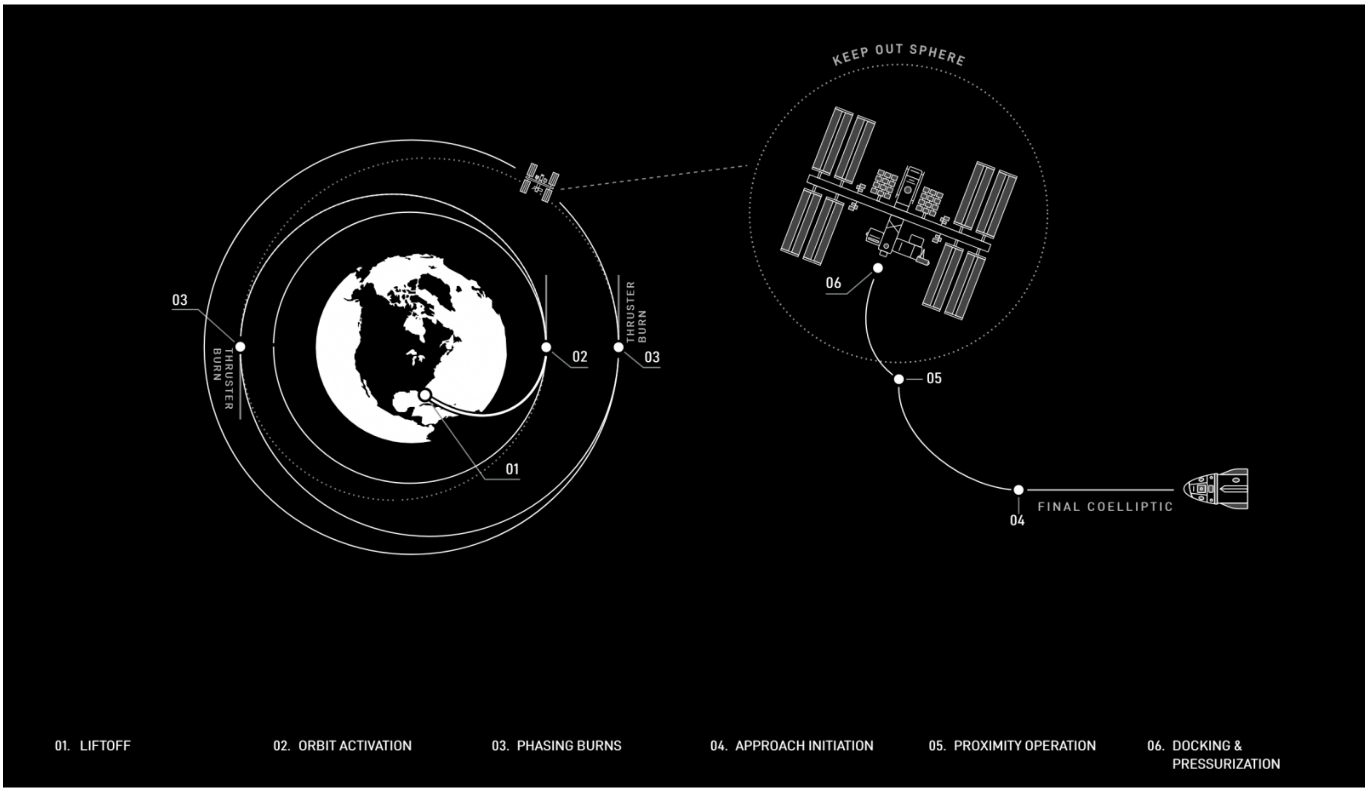



Fig-10: Orbital Dynamics Representation

$$\frac{d}{dt}\dot{\theta} = \frac{T - D}{r * m} \sin(\alpha) \tag{9}$$

$$\frac{d}{dt}m = -\frac{T}{I_{sp} * g_0} \tag{10}$$

All these equations can be easily derived by force balance of the rocket in the radial and tangential directions.

Trajectory optimization, which uses gravity as the driving force to steer the rocket into a particular trajectory. During the gravity turn phase of the ascent trajectory the thrust direction is forced to be parallel to the relative velocity. In order to maintain the same equations of motion across all phases, the thrust magnitude, T is fictitiously split into two attributes, $T_a$ and $T_b$. $T_a$ represents the optimally controlled thrust contribution, while $T_b$ is always parallel to the relative velocity. It can be noticed that $T_a$ and $T_b$ are alternatively null: during the zero-lift arcs, $T_a$ is zero, while $T_b$ is equal to the real thrust magnitude; conversely, $T_a$ = T and $T_b = 0$ during the other propelled arcs. It offers two main advantages over a trajectory controlled solely through the vehicle's own thrust:

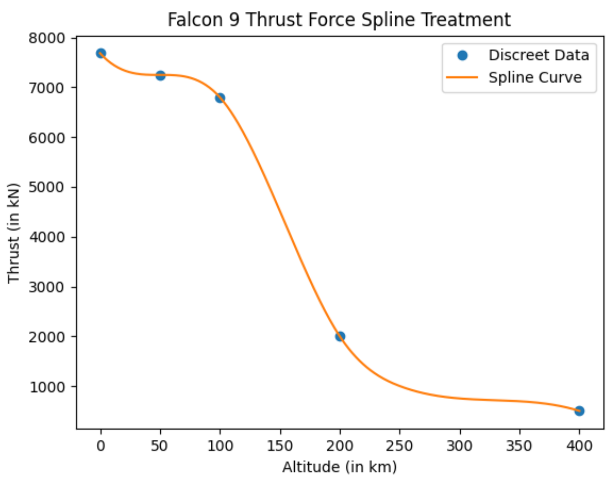
1. The thrust is not used to change the spacecraft's direction, so more of it is used to accelerate the vehicle into orbit.
2. During the initial ascent phase the vehicle can maintain low or even zero angle of attack. This minimizes transverse aerodynamic stress on the launch vehicle, allowing for a lighter launch vehicle.

## 16. Plotting Curves

### 16.1. Thrust Force Spline Treatment

As the initial parameters, we are given thrust force generated by the Falcon 9 at 5 different altitudes: 0km, 50km, 100km, 200km, 400km as $T_1$, $T_2$, $T_3$, $T_4$ and $T_5$ respectively.

In between these altitudes the thrust is interpolated linearly. However, this approach could be adapted to use a spline instead of a simple linear interpolation. Initially the model used an exponentially decaying thrust, but this did not capture all of the characteristics of typical actual thrust profiles. Here is the spline treatment of the thrust curve of Falcon 9 as per available data:




Graph-1

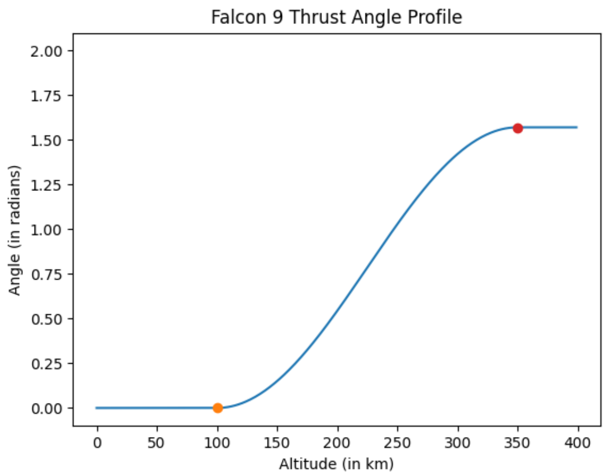
### 16.2. Thrust Angle

The thrust angle parameter variables $\alpha_1$ and $\alpha_2$ define the angle (with respect to a normal from the Earth's surface) of the thrust vector over the course of the trajectory. $\alpha_1$ is the altitude in km to start turning the rocket, while $\alpha_2$ specifies the additional altitude over which to complete the turn.

If the altitude is less than $\alpha_1$ then the angle is zero, and if it is greater than $\alpha_1 + \alpha_2$ then the angle is $\pi/2$. If it is in between then it is defined by:

$$Angle = [1 - cos(\pi * (\frac{A - \alpha_1}{\alpha_2}))] * \frac{\pi}{4} \tag{11}$$

No data was available for altitudes at which Falcon 9 started or ended the gravity turn maneuver, hence, data from the thrust force spline was used to estimate $\alpha_1$ to be 100km and $\alpha_2$ to be 250km.




Graph-2

### 16.3. Drag Force

The drag force on a rocket due to the atmosphere can be simply written as:

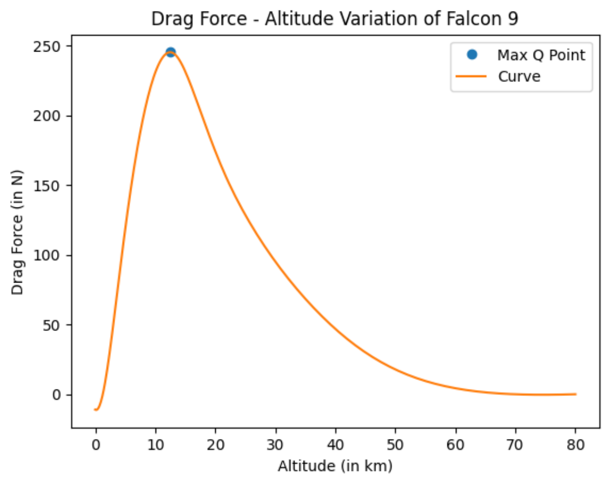
$$D = \frac{1}{2} C_d A \rho v_{rel}^2 \tag{12}$$

where..

$C_d$ = Co-efficient of drag = $2\sin^2(\theta_C)$
$A$ = Reference surface
$\rho$ = Atmospheric Density
$v_{rel}$ = Velocity of Falcon 9 w.r.t the atmosphere

We consider the variation of $\rho$ to be via isothermal exponential atmospheric model i.e:

$$\rho = \rho_0 \ exp(-\frac{r - r_0}{H}) \tag{13}$$




Graph-3

### 16.4. Mass and Cost Calculation

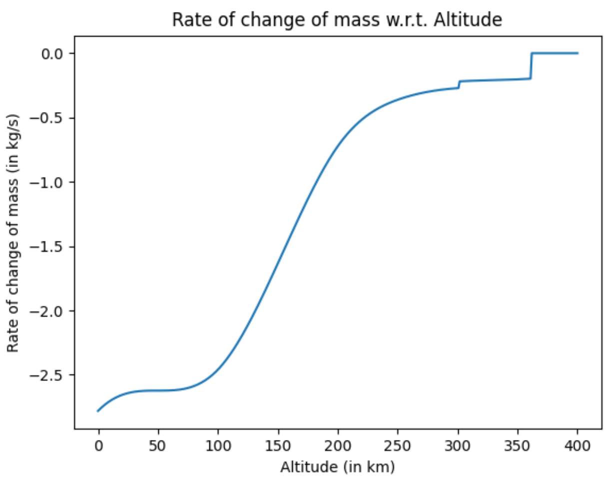
The propulsion subsystem inputs the mass of propellant from the trajectory subsystem, divides this mass up into oxidizer and fuel, and adds an ullage penalty. It also calculates the mass of the engine by scaling the Space Shuttle engine with max thrust according to the following equation:(Engine nozzle efficiency was not taken into account at different altitudes.)

$$m_{engine} = T_{max} * \frac{m_{ss}}{T_{ss}} \tag{14}$$

The cost subsystem calculates the cost for both materials and manufacturing. The material costs are based on material masses and engine mass. The engine is the largest of the material dry masses, and has the highest cost per kilogram, so it makes up the bulk of the material cost. The manufacturing cost is based on seam lengths. The cost parameters include cost per meter of seam and cost per kg of material. These parameters were taken from an external fuel tank model and have been scaled to produce numbers in the expected amounts.

Finally, the costs are summed and the payload mass is calculated according to following equation. Since the wet mass was an input, the mass that was not used up as fuel or taken up by structures is the available payload mass.

$$m_{payload} = m_{total} - m_{structural} - m_{oxidizer} - m_{fuel} \tag{15}$$




Graph-4

The abrupt change in rate of change of mass was expected since at an altitude of 300km, first stage separation was successfully completed and the second stage was fired. Hence, there was an abrupt change in $I_{sp}$ value. At at altitude of 360km, we again observe a sudden jump. This is due to the fact that the second stage separation is also completed successfully. After that, we observe that there is virtually no change in mass. This is because the capsule resilience has now enough velocity to achieve an intersection of orbit with the ISS. Only minor fuel bursts are required for finer maneuvering, like docking with the ISS.

## 17. MOGA Modelling

Multi-Objective Genetic Algorithm, or MOGA, for short, is one of the most widely used algorithm for multiple variable optimization, in this case, maximizing payload capacity ($J_1$) while simultaneously minimizing the launch cost ($J_2$).

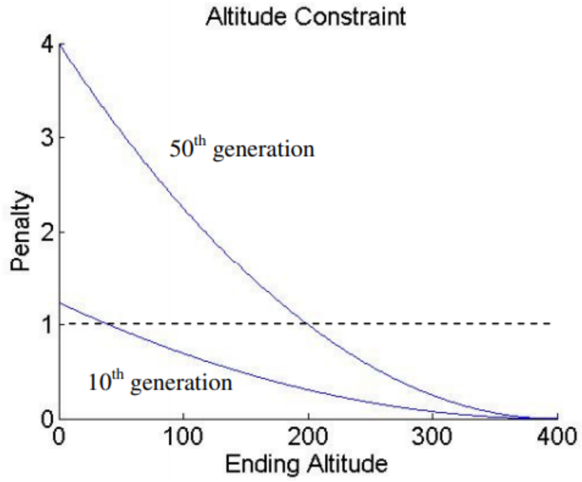
### 17.1. Algorithm:

1. **Choosing Design:** First, we choose multiple possible designs that could lead to a potentially optimized design. These designs are generated randomly and without any constraints.
2. **Populate:** We then proceed to populate the pareto front (the graph) using the data from these designs.
3. **Optimization:** Next, to optimize the data, we give a penalty to each design that dominated it by having a lower cost and higher payload capability. We also gave a penalty if the ending altitude was less than 400 km. The fitness was then squared to increase the gap between the more and less dominated designs. Finally, we give zero fitness for designs that were otherwise infeasible.
4. **Next Generation:** This fitness value was then used to decide which designs carried on to the next generation of the genetic algorithm. The fitness function for a feasible point is shown in the following slide:

### 17.2. Fitness Calculation

$$F = max(1.0 - 0.01 * n_{dom} - p(A_{final}), 0)^2 \tag{16}$$

A variable penalty shown below was used for the altitude constraint. The further the constraint was violated, the more severe the penalty applied. The penalty curve steepened with each generation. This is because a low curve would not penalize the infeasible designs enough, but a high curve would often cause the entire starting population to have zero fitness. By starting with a low curve and raising it, the MOGA was able to find the largest number of feasible designs. Example penalty curves from the 10th and 50th generations are shown here. If the penalty is greater than 1, then the fitness bottoms out at 0. This means that a penalty above the dotted line in the shown figure would lead to an infeasible design.



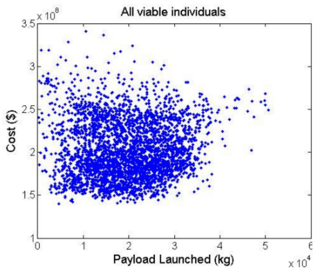

Graph-5

$$p(A_{final}) = [(400 - A_{final})/max(1400 - 4 * generation)]^2 \quad (17)$$

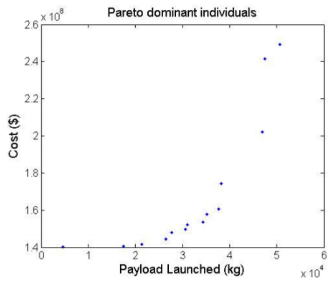
where $n_{dom}$ = no. of times an individual is dominated on the pareto front and $A_{final}$ = Ending Altitude

### 17.3. Populating Pareto Fronts

The pareto front is populated by all the test cases that passed the fitness function. As we can see, a cluster is formed. Now, we need to choose the non-dominated individuals i.e. those points that have a better payload capacity and lower cost than their peers. (Refer the figure shown below for visual representation)

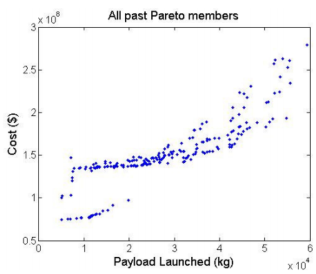



Graph-6

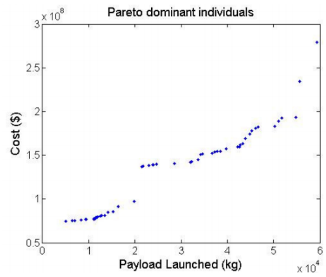



Graph-7

The above process was repeated 10 times to get 10 different pareto fronts. Then all these scatter plots were merged and the dominated individuals were rejected due to the exact same reason and the dominant ones were kept/ selected. Below is the graphical depiction of the same:

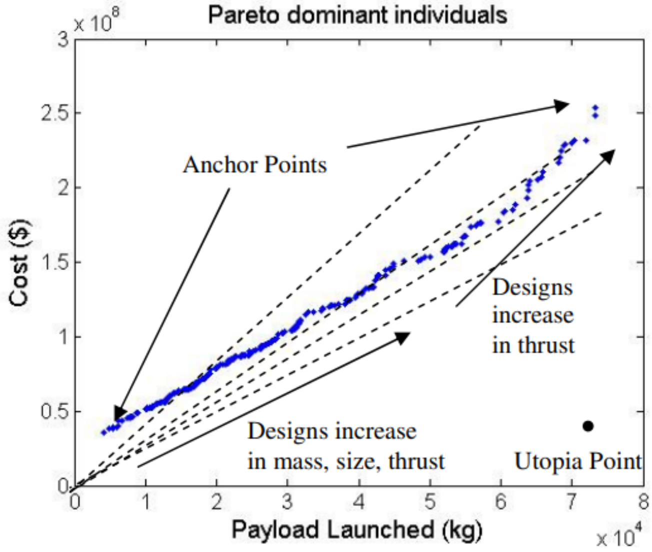



Graph-8




Graph-9

As we can clearly see, the latest graph is not continuous and this was expected, since we were dealing with random point generation. In order to get a smooth curve, more computation was required i.e. much more fronts were needed. So, instead of repeating the process 10 times, we did it 1640 times and obtained a pretty smooth curve of dominant individuals:

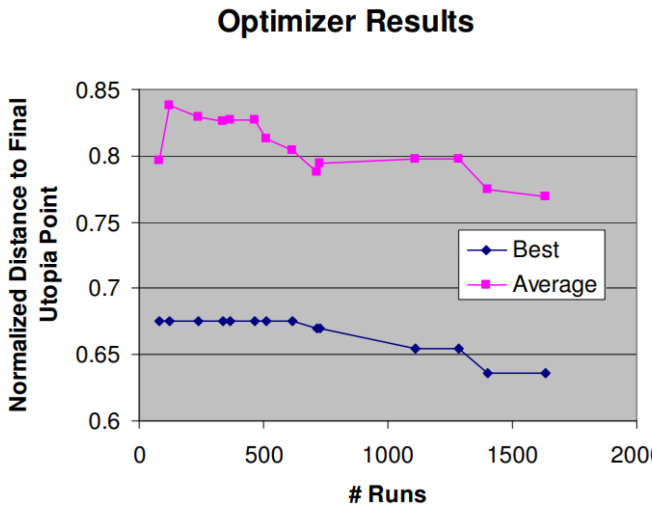



Graph-10

The Pareto front is very linear, which is likely a result of the cost model being simple and heavily driven by engine size. We can also see the low cost and high payload mass anchor points. From those anchor points we can construct a normalized space with vertices (0,0), (1,0), (0,1), and (1,1). (0,0) is the low cost anchor point, (1,1) is the high payload anchor point, and (1,0) is the normalized utopia point. From this utopia point we can find the closest design, hereafter referred to as the "best" design.

### 17.4. Utopian Point

The following figure shows the normalized distance to the final utopia point as an increasing number of runs was performed. The Average line shows the progression of the average distance of each non-dominated point, while the Best line shows the distance of the closest point. The average distance tended to fall a little at a time, while the best distance tended to fall in jumps, which suggests a greater degree of randomness.




Graph-11

### *17.5. Comparision with actual rocket*

Here we have summarized the rocket model that we generated from our optimization process, it's comparison to the actual Falcon 9 rocket and the error margin. As you can see, MOGA Modelling generated a pretty low error percentage which is in the acceptable range.

| Data | Calculated | Actual | Error (%) |
|---|---|---|---|
| Mass (in kg) | 6144.7 | 6000 | 2.41 |
| Cost (in million $) | 64.59 | 62 | 4.31 |
| Mass/ Cost | 95.13 | 96.77 | 1.69 |

## 18. Aerodynamics

Shock wave is a propagating disturbance which is formed when a pressure front moves at supersonic speeds (Speed more than that of sound) and pushes the air surrounding it and is characterized by an abrupt, nearly discontinuous, change in pressure,temperature, and density of the medium. Shock waves are mainly comprised of three types-

- Oblique shock waves
- Normal shock waves
- Crossed shock waves

## 19. Mach Number

The Mach number is the ratio of the speed of the rocket to the speed of sound .

$$M = \frac{u}{c} \tag{18}$$

..where u is the speed of rocket and c is the speed of sound

For M<1,the flow is said to be subsonic.
For M=1,the flow is said to be transonic
For 1 < M < 5,the flow is said to be supersonic
For M>5,the flow is called hypersonic.

## 20. Max - Q

Max-Q is a point when an aerospace vehicle's atmospheric flight reaches maximum dynamic pressure. This is a significant factor in the design of such vehicles because the aerodynamic structural load on them is proportional to dynamic pressure. Dynamic pressure, q, is defined mathematically as

$$q = \frac{1}{2}\rho v^2 \tag{19}$$

..where $\rho$ is the local air density, and v is the vehicle's velocity

It can be thought off as equivalent to kinetic energy density of air with respect to the vehicle. For a launch of a rocket from the ground into space, dynamic pressure is:

- Zero at lift-off, when the air density $\rho$ is high but the vehicle's speed v = 0
- Zero outside the atmosphere, where the speed v is high, but the air density $\rho = 0$
- Always non-negative, given the quantities involved

During the launch, the rocket speed increases but the air density decreases as the rocket rises. Comprehending by Rolles theorem,there is a point where the dynamic pressure is maximum.

Before reaching max q, the dynamic pressure change because of the increasing velocity is greater than that happening due to the decreasing air density so that the dynamic pressure which opposes kinetic energy acting on the craft increases. After passing the value of max q, the converse happens. The dynamic pressure acting against the craft decreases as the air density decreases, eventually reaching zero when the air density becomes zero.

The LEO mission had it's max q reported at 67 seconds after the liftoff and at an altitude of 12.57 kilometres. For the graph of drag vs altitude,refer Trajectory optimisation..

SpaceX has designed Falcon 9 in a such a way that it's horizontal manufacturing, processing and integration reduce work at height during various integration, processing and manufacturing procedures, and eliminates numerous overhead operations. The side-boosters restraint and release and the separation systems use pneumatic devices thereby providing low-shock release and positive force separation over a comparatively long stroke. Four events happening during flight result in loads that are characterized as shock loads are as follows:

1. Release of the launch vehicle hold-down at liftoff.
2. Stage separation.
3. Fairing deployment.
4. Spacecraft separation.

Events 1 and 2 are negligible for the payload relative to fairing deployment and spacecraft separation because the shocks will travel and dissipate because of the large distance and number of joints. The maximum shock environment predicted at the 1575-mm interface for fairing deployment is enveloped by the shock environment from typical spacecraft separation. As a result of which, the shock environment is a function of the spacecraft adapter and separation system selected for the mission. However, the actual shock environments experienced by the payload at the top of the mission-unique payload adapter are determined after the selection of a specific payload adapter and separation system.

## 21. Re-Entry

Re-entry of a spacecraft is the most important part of any mission especially when it is returning back from a mission with the crew members. Similarly in the case of Crew Dragon C207 it splashed down in the Gulf of Mexico, off the coast of Panama City, Florida, at 2:57 AM EDT (06:57 UTC) on Sunday May 2, marking the end of the first of six contracted, long duration, operational missions for SpaceX as a part of NASA's Commercial Crew Program. Resilience undocked from the International Space Station (ISS) at 8:30 PM on Saturday May 1 (00:30 UTC on May 2) to begin the journey home. Its return marks the end of Expedition 64 and the start of Expedition 65, with JAXA Astronaut Akihito Hoshide becoming the commander of the ISS. He's the second Japanese astronaut to command the station, the first being Koichi Wakata during Expedition 39.Previously scheduled for Wednesday, April 28, and Friday, April 30, the Crew-1 undocking and splashdown was postponed due to unfavorable weather in the splashdown zones off the coast of Florida. The new schedule for Sunday morning is the first night time splashdown of a crewed American spacecraft since Apollo 8 in 1968.

The last time NASA and SpaceX returned astronauts from the ISS was for the historic Demo-2 mission. Since this is the first return and recovery of a fully operational crewed mission, there have been several lessons learned from the Demo-2 test flight which were implemented for Crew-1. After post-flight inspections of Crew Dragon Endeavour, teams noticed greater than expected erosion of Dragon's heat shield at four points where the capsule bolts to the trunk of the vehicle using tension ties. SpaceX stated that the erosion was likely caused by airflow phenomena that were not expected to occur.

The heat shield design was changed to include more erosion-resistant materials at the ties. The heat shield was reinforced, and tested both on the ground and in-flight during the Cargo Dragon CRS-21 flight.

In addition, the drogue parachutes on board the Endeavour spacecraft deployed lower than expected, although it was still within the allowable range. A new instrument — which measures barometric pressure — was added to determine the altitude for parachute deployment and resolve this issue. "We made changes to the design and part of the heat shield and drogue chute deploy algorithm," said Nicole Jordan, NASA Mission Manager for Crew-1 in an interview with NASASpaceflight. "Fortunately, those changes were made on CRS-21 Cargo Dragon first, so we've actually not only tested it on the ground but also validated those changes in CRS-21. They've both worked as intended, but that is something we'll see for the first time with the crew onboard on Crew-1 landing."

NASA and SpaceX teams have designated seven splashdown zones for Crew Dragon. This includes four sites at the Gulf of Mexico, namely Pensacola, Panama City, Tallahassee, and Tampa, and three sites in the Atlantic Ocean: Jacksonville, Daytona, and Cape North.

Two weeks prior to the return, teams select the primary and the alternate landing sites, pending weather conditions. For the Crew-1 mission, the selected primary splashdown site was Pensacola, with Panama city being the alternate location, both located in the Gulf of Mexico, off the coast of Florida. The Panama City landing zone was selected for splashdown on Sunday morning.

Additionally, a backup unsupported landing site (outside of the seven sites mentioned earlier) with suitable weather conditions is also identified to mitigate the risk of weather changes and ensure a minimum of two landing sites are identified at all times. In the unlikely scenario this site is used, the rescue operations will be conducted by the U.S. Department of Defense. The images below are of spacex crew dragon reilience before undocking from the ISS and after it lands safely on earth.

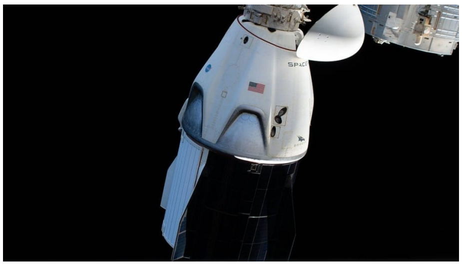


Fig-11: Docked with ISS

Fig-12: Splashdown!

## 22. Heat Shields

Heat shields are a cool or rather, hot piece of technology. They are a relatively simple solution for any extreme problem. The problem being when a spacecraft reenters the atmosphere 10 times faster than a bullet, it must cope with temperatures half as hot as the surface of the sun.

NASA and SPACEX collectively played an important role in making of heat shields for crew dragon resilience. The features of crew dragon were improved so as to include 4 member in the mission and also remain in the space for 210 days. The spacecraft also features an improved backshell that will increase the wind limits for reentry. Most heat shields, the Dragon Capsule included, use an ablative material. These work by ablating, or flaking away, as they heat up. Thereby taking some of the heat away with them. Meaning, you could even use wood as a heat shield per se.

Both the old and new Dragons use PICA-X, which is SpaceX's variant of the NASA designed Phenolic Impregnated Carbon Ablator. The material, engineered in the '90s, has been used on Mars missions and the Orion spacecraft. The heat shield, in conjunction with the thrusters, can precisely steer the spacecraft through re-entry.

Dragon is engineered such that the centre of mass is offset, allowing for the heat shield to produce lift. Through careful control, the lift generated can be exploited to guide the vehicle. By rotating the spacecraft, the lifting vector changes. Therefore, if turned in one direction, Dragon pulls up from the normal vector. Conversely, if rotated 180 degrees, it will pull down deeper into the atmosphere. The image given below is of heat shield used in crew dragon

Fig-13: Heat Shield

## 23. Parachutes

The final, and perhaps most important, piece to the mission is the parachutes. After all, without chutes, an otherwise successful mission would certainly lead to the loss of craft and crew members.

Parachutes, although they seem a simple technology, have proven to be one of the most challenging components. You'd think such an old field would be completely explored by now. NASA and its commercial partners, Boeing and SpaceX, through rigorous testing and certification for the Commercial Crew Program, found new errors and failure modes.

As NASA administrator Jim Bridenstine mentioned in a 2019 interview a reporter had with him: "We were taking risks with other parachutes that we did not know we were taking… because we have done testing, we now know what we didn't know before."

Fig-14: Parachutes

It took SpaceX about 100 failed tests and three generations of chutes to certify them completely. The most recent, inventively designated Mk3, managed to pass the stringent safety requirement for the mission.The Mark3 design itself went through 27 drop tests before it was considered safe for human use. As a result of the huge testing campaign, SpaceX now has one of the safest and most reliable parachutes ever made in the world. The biggest challenge was that parachutes had very narrow window for operation. If you're going too fast and try to deploy a chute, the airstream can destroy the canopy, rip the lines or their attachment points to the canopy.

SpaceX started using Zylon, a unique polymer, in place of the nylon previously used in other parachute. The risers, which attach the canopy lines to the capsule, had to be bolstered when a load modelling inaccuracy proved that they did not meet the human safety factor . After all, as the chutes initially deploy and reef open, there can be very big shocks. The trick is developing a chute that deploys slowly and smoothly, doesn't tangle, and most importantly, doesn't fall apart.

## 24. Landing

At an altitude of 2 km, Crew Dragon deploys its four main parachutes. The vehicle has undergone "parachute out" testing, meaning it can safely splashdown under only three chutes. This is quite the change from the original Dragon capsule, which only had three chutes to begin with. But all these systems have to work in unison for a successful mission. If the shape of the capsule were designed wrong, it wouldn't slow down enough in the upper atmosphere, and its terminal velocity could be much higher, resulting in harsher landing conditions for the parachutes or less time for them to deploy fully.

It's the entire system that makes re-entry safe, not just any one particular component. The depth of thought that has to go into each and every aspect of the vehicle to safely return from orbit is amazing.

## 25. Communication

### 25.1. Ground Communication

A ground station is a terrestrial radio station designed for extraplanetary telecommunication with the spacecraft or reception of radio waves from astronomical radio sources. Ground stations may be located either on the surface of the Earth, or in the atmosphere. Earth stations communicate with spacecraft by transmitting and receiving radio waves in the super high frequency (SHF) or extremely high frequency (EHF) bands (e.g. microwaves). When a ground station successfully transmits radio waves to a spacecraft (or vice versa), it establishes a telecommunications link. A principal telecommunications device of the ground station is the antenna.

Ground stations may have either have a fixed position or it may change it's position according to the convenience. Article 1 of the International Telecommunication Union (ITU) Radio Regulations describes various types of stationary and mobile ground stations, and their interrelationships.

Specialized satellite Earth stations are used to telecommunicate with satellites — chiefly communications satellites. Other ground stations communicate with crewed space stations or uncrewed space craft. A ground station that primarily receives telemetry data, or that follows space missions, or satellites not in geostationary orbit, is called a ground tracking station, or space tracking station.

When a spacecraft or satellite is within the ground station's line of sight, the station is said to have a view of the spacecraft . A spacecraft can communicate with more than one ground station at a time. A pair of ground stations are said to have a spacecraft in mutual view when the stations simultaneously share line-of-sight contact with the spacecraft.

Dragon supports communications via satellites such as NASA's Tracking and Data Relay Satellite System, but it is also capable of communicating via Ground Stations on Earth. Data Rates are 300kbps for Command Uplink and 300Mbps or more for telemetry and data downlink. Payloads on the Vehicle can be integrated via standard communication interfaces like Ethernet or RS-422 and 1553 standards. Redundant telemetry and video transmitters in S-Band helps accomplish vehicle communication. Dragon is equipped with on-board compression as well as encryption/decryption systems.

### 25.2. Communication with space station

As Dragon chases the station, the spacecraft will establish UHF communication using its COTS Ultra-high-frequency Communication Unit (CUCU). Also, using the crew command panel (CCP) on board the station, the space station crew will interact with Dragon to monitor the approach. This ability for the crew to send commands to Dragon will be important during the rendezvous and departure phases of the mission.

During final approach to the station, a go/no-go is performed by Mission Control in Houston and the SpaceX team in Hawthorne to allow Dragon to perform another engine burn that will take it 250m (820 feet) away from space station. At this distance, Dragon will starts using its close-range guidance systems, composed of LIDAR (light radar) and thermal imagers. Then these systems will confirm that Dragon's position and velocity are accurate by comparing the LIDAR image that Dragon receives against Dragon's thermal imagers. Using the Crew Command Panel, the ISS crew, monitored by the Dragon flight control team in Hawthorne and the NASA flight control team at the Johnson Space Center's International Space Station Flight Control Room, will command the spacecraft to approach the station from its hold position.

After another go/no-go is performed by the Houston and Hawthorne teams, Dragon is permitted to enter the Keep-Out Sphere (KOS), which is an imaginary sphere drawn 200 meters (656 feet) around the station within which the Dragon approach is monitored very carefully so as to minimize the risk of collision. Dragon will proceed to a position 30 meters (98 feet) from the station and will automatically hold. Another go/no-go is completed. Then Dragon will proceed to the 10-meter (32 feet) position that is the capture point. A final go/no-go is performed, and the Mission Control Houston team will notify the crew they are go to capture Dragon.

- Communications between Dragon and the ISS are provided by the COTS UHF communications unit (CUCU) which was delivered to the space station on STS-129.
- Crew command panel (CCP) was used for SS crew command dragon.

– Dragon can also communicate on S-band via either tracking data relay system (TDRSS) or ground stations.

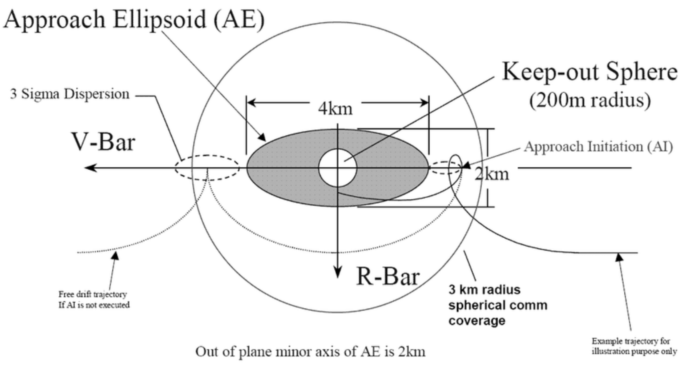



Fig-15: Keep Out Sphere

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