Introduction to Launch Vehicle Analysis and Design

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Lecture - 29

Reentry Concept

Hello and welcome. In this lecture, we will start our discussion on one of the most important as well as a critical mission of any space activity that is the reentry or return mission. The mission becomes critical because we are now recovering the object that we had sent to space and then we need to deal with the atmospheric effects, the gravitational effects as we had dealt with while creating the ascent mission. So let us begin our discussion with the basic entry concept.

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So let us first define what is the problem that we are talking about.

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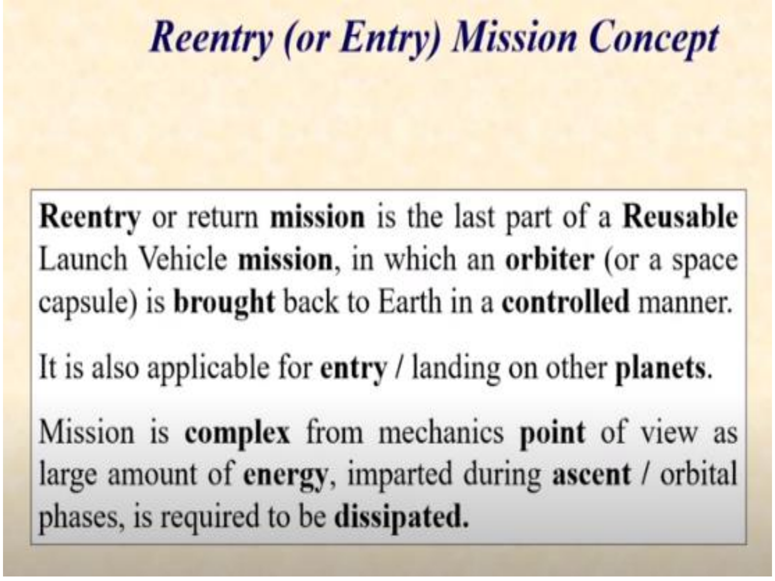

Reentry or return mission is typically the last part of a reusable launch vehicle mission in which an orbiter or a space capsule or any other similar object is brought back to earth in a controlled manner. It is also applicable for entry or landing on other planets. And for that reason, it is an extremely important aspect of any space mission.

We also realize that this mission is complex from a mechanics perspective as large amount of energy which is imparted during the ascent or orbital phases is now required to be dissipated which is going to be a challenging task.

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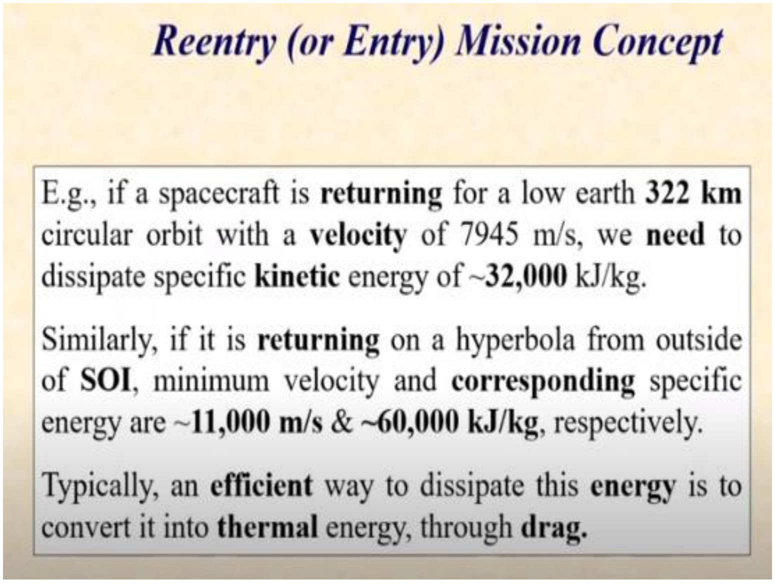

Just to understand the toughness of the problem, let me just give a few statistics that is commonly applicable in such scenarios. So, if we assume that a spacecraft or a capsule is returning from a low earth orbit of 322 km circular in nature, typically such orbits will have a velocity close to about 8000 m/s. And this represents a specific kinetic energy of the order of 32,000 kJ/kg.

That is total kinetic energy per unit mass. It is not very clear from this number, whether this is large or small. So let us take one more example of an object which is returning from outer space mission on a hyperbolic trajectory. Typically, the minimum velocity would be of the order of 11,000 m/s and the corresponding specific energy is likely to be of the order of 60,000 kJ/kg.

So that is practically double the amount. Even now it is not very apparent whether these numbers should be worried about or they are manageable. In order to understand this aspect, let us first explore the mechanisms which will dissipate this energy. Of course, we can use propulsion as we have used in the ascent mission to overcome the gravity.

We can now use propulsion to generate a retarding acceleration so that the velocity will reduce continuously until it becomes zero at the landing or the touchdown point. But generally, it is found that a more efficient way to dissipate this energy and without expending costly propulsion is to convert this into thermal energy through aerodynamic drag.

So, you allow the drag to retard the vehicle and that energy which is consumed by the drag appears in the form of heating of the vehicle and if you can manage the heating, then it is possible to dissipate the energy is an efficient manner. So, supposing we were to do this to complete the return mission, what would happen?

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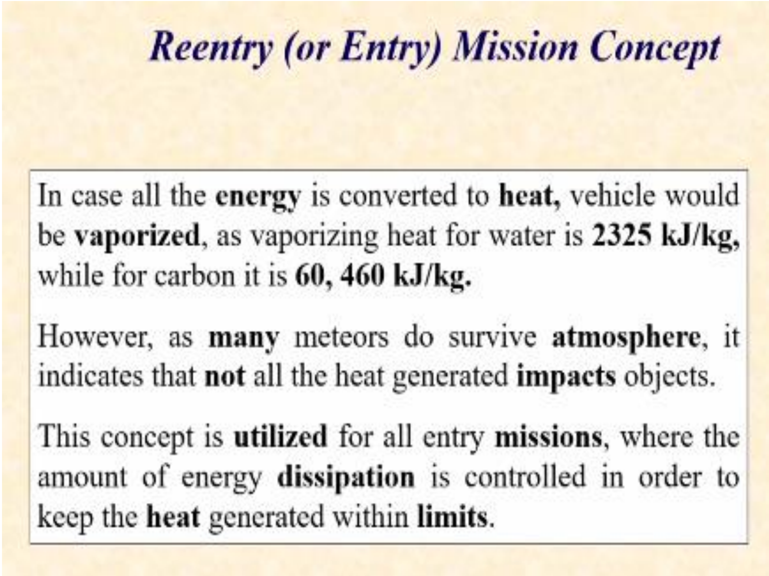

So let us take a hypothetical case that if we converted all the energy to heat. Of course, it will not happen like this. We would find that the vehicle actually would get vaporized while entering the atmosphere because the vaporizing heat for water is only 2300 kJ/kg. Whereas, even from the mission which is from a low earth orbit of 322 km, the total energy content is of the order of 32,000 kJ/kg.

Similarly, the vaporizing heat for carbon is 60,460 kJ/kg. So, if you are coming from the low earth orbit, you might still survive in terms of carbon, but anything else would simply disappear. And the 60,000 kJ/kg is the minimum energy with which you will come when you are coming from a mission to outer planet.

So obviously, you realize that using this mechanism is not going to be directly practically feasible unless you can manage the heat generation in an appropriate manner. Of course, we have examples of many meteors that do survive the atmosphere, which also contain similar material as the vehicles that we sent out in the atmosphere and outer space. So always it means that not all the heat is going to be impacting the objects.

Because, we realize that a significant part of this heat would get lost through radiation. So, there is a little bit of comfort in that idea. Further most of the return missions and vehicles that are required to return make use of heat sheets that prevent a large amount of heat transfer to sensitive and critical parts of the vehicle so that the heat load can still be managed by entering the atmosphere.

Which obviously means that we now need a mechanism by which we control the way in which the heat is going to get dissipated or generated so that it remains within limits during the entry mission and that we can bring the spacecraft or a space capsule back in a safe manner.

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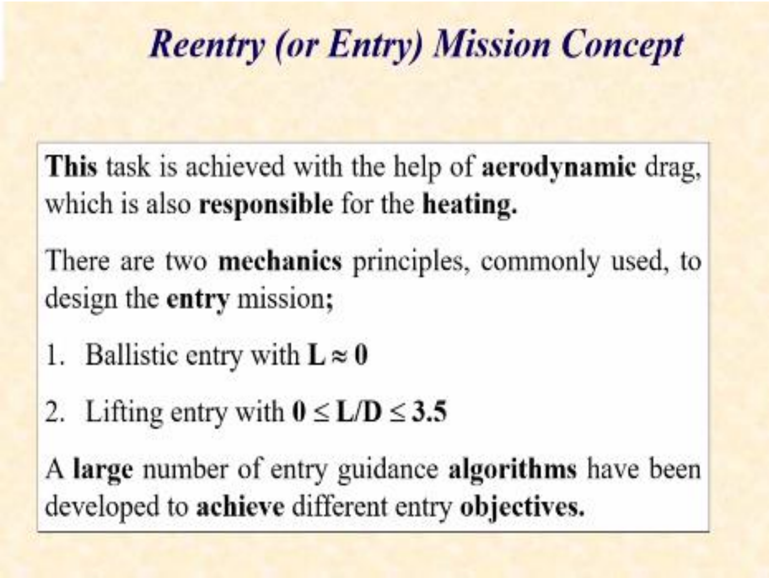

So, in order for us to manage the heat, it is directly clear that we are going to have to manage the aerodynamic drag, which obviously means that we have to manage the trajectory because the aerodynamic drag is going to depend on the velocity and the altitude, together we decide the amount of drag force which is going to get generated.

And which brings us to the idea that the trajectory design for reentry mission is equally complex if not more in comparison to an ascent mission. However, in contrast to what we do as part of our ascent mission, in entry missions there are two mechanisms that are commonly employed. In one case, it is purely a ballistic object.

Which means, it does not have any aerodynamic lift that is similar to our ascent mission, where we neglect the aerodynamic lift and we make use of only gravity to achieve the trajectory inclination along with the large amount of propulsion which generates the desired velocity. And a large class of return vehicles follow this strategy of entry which is simpler to design and implement.

Of course, with the advent of space shuttle and similar objects, which are currently under development, it is also a possibility of using lift to manage the drag appropriately through a parameter called lift to drag ratio. So, you design a vehicle in such a manner which looks like an aircraft, which what the space shuttle looks like. And then appropriately design external geometry such that the lift to drag ratio is in this range of 0 to 3.5.

And with that, it is possible for us to manage the drag by generating an appropriate amount of lift. As long as $\frac{L}{D}$ is fixed, the drag will be fixed the moment we fix the lift. And if we can control the lift through appropriate control surfaces, we can control the drag. So, this is the philosophy of lifting entry. We will discuss a little bit more about this in subsequent lectures.

And in addition to this, there are large number of different guidance algorithms that help us to manage the lift and consequently the drag having different objectives including optimality criterion to achieve different kinds of entry missions with different constraints.

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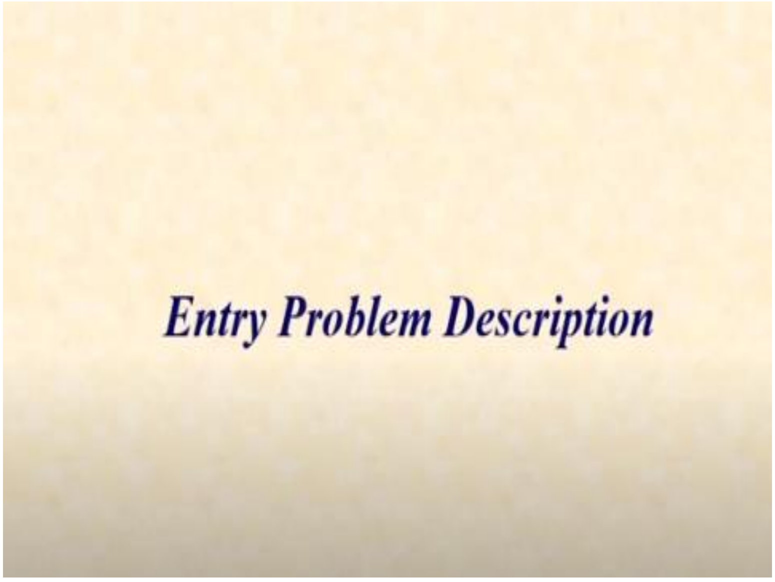

Let us now move over to the description of the entry problem.

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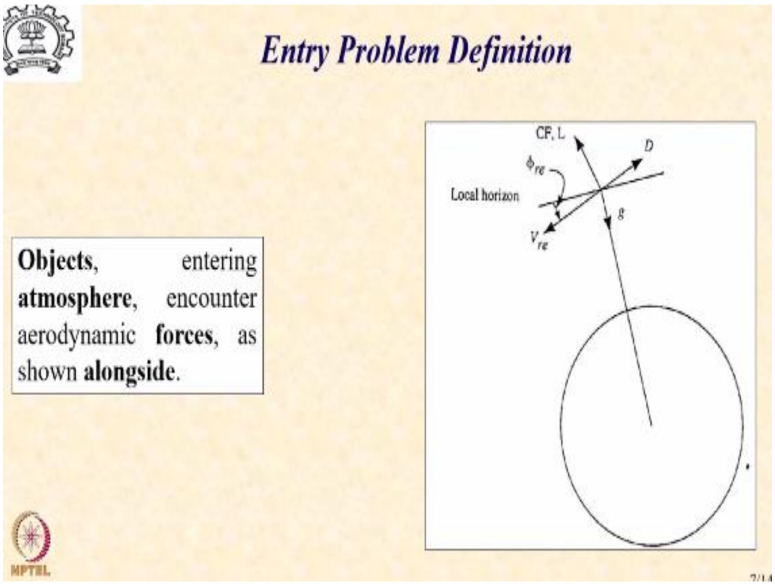

So, objects when they enter the atmosphere encounter aerodynamic forces as shown in the picture alongside. So, we here make use of a spherical earth model and then we say that there is a concept of local horizon, which is nothing but a tangent at the intersection points and represents the local horizon of the object with respect to which we now define an entry velocity, what we call V_{re} and a flight path angle or what we call elevation angle by ϕ_{re}, which is in the opposite direction, and generally it is a negative number.

Apart from this, we can clearly see that as it enters the atmosphere, it will generate a drag force which is opposite to the velocity direction. It will have a gravitational force which will be pointed towards the radial direction. And in general, if it is a lifting vehicle, it will also generate a lift and a new force which will appear in this context is represented to CF or what is called a centrifugal force.

Because, the trajectory will not be a straight line, but it will be a curved trajectory, either circular or any other curvilinear form.

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The Entry Problem Definition

In general, it is the **periapsis** which enters **atmosphere** first, where **velocities** are also large, resulting in **large** drag forces that **help** reduce the orbital **velocity.**

In particular, if **incoming** path has 'e' marginally > 1, then **after** one pass of **periapsis**, the object is **likely** to form an **orbit** around earth /**planet**.

Once this **happens**, we can either use residual **propulsion** to directly make **'e^2' < 0** or allow the **object** to complete multiple **cycles** until 'e^2' < 0.

Next, we will generally find that when a vehicle starts the entry into the earth's atmosphere, the first point of contact with the orbit of that object or the trajectory of that object is the point which is closest to the earth's surface, which has a generic name called the periapsis. In the context of earth, a more common terminology of perigee is used.

But if you are talking about this problem in the context of another planet, then a general name of periapsis is used to define a point which is closest to the surface of that planet. So obviously, that is the point which will enter the atmosphere first. The reason why this point is mentioned is that, that is the point at which the object has the maximum velocity while in the orbit or on trajectory.

So, the object will enter the atmosphere with a very large velocity. And even if it is entering at a very high altitude so that the densities are small, because the velocities are very large, it will immediately generate a large amount of drag force. Of course, you can see that, if we are able to manage the heat load, then this large drag force will be useful in generating a large deceleration and the velocity will quickly reduce.

And if the velocity reduces quickly then it is possible for us to manage the trajectory such that we are in a position to dissipate the heat by the time the vehicle is required to land or reach the destination. So, in this context what is commonly done is to design the entry trajectory from outer space in such a manner that the eccentricity of the trajectory is marginally greater than 1.

So that after it passes once through the earth's atmosphere or planet's atmosphere its velocity becomes sufficiently small, so that it can form immediately and orbit about the planet. Here, let me make a mention of this parameter e or eccentricity, which is an important parameter that defines the nature of the orbit of which you will learn more, when you go through a course on orbital mechanics, which I presume either you may have gone through or you might want to go through after this.

So, I will not spend too much time on it, but I will just make a mention that this is the parameter which is under the control for an entry object and can be designed suitably such that the moment it hits the atmosphere, it will never go out of the atmosphere again as it would form an orbit and then it would keep cycling around that planet. Now once this happens, there are two possibilities.

Either we can use residual propulsion to directly make $e^2 < 0$ so that the vehicle will have a trajectory that will directly bring it back to earth straightaway or instead of using the propulsion, we allow the vehicle to orbit with part of a trajectory in the atmosphere so that in every cycle a certain amount of energy get dissipated slowly until the same condition of $e^2 < 0$ is achieved after which the same act of vehicle coming back to earth straight away will happen.

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Entry Trajectory Example

An object enters earth **SOI** with 'V' of 2000 m/s & 'h_p' of **55.2 km**. If one **pass** through atmosphere **reduces** speed by 500 m/s, determine (a) path **after** 1 pass & (b) **No**. of passes before it **falls** to earth.

$(a) r_p = 6.433\times10^6; \quad \varepsilon = 2\times10^6; \quad V_p = 11{,}310 m/s; \quad h = 7.276\times10^{10}$

$e = 1.064; \quad \Delta V_{aero} = -500 m/s; \quad V_{p-1pass} = 10{,}810; \quad h_1 = 6.954\times10^{10}$

$\varepsilon_1 = -3.534\times10^6; \quad e_1 = 0.886; \quad a_1 = 56{,}400 km$

$(b) \quad \Delta V_{aero} = -500n; \quad V_{p-npass} = 11310\times(1-0.0442n)$

$$V_{cir} = \sqrt{\frac{3.986\times10^{14}}{6.433\times10^6}} = 7871.6 m/s = V_{p-npass}; \quad n > 6.88 = 7$$

Let us try and understand this through a simple example. So let us take the case of an object which is entering earth's atmosphere. The SOI expands as sphere of influence, which is a common term used to say that the object is now under the influence of the gravitational field of a specific planet with a velocity of 2000 m/s and at an altitude of 55.2 km.

Now if after one pass through atmosphere, the speed reduces by 500 m. It is an estimate of amount of drag and the energy that it dissipates. Then determine after one pass what happens to the vehicle and the number of passes before it will fall back to earth. So let us start with the basic orbital mechanics relation which I am reproducing here. You can refer to these relations independently for greater clarity.

But it can be shown that the velocity at periapsis the V_p which is the point closest to earth will be of the order of 11,310 m/s for the case when it enters the earth's sphere of influence at 2000 m/s. And with that the eccentricity as you can see is slightly greater than 1. So, we are considering the case which we have discussed the previous slide.

Now we assume that in one pass it will reduce the velocity by 500 m/s. So, at the periapsis we assume this to be an instantaneous act because the velocity is very large. It will reduce the velocity from 11,310 m/s, 10,810 m/s. And at this point the altitude is 6954, sorry not altitude, this is the angular momentum term.

We look at the energy and we find that after one pass the eccentricity becomes less than 1. So, the e^2 is also lesser than 1, but not less than 0. With these parameters, we find that it will take approximately seven passes before e^2 will become less than 0 and then it will start falling back to earth as a ballistic object.

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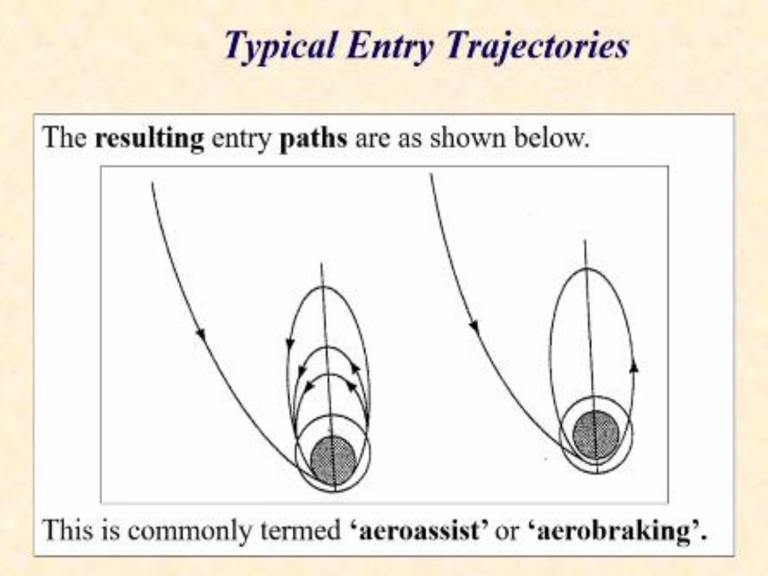

So, in such situations, you will find that following kind of trajectories are possible. So, on the right side when you arrive on a hyperbola you enter the atmosphere, dissipate a certain amount of energy and immediately you end up forming an elliptic orbit.

And once you have formed the elliptic orbit, either you can use the residual propulsion to directly reduce the velocity such that e^2 is less than 0 or you can allow multiple passes such that the trajectory becomes closer and closer until it reaches a point where e^2 again becomes less than 0 and then the vehicle falls back to earth.

You can clearly see that, while this strategy that is on the right-hand side is time efficient, the strategy on the left-hand side is energy efficient. This is sometime also called aero assist or aerobraking strategy of preentry.

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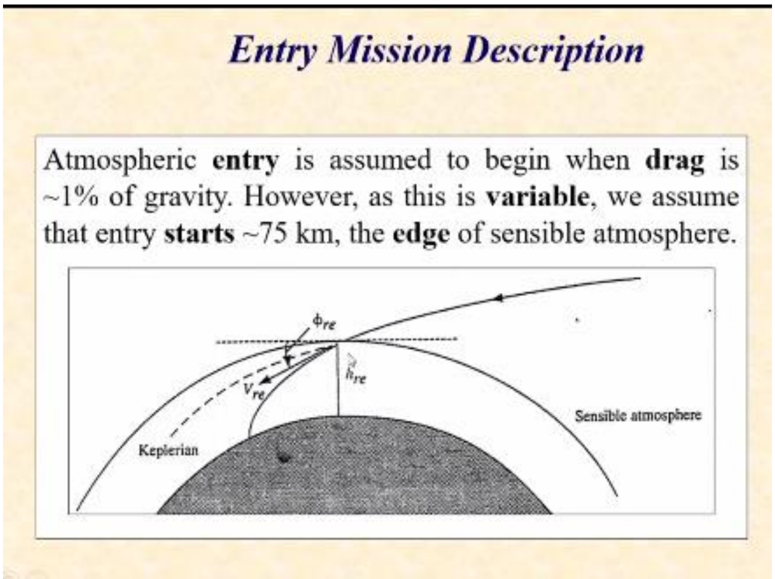

Now let us describe the problem in a generic context. Where does this activity actually begin? So contrary to what we do in the ascent mission where beyond 40 km we assume that the atmosphere is absent, which is primarily because of the fact that our thrust is a much larger force compared to drag, in the entry mission, there is no thrust and drag is the important force.

So obviously, we need to estimate it with better accuracy. And then we say that the drag is going to be considered to be significant when it becomes 1% of gravity. Which means, if it becomes point 0.01g that is the point at which we will assume that the atmospheric entry has begun. And this we find is going to happen at a much higher altitude of about 75 km because our velocities are very large.

And because of which our entry altitudes generally will be of the order of 80 to 120 km. So, we now draw a boundary of what we call the sensible atmosphere and show you the same picture with respect to a local horizon and the entry elevation angle of ϕ_{re} and the entry velocity V_{re}.

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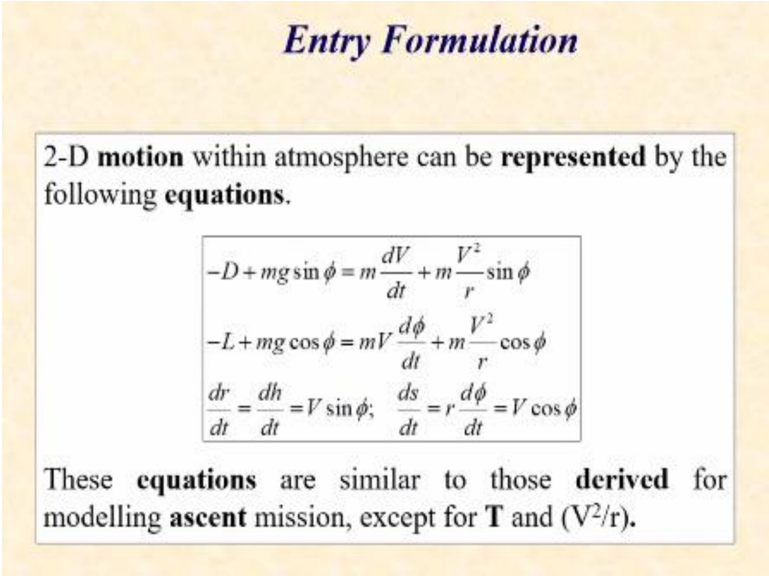

Now we have done enough modeling of two-dimensional motion in the atmosphere. So, we simply recall those equations, but we will see that there are certain differences. So, as you can see, we have the drag term, which is now opposite to the velocity direction. We have the gravitational component. Then we have $\frac{mdV}{dt}$ the force term, the thrust is missing. And then we have one extra term, $\frac{mV^2}{r}\sin\phi$.

This is the centrifugal force term, because $\frac{V^2}{r}$ is the centrifugal acceleration as we are using a spherical coordinate system. Here, it is worth noting that for small velocities, if V is small then $\frac{V^2}{r}$ is a small term and perhaps can be ignored as has been done in the context of ascent mission. But in this case, even though r is of the similar order, the V is very large.

So, this term also is reasonable and needs to be included in the trajectory model. Now this is the equation along the velocity direction. We now have another equation perpendicular to the velocity direction where now you have the presence of a lift, the gravitational component and then you have the normal inertia force and the component of centrifugal force in the normal direction.

Of course, similar to our ascent mission, we also have $\frac{dr}{dt}$ the kinematic equation which is same as $\frac{dh}{dt}$ as $V\sin\phi$. And then we have the $\frac{ds}{dt}$ which is another kinematic equation as $V\cos\phi$. So, we realize that these equations are similar to those that we derived for modeling ascent mission except two quantities, the thrust is missing and, in its place, we now have the centrifugal force term.

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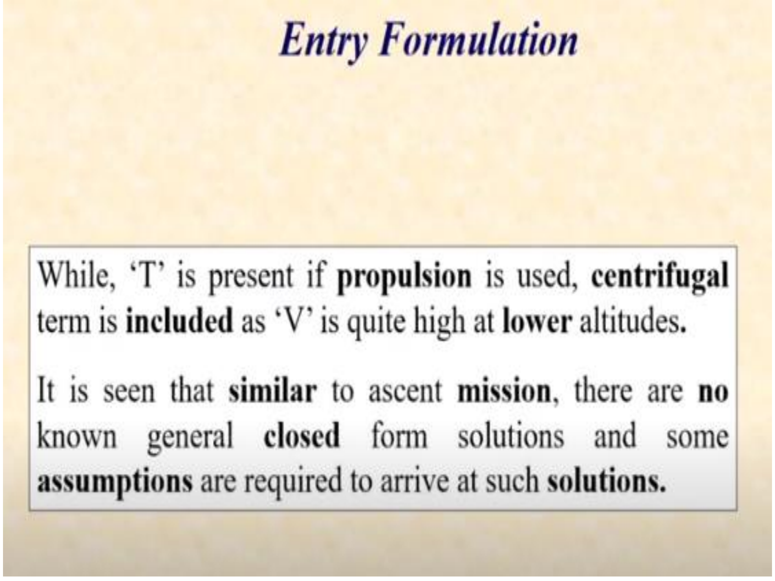

Of course, if we are going to make use of propulsion to retard the vehicle, then we can add thrust to these equation without making any further changes. And the centrifugal force term will always remain until you feel that velocities are sufficiently low for it to be ignored. Of course, similar to ascent mission, we immediately realize that there are no known general closed form solutions and some assumptions are going to be required to arrive at such solutions that we will look at in the next lecture.

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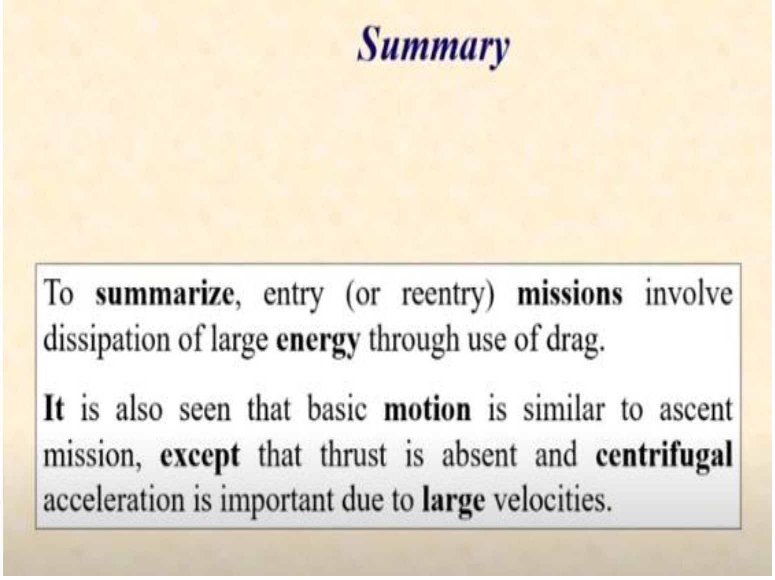

So, to summarize, the entry or the reentry missions involve dissipation of large energy through use of drag. You will also see that basic motion is similar to ascent mission except that thrust is absent and centrifugal acceleration is important due to large velocities. Hi, so in this lecture, we have looked at some of the basic concepts of an entry mission, which requires that a vehicle on a mission in outer space is brought back to earth in a safe manner.

We have also noted that an important requirement would be to manage the heat load which can be done indirectly through managing the drag acting on the vehicle which is responsible for heat generation. In the next lecture, we will look at some basic solutions of the kinematic model that we have developed in this particular lecture for the return mission and understand the attributes of the solutions in different contexts. So, bye. See you in the next lecture and thank you.