Introduction to Aerospace Propulsion

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Lecture No. # 37

Fundamentals of Missile engines

We have been talking about rockets in the last class. I introduced to you a number of rockets missiles and some of the ones, which can be called spacecrafts, take not only crafts, but even human beings up in the space. The fundamental science that governs the engine of these crafts is more or less the same. So, we have started talking about the fundamental rocket science.

We were introduced to some of the fundamental parameters that govern these various crafts and their engines. Here, we are talking about the rocket engines. We have already introduced some of the parameters in the last class. We shall continue with those introductions of parameters and the fundamental rocket science.

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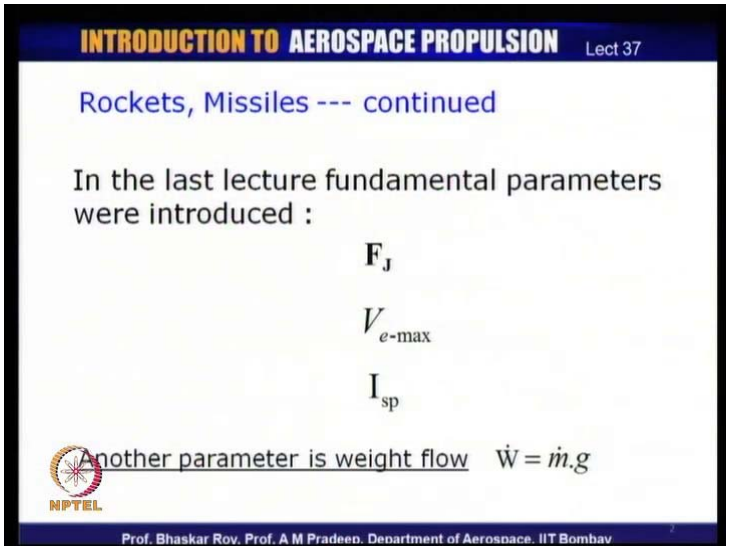

Let us look at what are the issues that we have been talking about in the last lecture. The fundamental parameters that have been introduced are the jet thrust that is created, F j and the exhaust velocity. In the process, we also introduced the maximum exhaust velocity that is possible actually in vacuum, when the rocket operates in a vacuum atmosphere. It means that there is no atmosphere and the fundamental parameter I sp is called specific impulse.

Now, these parameters are the fundamental parameters of any kind of rocket engine. Whether we call them as rockets or missiles or spacecrafts, they all have to be specified with these parameters to begin with. I will just add another parameter, which is called weight flow in most of the rocket engines. The important flow rate of the propellants and the oxidizers are often expressed in terms of weight flow rather than mass flow, as it is done in most of the air breathing engines. So, all the air breathing jet engines that we have studied earlier, the mass flow is going in and coming out of the engine. They were measured and expressed in terms of mass flow.

Most of the time, those crafts flow parallel to the surface of the earth and as a result of which, the amount of mass flow that is coming out is directly proportional to the thrust that is generated for flying those crafts. In rocket engine, most of the time the rocket would be flying in a direction, in which it has to support all of its weight most of the time or part of its weight most of the time. As a result of which, the amount of mass flow that activates the thrust is now measured more in terms of weight flow rather than in mass flow.

In rocket engines, the expressive terms of the flow rate contributes to the thrust making. It is measured in terms of weight flow and in simple terms, it is the mass flow into the gravity. So, m dot into g is a weight flow that would normally be used in our fundamental rocket science development.

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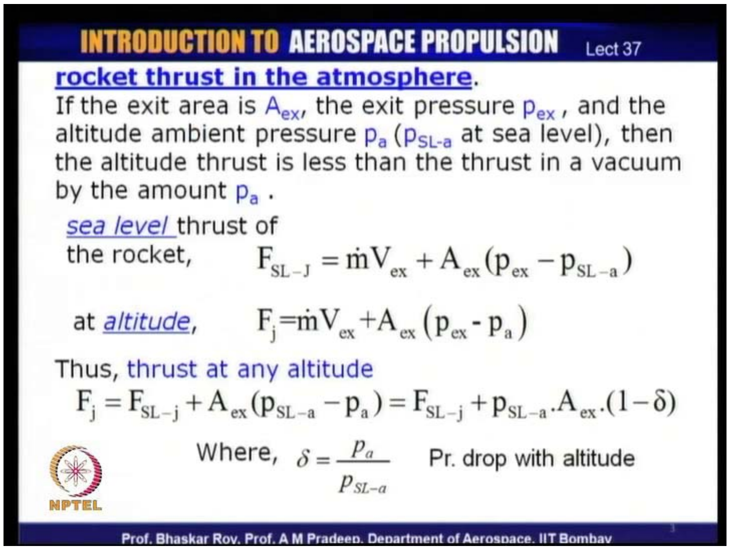

Let us look at some of the fundamental parameters that we need to deal with a good part of the rocket trajectory. It would have to be within the atmosphere and many of the ballistic missiles work all the time within the atmosphere. So, the first thing the rocket needs to negotiate in its flight is the atmosphere. Hence, the first thing that it has to do is to take off or in terms of rockets, it is called lift off. So, the aircrafts actually take off and the rockets normally lift off because the entire rocket goes up vertically, it is normally a vertical takeoff and hence called lift off.

Now, we express the exit area of the nozzle of the rocket chamber as ex, the exit pressure in terms of p ex and the altitude ambient pressure at which it is operating as p a that is p subscript a and if it is at sea level, we would call it p subscript SL a. The altitude thrust is less than the thrust in vacuum by the amount p a.

The second term that you see here is something that you are familiar with. In the jet thrust creation, you can see the second thrust is dependent on the pressure that is available or the differential pressure that is available across the exit pressure and exit section of the thrust nozzle. In case of sea level, as you can see, exit pressure is p SL a, which subtracts from the exit pressure and as a result of which, the thrust is so much lesser. At an altitude, the second term shows p ex minus p a, which is p a. It is the ambient pressure at that altitude and as a result, the thrust is lesser by that much.

Now, this is something, which varies with altitude. As the rocket is continuously changing its altitude, the actual pressure at which it would be operating is continuously changing. Hence, the second term is actually continuously changing and as a result of which, the actual value of the thrust would be a continuously changing phenomenon. We have seen and we shall see more and more that the flow is often quite near the maximum value most of the time. However, the value of V ex would depend on the exit pressure. If the exit pressure is changing, the pressure ratio across the nozzle is changing and then the value of V ex would continuously change.

From sea level to some altitude, at which it has to go the target altitude, let us say the value of the thrust would be continuously changing from maximum at sea level, which is normally required for the lift off purpose. You need to produce maximum thrust at sea level. At some altitude, it would reach its final high level altitude; the maximum altitude. It may take some other trajectory or it may have reached the orbit, at which it is going to rotate around the earth.

If we write a generalized version of thrust at any altitude, we can write down that F j is equal to F SL j plus A ex into p SL a minus p a. Now, this boils down to the second term. If you take out the p SL a out of the bracket, you would find the term 1 minus delta and this delta is nothing but the pressure drop in altitude with varying altitude of operation. Now, this can be obtained from any normal atmospheric charts or tables that are available. Hence, it is comparatively a known or easily knowable parameter.

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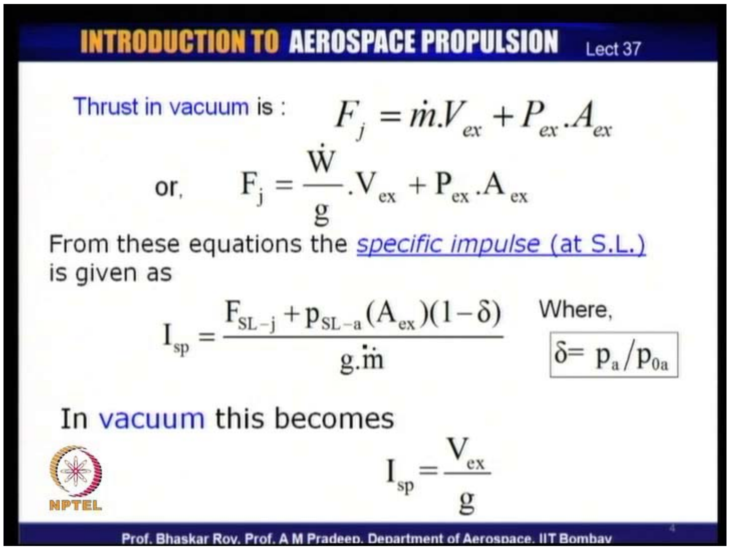

The basic thrust that any rocket creates can now be obtained from this simple equation. If we progress to the thrust that is created in vacuum, we see that in vacuum the ambient pressure p a is to be taken as 0, in which case the thrust equation becomes F j equal to m dot into V ex plus P ex into A ex and the second term is not there anymore.

As I mentioned in the beginning, most of the thrust generated by rockets is normally expressed in terms of weight flow rather than in terms of mass flow. As a result of that the earlier thrust equation can now be expressed in terms of weight flow and that is expressed as W dot. Hence, W dot by g is the mass flow and the first term is slightly modified. If you write the specific impulse that we had introduced in the last class, we can write it down as I sp. It is equal to S SL j plus p Sl a into A ex into 1 minus delta divided by m dot g. As you can see, this is the general I sp term, which can be used for finding out the specific impulse at sea level. You need this value first for the rocket to lift off. So, one can find the specific impulse at sea level.

Earlier, in the last lecture, we had written down the specific impulse for vacuum. If we bring that back this equation, then I sp is equal to V ex by g. So that is simple and it is expressed in terms of seconds. I sp is normally given in terms of seconds. In a few minutes now, we will see what kind of values normally I sp's have. We will get an idea about the kind of values that we could expect from a good rocket engine.

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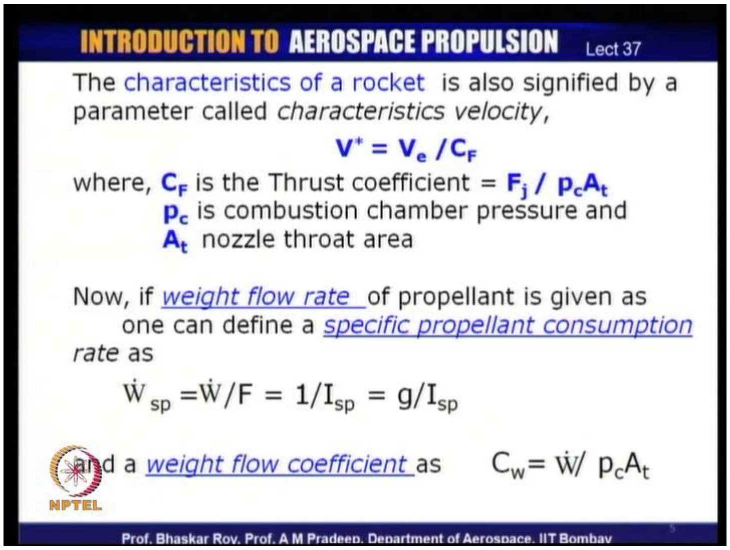

Another parameter that is quite often used for characterizing the rocket or rocket engine is signified by the parameter called characteristic velocity. Now, characteristic velocity V star is expressed in terms of V e, which is an exit velocity divided by C F. C F is the thrust coefficient, it is different from specific impulse and this thrust coefficient is expressed in terms of F j divided by p c into A t in the denominator.

Numerator is the thrust and the denominator are the two terms - the product of two terms p c and A t. Now, p c is the combustion chamber pressure that is one of the primary parameters of rocket engine performance. A t is the nozzle throat area; this is now being considered as a primary parameter for nozzle operation and nozzle performance. If we write down that the characteristic velocity is expressed in V star, they are now shown in terms of V e, the exhaust velocity and C F, the thrust coefficient. I have mentioned that it is not same as specific impulse and this thrust coefficient is different from the thrust coefficient that we have defined for other kinds of jet engines. So, the rocket engine thrust coefficient is defined somewhat differently.

Now, if you look at use of the weight flow, we can designate its relationship with I sp. We can say that the specific propellant consumption can be written down in terms of weight flow divided by thrust and that would be 1 by I sp or it can be also expressed in terms of g by I sp, depending on the units. So, the specific propellant consumption or simply what we used to call for jet engine as specific fuel consumption can be written down in terms of weight flow rather than mass flow.

The weight flow coefficient is again different from the specific fuel consumption. Before, the specific fuel consumption was weight per unit thrust. Weight flow coefficient on the other hand is weight flow divided by p c into A t that is the combustion chamber pressure and the nozzle throat area. So, the two coefficients are now introduced. One is the weight flow coefficient and other is the specific fuel consumption or specific propellant consumption. In case of rockets, we know it is fuel plus oxidizer and as a result of which, both of them together are here in this specific propellant consumption and expressed in terms of weight flow.

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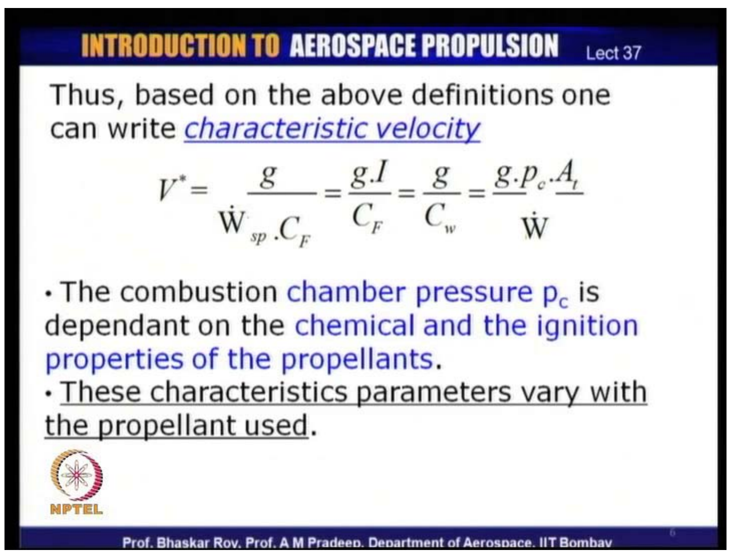

If we move forward, we find that the characteristic velocity has been expressed in terms of V star and in terms of weight flow coefficient. As a result of which, we get an expression, which is V star equal to g into p c into A t, which are the combustion chamber pressure and the throat area divided by the weight flow. It can also be expressed in terms of g by weight flow coefficient - C w that is C subscript w. So, these are simple ways of characterizing a rocket engine. Sometimes in many literature, it is often referred to as rocket motor. These are the characteristic terminologies, which are used to normally characterize a particular rocket engine.

Combustion chamber pressure - p c is used here as a normalizing parameter for many of these fundamental parameters. It is dependent on the chemical properties of the propellant and it is also dependent on the ignition properties of the propellant. So, the way the chemical properties are selected, the propellants are selected, the oxidizer, the fuel and the way the ignition is done or the combustion is done in the combustion zone would create the combustion chamber pressure. It is calculated from the basic propellants that are being used and hence it requires a separate attention.

As we see here, the combustion chamber pressure at any given point of operation is a fundamental parameter of importance. Hence, we can say that since they are dependent on the fundamental combustion chamber pressure, they depend on the propellant chemical properties of the basic propellants that are used. Hence, the rocket engines are very strongly dependent on the basic propellants and their chemical properties that are used.

We shall very soon see that we have a large number of actual propellants that are used for various rockets, unlike in aircraft, where you have only one kind of fuel. In rocket, you have a large amount of variation of fuel, oxidizer and their combinations. We will have a look at some of them. Some of them are good and some of them are known to be a little toxic. Some of them have very high specific impulse and as I mentioned, they are typified the by their specific impulse value. We shall see that and we have a large choice there. As we go along, we shall have a look at some of the propellants, not only liquid propellants, but also the solid propellants, where we have large choices.

Unlike in aircraft or other kinds of jet engine, where you normally use kerosene based hydrocarbon fuel. In case of rockets, you have a very large choice. The best choice by many parameters is normally hydrogen and oxygen, which is liquid and you cannot use them in solids. They are used more and more, but we have many other options available as far as a liquid propellants are concerned. We shall have a look at some of these, as we go along today.

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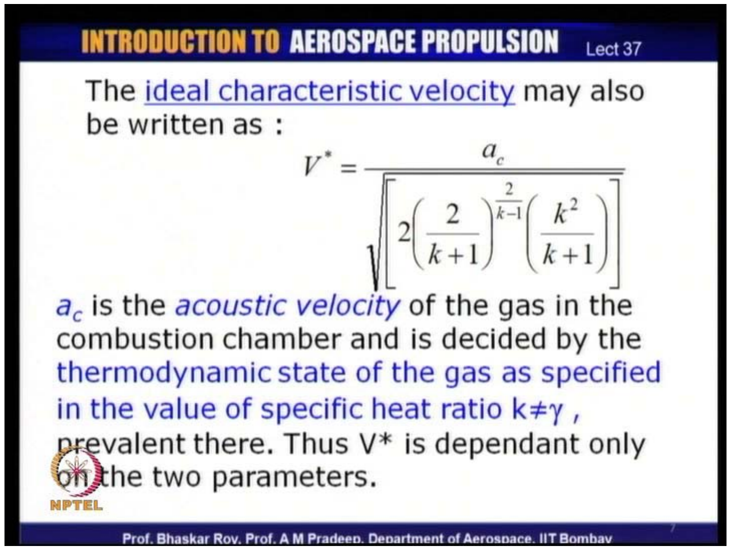

The ideal characteristic velocity can be expressed in terms of more fundamental parameters, in terms of the acoustic velocity of the gas in the combustion chamber. Now, acoustic velocity is dependent on the local temperature. As a result of which, the combustion chamber pressure is not only about pressure, but the temperature will now decide what the acoustic velocity is. As a result of which, the characteristic velocity would be decided.

The other parameter, which will decide the characteristic velocity is the thermodynamic state of the gas, as specified in the value of specific ratio of k, which may be different from gamma and it is the ideal value of the gas. The value of k is also dependent on the local temperature. In case of combustion chamber, the temperatures can be indeed rather high. They can be of the order of more than 2000 degrees and sometimes close to 3000 degree. At that temperature, the value of k would be quite different from gamma.

We shall see that they actually decide what the characteristic velocity is going to be. So, the ideal characteristic velocity or what can be called as the first cut value of characteristic velocity can be simply calculated from the basic specific heat ratio and the acoustic velocity of the gas in the combustion chamber. It is dependent only on two parameters from idealistic point of view.

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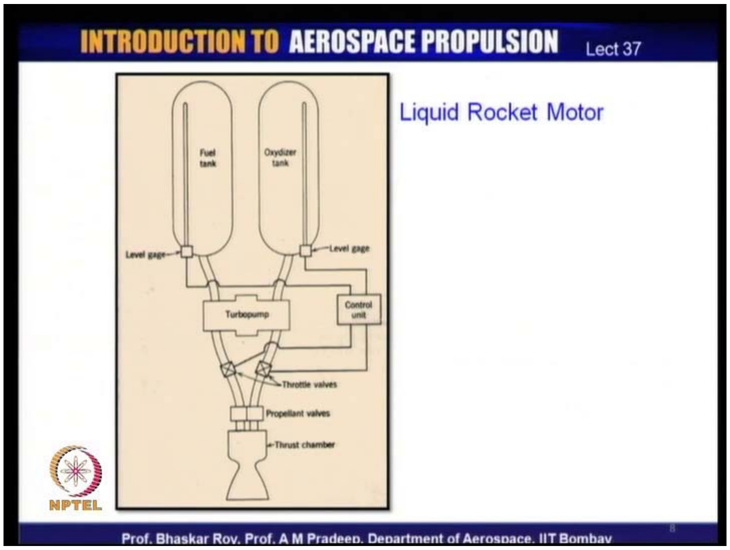

We can take now a look at some of the rocket engines and some of them are called rocket motors. If you take a liquid rocket motor; a very simple version of liquid rocket motor and what you see here is two tanks, which actually store the fuel and the oxidizer. Now, the fuel and the oxidizer are pumped from these tanks with the help of pumps, which are run by some turbines and hence, they are called turbo pumps.

They flow from these tanks through these piping. The pumps pump them out of the tank and then supply them towards the rocket engine. Now, this is your rocket engine and you have the nozzle here. So, it comes through the throttle valves and then it is pumped into the combustion zone over here, which is the combustion chamber. So, the fuel and the oxidizer are pumped in separately. They do not mix together, as it is done.

Let us say in a normal IC engine, there is no carburetor here. They are pumped in separately into the rocket chamber. You have two separate sets of pumps and two separate sets of throttle valves to throttle them. We shall see that they actually have different ratios for different kind of fuels and oxidizers. So, these ratios require that they need to be pumped differentially. Quite often, you have some kind of a control unit to control the rate at which they are pumped and the control the rate at which they should be throttled. These need to be controlled continuously during the operation of the rocket starting from the lift off. So, this is a very simple configuration.

Now, as you can see here, a liquid rocket motor in rocket combustion chamber is indeed very small. It is relatively small and a very large space is to be allotted for carrying the fuel that is the oxidizer and the fuel. These tanks need to be housed within the body of the rocket. You also need to carry the pumps, the throttle valves, all the piping that are required the control unit that controls these pumps and throttle. So, you need to carry all this with you all the time during the rocket's actual flight. It means that other than just a combustion chamber, you are carrying the whole paraphernalia including the tanks and the turbo pumps and etc.

Now, the tanks normally house the fuels in liquid form. If they are liquid oxygen or liquid hydrogen, they are likely to be at very low temperature and at very high pressure. So, the tanks need to be built very strongly to house them and as a result of which, the weight that a liquid rocket would have is normally quite high. As a result of that it is necessary that one use liquid rocket or liquid rocket engine, only when the rocket itself is big in size. Normally, liquid rockets may not be used; unless the rocket is big in size and smaller rockets normally use solid propellants, which we shall be discussing a little later. So, liquid rocket means that you need to carry lot of things with you, besides the rocket engine itself. It is proportionally much smaller in size compared to the other things that you need to carry with you.

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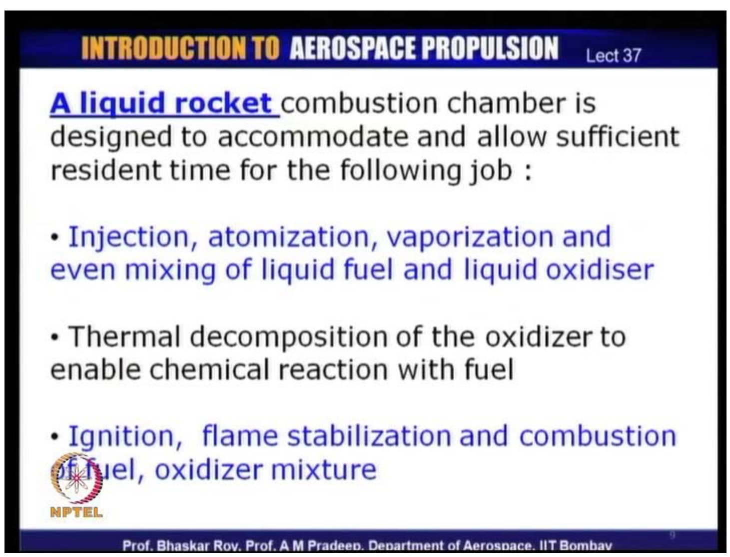

The method by which the liquid combustion chamber operates is somewhat similar to the combustion chambers that we have seen earlier. In the other kinds of jet engines, the combustion chamber is designed to do some of the things that we are little familiar with and let us look at them one by one. The combustion chamber needs to have injectors for both fuel and oxidizer. We have two sets of injectors, one for injecting the fuel and other for injecting the oxidizer. Both of them has to do injection atomization, vaporization and then mixing of the liquid fuel with the liquid oxidizer in a correct proportion. So, this needs to be done.

The job here is with reference to the jet engines, where the fuel was injected into the combustion chamber into air. Only one fuel is to be injected, atomized, vaporized and mixed with the air. Here, two fuels that is a fuel and the oxidizer needs to be injected, atomized, vaporized and then mixed in correct proportion with respect to each other for the combustion can take place. So, these are prerequisites or pre-requirements, before the combustion can actually take place.

There is a question of thermal decomposition of the oxidizer to enable chemical reaction with the fuel. This must be allowed to happen, then the ignition has to take place and the flame needs to be stabilized, once the ignition takes place. The fuel and the oxidizer have to be mixed in correct proportion and the flame is created. Now, the next job is to stabilize the flame. If the flame is subjected to a large amount of flow of gases, the flame may be extinguished.

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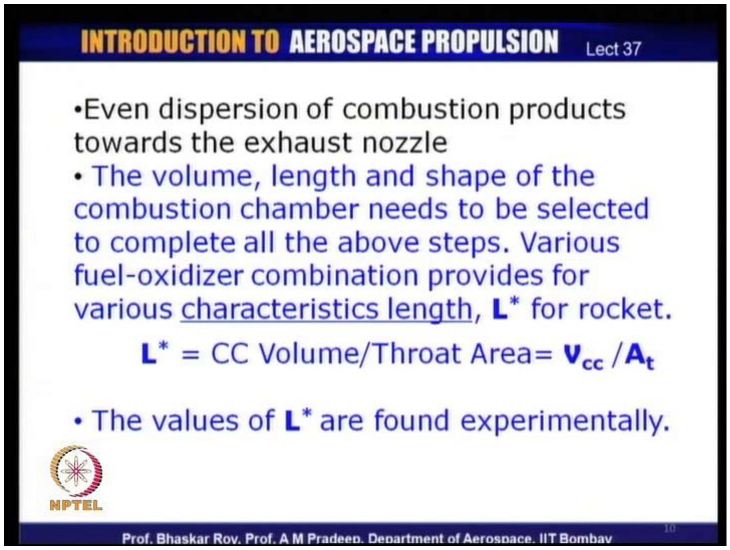

The flame needs to be stabilized, so you probably need to have some kind of flame stabilizer or flame holder around there in the combustion zone. The combustion of fuel and oxidizer would have to be mixed in correct proportion. This mixing would have to continue even after the combustion is over. Hence, the process of combustion may continue until it hits the exhaust nozzle.

Now, through the exhaust nozzle, the flow goes out and once the flow goes out, a process of motion of the gas or the combusted gas starts happening. Once that starts happening, the combustion products from the combustion zone starts moving towards the nozzle and movement starts automatically. There is a continuous motion of combustion products from the combustion zone to the exhaust nozzle and it sets up a continuous motion of gas from combustion zone through the nozzle to the exhaust.

The volume, the length and the shape of the combustion chamber also needs to be selected or designed for a rocket design. The various fuel oxidizer combinations are provided for various characteristic lengths. Now, characteristic length of a combustion chamber of a rocket is defined as L star and this is simply defined as combustion chamber volume by the throat area. So, volume of combustion chamber by throat area A t gives us the characteristic length of a rocket.

The combustion chamber volume that we have seen is somewhat dependent on the combustion chamber pressure and combustion chamber temperature, which are also dependent on the chemical properties of the fuel and the oxidizer. As a result of which, these are determined independently. Hence, the value of L star is often found experimentally in the laboratories and then they are characterized. Once they are characterized, the value of L star for a particular fuel and oxidizer may be selected for a particular kind of rocket, from which we can find out what the combustion chamber volume could possibly be or what the throat area could possibly be for movement of the combustion products. So, these are characteristic parameters that need to be arrived at somewhat early in the rocket design.

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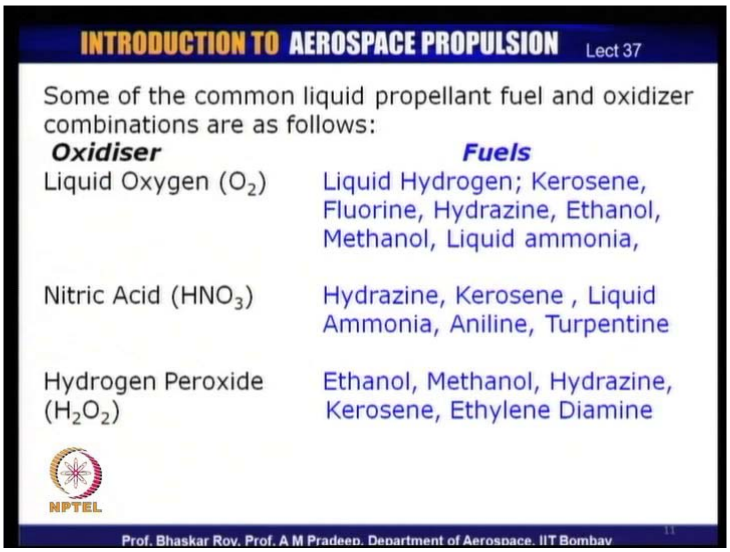

Let us look at some of the common liquid propellant fuel and oxidizer combinations. These are in terms of oxidizer and we have liquid oxygen nitric acid and hydrogen peroxide. Each of these oxidizers can use various fuels. We have liquid hydrogen, we can have kerosene, we can have fluorine, we can have hydrazine, ethanol, methanol and liquid ammonia. So, all these are possible fuels and some of them could be a little toxic. It is something, which one has to be a little careful while using. Kerosene is a very well-known hydrocarbon and people have used it quite a lot. Many of the bigger rocket engines are using liquid hydrogen and liquid oxygen as primary fuel and oxidizer.

The other possibilities are if you use nitric acid as oxidizer, you can have hydrazine, you can also have kerosene and you can have liquid ammonia aniline and turpentine. If hydrogen peroxide is the oxidizer, you can use ethanol, methanol, hydrazine, kerosene and ethylene diamine. There are number of possibilities and number of combination that are possible. As I mentioned, some of them may have certain amount of toxicity involved. Hence, they may be somewhat prohibited or objected for usage due to atmospheric pollution, but some of them do have a very good performance indexes.

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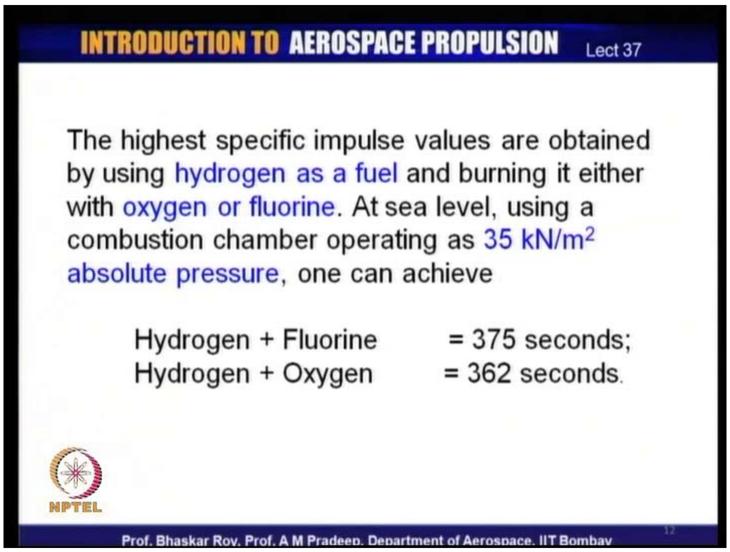

Let us look at one or two of them, in terms of how they actually perform. The high specific impulse values are indeed obtained with hydrogen as fuel and burning it either with oxygen or fluorine. If you use hydrogen as fuel and fluorine, you would get specific impulse of the order of 375. On the other hand, if you use hydrogen and oxygen, then both of them are liquid, so you would get 362. With fluorine, you can actually get a higher specific impulse. These numbers are arrived at using combustion chamber pressure as 35 kilo Newton.

The numbers just give a hint that certain fuels actually give you a higher specific impulse than liquid hydrogen and liquid oxygen. If there is a fear that combination of hydrogen and fluorine could actually give you certain amount of toxicity, which may not be acceptable to many of the environmentalists. So, more and more people are using hydrogen and oxygen because they are clean fuels and their product normally is in terms of steam, which is a largely water. Hydrogen and oxygen gives very good specific impulse. It is not the best, but very good and they are normally clean fuels.

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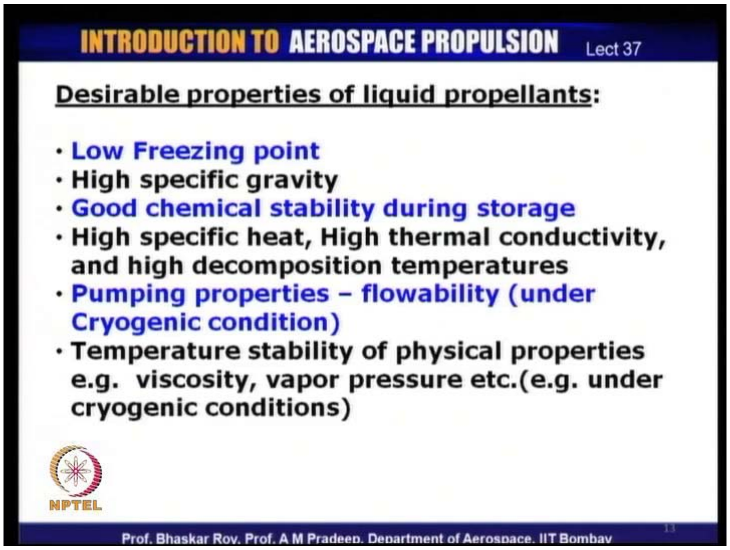

If you take all this into account, we can talk in terms of what can be called as certain desirable properties of the liquid propellants. You see the rocket has to operate very quickly at high altitude and the atmosphere there has very low temperature and of course, very low pressure. As a result of which, it needs to be ensured that it operates with a characteristic property, which has a low freezing point. It should have high specific gravity; it should have very good chemical stability during storage.

Now, this is a problem because when the rocket fuel is stored in a tank and over a period of time, it loses its chemical properties. If that happens, then it will not perform as per the desired predictions of the rocket engine. Hence, it is necessary that the rocket fuel preserves its chemical stability and properties during the storage. It should have high specific heat, high thermal conductivity for the heat to be conducted through its operation during the combustion and high decomposition temperature. It means that it should not decompose quickly, before the actual combustion is initiated.

Now, you need to realize that combustion is a process, in which we mentioned that it has three or 4four steps. It requires injection, it requires atomization, it requires vaporization and then it requires good mixing between the fuel and the oxidizer. Only when they are mixed in correct proportion, you have the combustion. If the proportion is very bad, you may not have any combustion at all. As a result of all this, there is a certain time period during which the combustion zone and the temperature, which is already been created by the combustion products may travel into the products, which are just being injected into the combustion chamber. As a result of which, it is entirely possible that some of the fuels or oxidizers may be subjected to decomposition. It is important that they do not decompose before the combustion actually takes place.

These are chemical properties and they need to be built in to the chemical properties of the fuels and oxidizers that are selected. They are the ones that we looked in the previous slide. Actually, some of those properties are already built in them. If you are looking for new fuels and new oxidizers, you need to ensure that they carry these properties that we are discussing right now.

The next property that you need to look is the flow ability. Now, you see when the rocket is flying, it does not fly straight in level like an aircraft; it flies in a trajectory. It initially flies straight up and then it flies in some trajectory, during which the liquid has to be pumped from the tanks into the combustion chamber. This means that the liquid should flow during its various flight trajectories and during which you have a strong force of gravity. You have the motion of the rocket, which itself creates a certain motion. Of course, it flies to very high altitude quickly, where the temperatures available are very low. As a result of which, the fluibilty of the fuel and the oxidizer needs to be ensured during the entire time and also during the operation of rocket. This is specifically true when the rocket needs to operate for quite some time in very low temperatures; definitely subzero and those are known as cryogenic conditions.

In the cryogenic conditions, you need to ensure that the fuels that are used retain their property. They can be taken from the tank to the combustion chamber, they can be injected, they can be vaporized, they can be atomized and they can be vaporized. So, all these has to happen under cryogenic operating condition. Hence the entire rocket engine needs to be built and their fuels that are used in a manner that conforms to cryogenic operation. So, cryogenic rocket engine is a slightly specialized field of rocket engine and hence that needs to be built and designed separately for cryogenic operation. As a result of which, the cryogenic engines are the modern versions of the rocket engines. They need to be designed keeping in mind that most of the time; the rocket may be actually operating under cryogenic conditions. This leads us to the last point that is the temperature stability of the physical properties. You need to ensure that the physical properties of the fuel and the oxidizer are stable.

We mentioned the chemical properties and now, we have to look into the physical properties of the viscosity and the vapor pressure and this need to be looked during the cryogenic operation. So, it is necessary that the rocket engines look into these aspects, before the rocket is actually designed and before the fuels are put in place and the rocket is operated. The viscosity and the vapor pressure are some of the elements of physical properties that should be built into the fuel and the oxidizer that are used for rocket engine operation.

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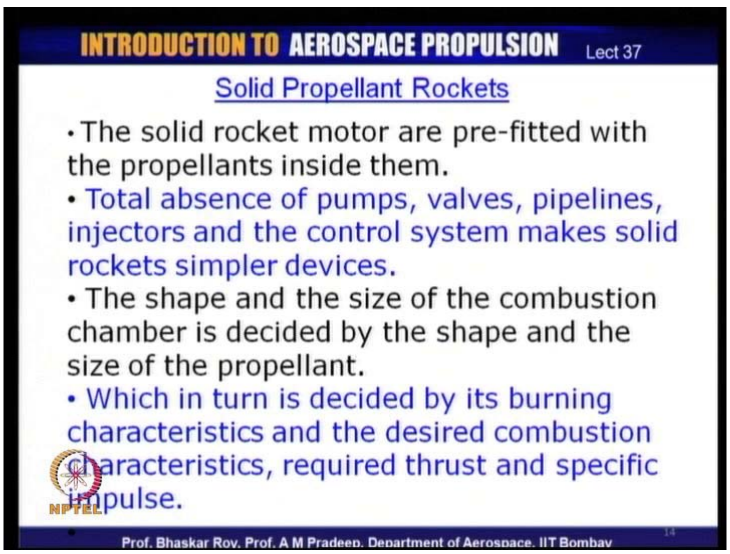

We may now look into various kinds of solid propellants. We can see the solid propellants by basic definition. Instead of liquid fluids, you have solids. It essentially means that you have bodies that are placed inside the combustion chamber or what is called pre-fitted propellants inside the combustion chamber. This also means that there are no pumps, no valves, no pipe lines, no injectors, no control systems and hence, all the paraphernalia that we saw with the liquid rockets is completely dispensed within solid propellant rockets.

By nature, solid propellant rockets are much simpler devices. In some sense, the solid propellant rockets have been around for many years, probably centuries. For many centuries, people have been using one variety or the other of solid propellant rockets, mainly for various military purposes. The shape and the size of the combustion chamber are decided by the shape and size of the propellant. Unlike in a liquid fuel, the shape and size are decided by the combustion and fuel characteristics. Here, the shape and size are decided by the shape and size of the rocket propellant itself, which needs to be given particular shape and particular size.

We will look at some of the shapes in a few minutes. This means that the shape and the size are decided by the burning characteristics of the propellants. The propellants are the fuel and the oxidizer, in case of solid is a mixture of fuel and oxidizer. The desired combustion characteristics, the required thrust, specific impulse and the fundamental parameters are decided by the burning characteristics of the propellant. In case of solid, it is a mixture of fuel and oxidizer.

Now, this is a solid, which has a shape and size. All these are housed or stored or pre-fitted inside the combustion chamber of the rocket. Hence, all these together decide what the combustion characteristics is going to be, what the burning rate is going to be and what was the time, during which we will have the rocket operational.

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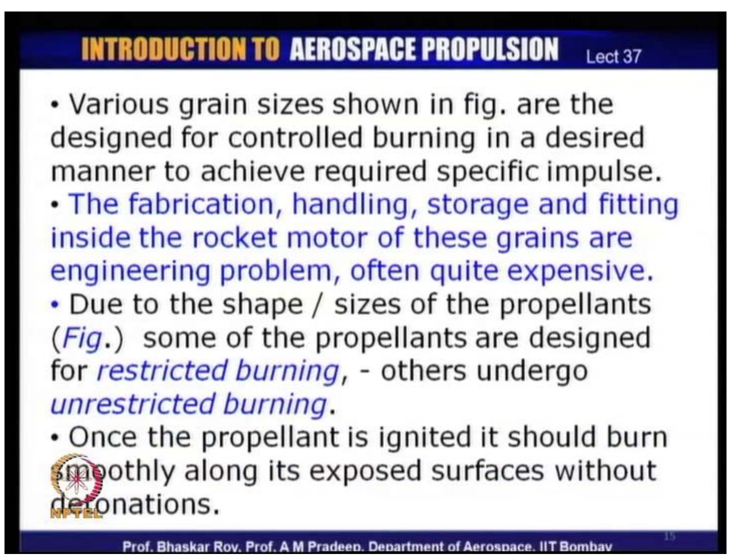

We shall look at some of the rocket propellant's shapes and sizes. These propellants are technically often known as grain. So, there are various grain sizes. We shall see in the next slide and these are designed for controlling the burning in a desired manner. To achieve certain specific impulse value, starting with sea level liftoff and at various altitudes, where you need specific impulse of certain amount for the trajectory to be carried out in a desired manner.

Now, you need to control the burning. As we know very well, combustion is fundamentally a controlled burning process. As a result of which, you need to have controlled burning. In solid propellant rockets, the control of the burning is built into the shape and size of the propellants, which we now saw and these are called grains. Now, these are fabricated. Since, they are solid bodies and they have to be fabricated. They need to be handled, stored after the fabrication in a factory and then later on fitted inside the combustion chamber of the rocket motor. Hence, there are lot of steps involved, before which these propellants are used actually in a rocket. Some of these have serious engineering issues; there is a lot of mechanical engineering involved here.

We have talked about the chemical properties and the physical properties, but now we see there are mechanical properties that are required for these solid propellants, which need to be taken care of. There is a lot of mechanical engineering involved here and that needs to be taken care of and some of it could be quite expensive. Now, due to the shape and the sizes of the propellants, some of the propellants are designed for what is known as restricted burning and others undergo what is known as unrestricted burning. We shall see what these mean.

Actually that some of the surfaces of the grains are restricted from burning, whereas in some other designs, all the surfaces are opened to burning. So, we shall have a look at these shapes and other factors in the next slide. Once the propellant is ignited, it should burn smoothly along its exposed surfaces without any detonations. We certainly do not want any explosion or small detonation anywhere during the combustion. It should be smooth combustion and as I mentioned, it should be smooth fast controlled combustion.

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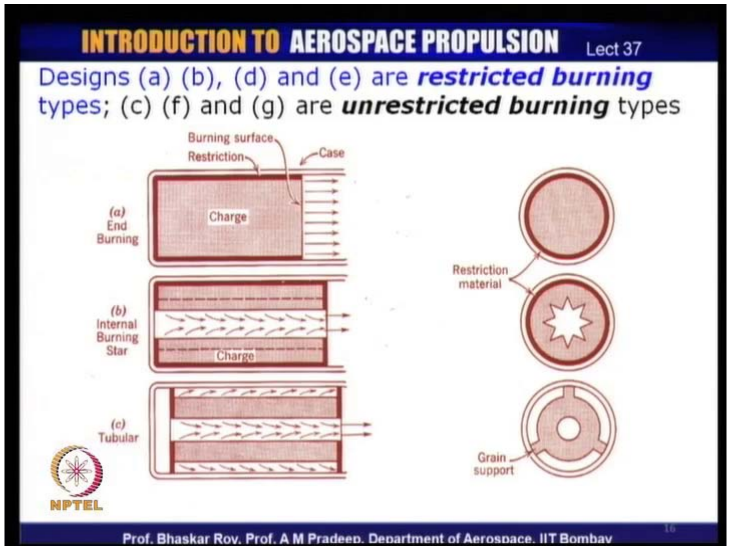

These are some of the cross sectional designs and the sidewise views of the grains of the solid propellant rockets. Now, you can see here some of them are mentioned as restricted burning types. The restricted burning times have these solid and linings around them, so a and b in this figure are restricted burnings. Around this, are the linings, which restrict the burning. They do not allow those surfaces to be participating in the combustion process and hence, this is called end burning. It means only one end is open for combustion or burning and all the other surfaces are closed to the burning process.

In the second one b, we have an internal burning, which means the internal surface actually has a star shape. This star shape is open to combustion or open to burning all the other surfaces including the two ends, specially this end is restricted and is not allowed for combustion or burning. Only the internal star shaped cross section is opened for burning. Now, the question here is why this star shape or any such shape is created. Essentially, if you look in closely compared to a circle, if you have a circle over here, the surface area of this star shape is substantially more than any shape that you put here; whether circle or ellipse or square. A star shaped would have more surface area of burning and this more surface area actually gives you faster burning. So, the star shaped has been created for enhanced burning capability of the rocket.

The third one, which you see here is one of unrestricted burning, in which you can see the number of surfaces are opened to burning. The two ends have certain amount of restriction, but all the other surfaces are opened to burning. The outer annulus and the inner hole are opened to burning. You have three supporting structures over here to hold the grain in place, otherwise they will move around or they may move off. So, you need to hold them. They are very fast and strong and this is where mechanical engineering comes in very strongly. Rest of the surfaces is opened to burning through this hole and as well as through this outer annulus, the burnt gas is continuously coming out. So, this burnt gas is released through this open spaces at the ends and it goes to the combustion chamber.

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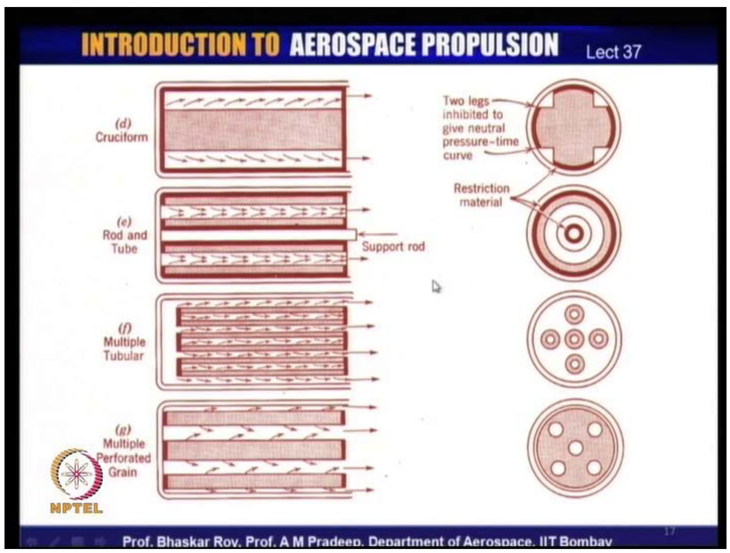

Let us take a look at more of these grains. As we can see here, this one has a lot of restricted burning, whereas the d has the main fuel over here. These are the surfaces, which are open to burning. So, this is a cruciform or cross type of shape, in which these surfaces are opened to burning. These are inhibitors, which are also used for holding the propellant in place firmly; otherwise they are likely to move. So, these are the restricted surfaces and these are the unrestricted surfaces, through which the burning can take place.

You can see in type e, there are restrictions put in the inner circle and there are restrictions put in the outer most circular shape. So, the inner one actually has a supporting rod to hold the propellant in place. The propellant is now built around a rod and this surface is not opened to burning. There is an annulus over here and an inner annulus, which is open to burning. So, the inner annulus surfaces are opened to burning. This is another type of design, in which some surfaces are restricted and some other surfaces are indeed unrestricted.

Here, you have a multiple tubular ones, where you have more or less unrestricted burning and all the surfaces are open to burning; outer as well as the inner surfaces is opened to burning. The last one, g is a multiple perforated grain. It has a lot of surfaces, which are open to burning here. It is more solid and as a result, there is a lot of propellant in this particular shape, but there are lot of surfaces that are opened to burning. So, all these surfaces actually contribute to the formation of the gas that finally would go out through the nozzle for creation of thrust.

The solid propellant would have an oxidizer, it has to have a fuel, but it also needs a chemical compound, which binds them together. So, it is a mixture and primarily, it can be a mixture. It needs to have a chemical compound, which will bind the fuel and the oxidizer together.

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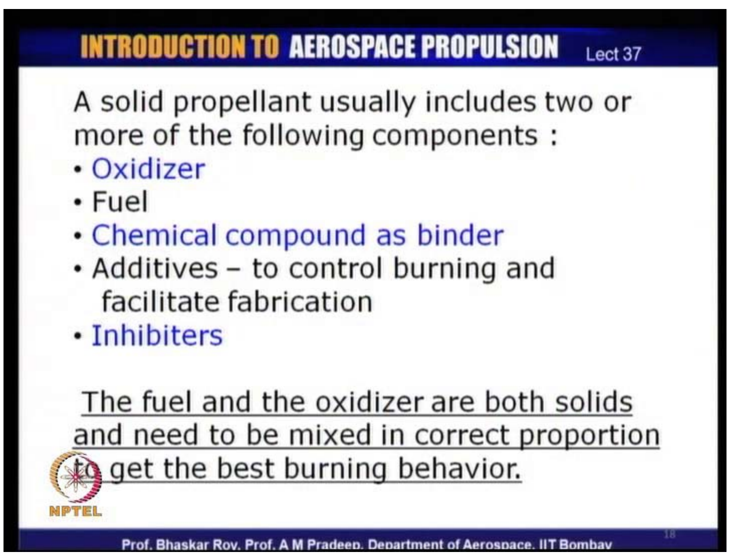

It also often has number of additives, which actually contribute to the control of the burning process and facilitate the fabrication process. As I mentioned, the fabrication is a mechanical engineering issue and some of it is quite a tricky issue. Some additives are often used for giving those shapes and to render those shapes through fabrication process. As a result of which, some of them are facilitating the fabrication, some of them to control the burning. There are some components of the propellant, which are inhibitors and they control the burning process.

Each of these components, which are mentioned should have a correct proportion. We know that the fuel and the oxidizer need to have correct proportion. Their proportion is decided by the chemistry of their mixing, but there are other components like the additives. So, we have the inhibitors and we have the binders. They should be included in correct proportion, so that we have a solid propellant, which caters to the combustion process without getting disturbed by any other mechanical or chemical issues.

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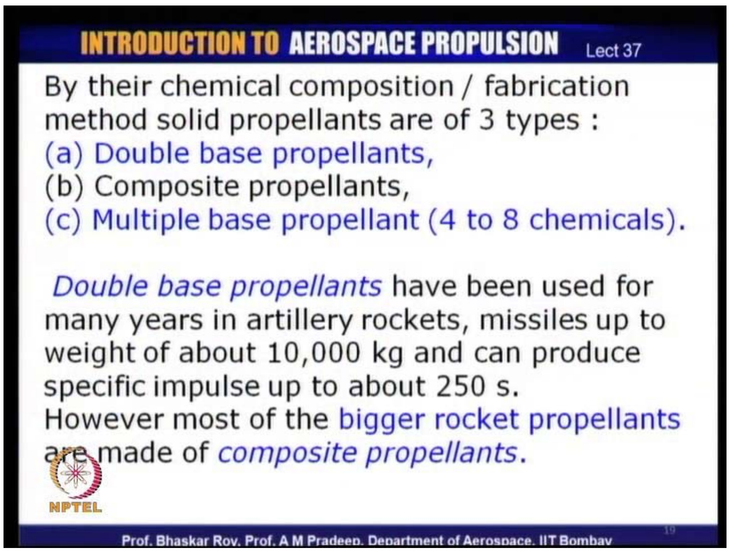

There are proportion that needs to be adhered strongly by their chemical composition and fabrication method. The solid propellants are of three types, you have the double based type, you have the composite propellants and you have multiple based propellants. You can have four to eight different chemicals mixed together into one solid propellant rocket. The double based propellants are the old ones, they have been used for many years in military purposes and missiles up to weight of about 10000 kg. It can actually produce pretty good specific impulse up to 250 seconds, which is considered as a good specific impulse.

Most of the modern rockets actually use composite propellants because you need to have more control over the whole business of propulsion and whole business of combustion. All the things that we have talked about is you need to have more control, so most of the modern rockets use composite propellants.

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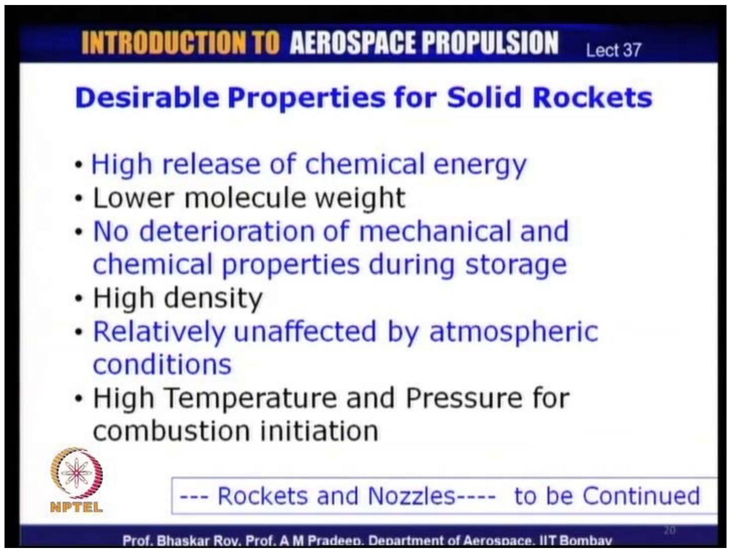

We have desirable properties of the liquid propellants and the desirable properties of the solid propellants are - high release of chemical energy, they should have lower molecular weight, no deterioration of mechanical and chemical properties during storage. Most of the solid propellant rockets are created in specialized factories. They have to be stored for long period, during which there should not be any drop in the mechanical or chemical properties because they need to retain them during their actual operation inside the rocket chamber.

They also need to be ensured that during this storage period, which could be many months and they must be unaffected by the atmosphere or atmospheric conditions. Of course, they should not be amenable to high temperature and pressure. For combustion, initiation combustion needs to take place at certain temperature and pressure. It should not get into combustion, before that temperature or pressure is arrived. So, these are some of the basic properties for solid propellant rockets that are used for choosing the solid propellants. The propellants that we talked about already are selected for these properties, but if some new propellants are coming in, you need to ensure that these new propellants conform to the properties that we have listed here.

We will continue with the rocket science and we will bring in the nozzles that we used for creation of thrust in the next lecture. We shall have some background of the theory of the liquid propellant and theory of the solid propellant in the next lecture.