Course Name: Combustion of Solid Fuels and Propellants
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Lecture: 09 Solid Propellants-Selection Criteria (continued)

Hello everyone, welcome back. So, we will continue our discussion on the solid propellants and under the solid propellants we are talking about the propellant selection criteria. In the previous lectures you have seen that the choice of the propellant will very much depend on fulfilling the major criteria of the rocket. For example, like it needs to provide high performance high performance means high I sp or high C star and there we have seen that in order to achieve high I sp the temperature of the combustion products must be higher. And, the temperature of the combustion products will be higher only when the heat release from the combustion of the propellants is higher. And, we have also looked at the looked at one equation where the heat release from combustion reaction was related to the the heat of formation of products and heat of formation of reactants.

And there we have said that in order to have high heat of combustion we need to have large negative heat of formation values for products and small negative or even positive heat of formation values for reactants. Now, I will show you one table here where you can see some of the you know typical heat of formation of various products. For example, like if the fuel is aluminum the product will be aluminum oxide. So, you can see it has large negative values like minus 61620 kilo joule per mole.

Similarly, like the other products like if it forms CO 2 you can see it is having like minus 393.5 and so on. I mean there are definitely various other products also like if we have HCl you can see it is having minus 92. So, generally for the products we we look forward to have negative large negative heat of formation and for the reactants we want to have small negative or positive heat of formation. On the molar mass side or which we said that molecular weight we said that the product side molecular weight should be lower in order to have high performance because ISP is proportional to 1 by square root of molecular weight.

So, if you look at we already told ourselves that for solid rocket generally the mixture ratio is chosen slightly fuel rich in order to have some you know products of incomplete combustion. If you look at the molecular mass of CO and CO2 you can see the difference and I think we have already shown through an example. So, if you look at the molecular mass of CO2 is almost kind of double not exactly double, but at least 1.5 times compared to the CO. So, if the products are containing both CO2 and CO the average molecular mass will be lower if the products are fully composed of only CO2.

So, taking the advantage of the reduced molar mass for the products generally the mixture ratio is slightly fuel rich for the solid problem in order to take the advantage of the reduced molecular mass. So, I think we have discussed there and we also talked about the density of the propellants would be high enough. So, that we can choose small volume motor because we want to have like compact motor and we all know that the rocket is a volume limited propulsion propulsive device. So, the volume is kind of restricted we need to use the high density propellant in order to you know make the compact size of the motor. So, up to there we have discussed.

Now, let us look at the other characteristics of the propellants which will help us to choose the selections of the propellant. So, one such thing is that we need to have like we said that predictable reproducible burning rate similarly, it needs to have the predictable reproducible ignition quality also like it needs to have reproducible and predictable ignition quality ignition characteristics. What does that mean? It means that whenever we are testing the a particular propellant the amount of energy needed for ignition the pressure rising curve for that ignition process this would follow exactly the same same way when you repeatedly test it. So, the ignition quality or ignition characteristics should not change abruptly when we test the similar ingredients of the propellant several times. So, it needs to have reproducible and predictable ignition qualities like later on we will see like for you know large rocket if you look at the pressure time curve the ignition will start from like by increasing you know the pressure will start increasing it will fill the chamber then ultimately reach to the equilibrium pressure.

So, this is the P equilibrium. If you look at the schematic view of the rocket you see the propellant grain is somewhere over here. Now, if you put this thing this is the igniter. So, it will let us say it will have some pyrotechnic igniter. So, there will be some you know ignition coil here.

So, the igniter will create some ignition plume that will actually going to you know heat up the initial propellant surface and that will start igniting the initial propellant surface and that will fill up the volume of the I mean the port volume of the grain with the combustion gases. So, the pressure will keep on rising and they it will continue till the it reaches to equilibrium pressure and then it will maintain for certain duration and then it will tail off means it will extinguish. So, this is typically the first portion of the this pressure time curve is the ignition then chamber volume like chamber has to be filled up it will reach to a certain pressure ignition will be maintained I mean ignition will be sustainable and it will go to the equilibrium chamber pressure. Now, if the ignition fails due to certain reason like let us say suddenly there is a spike in the pressure and then suddenly it falls we do not want that we want like kind of a predictable and reproducible ignition quality of the propellant every time. So, this is important criteria we do not want any kind of a misfire or any kind of a hang fire.

So, the ignition has to be like you know has to be proper. So, those type of processes we will talk later one once we talk about the the combustion processes of solid propellant, but at this point we should remember that the ignition characteristics of the propellant should be reproducible and predictable ok. There should not be any abrupt ignition or any kind of a you know unevenness in the ignitions once we repeatedly test it. The other criteria of course, that once we make a propellant grain it does not mean that we always use it immediately. So, we may need to store it for you know future use.

So, the ingredients should be good enough that it needs to maintain you know certain you know ageing characteristics when it will it needs to have like long life and and good ageing characteristics. So, let us say we made the grain for example, like if we make like cartilage loaded grain we know that it is a free standing grain the the grains are made separately they are casted cured separately and whenever is required they are loaded into the rocket motor. So, if it is not needed let us say for its missile applications it is not always necessary that we make the grain and immediately use it. So, they may be store in the the storage areas. So, the the chemical property or chemical quality of the propellant should be maintained for a longer period of time.

So, that is why the long life and good ageing characteristics needs to be maintained or needs to have with the propellant. So, we can say the long life and good ageing characteristics. Of course, this will depend on the type of you know ingredients we are we are using like that propellants chemical and physical properties that will of course, tell us that how long it is going to be stable without you know further chemical deterioration, but in summary we say that the propellant should have the characteristics of long life and good ageing. So, it will maintain the you know its quality for a longer period of time. It should not you know absorb moisture.

So, absorb moisture should be minimum you know it should even if you absorb it should be minimum because sometime it may so, happen that due to the absorption of moisture the there may be some chemical changes like it may change its crystal structure may be it may create some void inside the space of the crystals for certain oxidizers this may so, happen. The chemical property or chemical quality of the certain ingredients may even change for example, like certain metallic fuels if they absorb moisture they may not be you know may not remain the same good quality certain crystals they may form a different type of you know crystal phases which will actually eventually lead to its you know lower quality of performance. So, the propellant should have the quality that it should absorb minimum amount of moisture. Then of course, while making the propellants the process of making or we can say the process of manufacturing the propellant manufacturing of propellants that process itself should be you know simple and simple and you know low hazardous. We want to make the propellant propellant means we are talking about the fuel and oxidizers.

So, manufacturing process for making those propellants must be simple and low low hazardous of course, it needs to have like you know raw materials should be available all the time. So, we need to make sure that the raw materials are available for the propellant and it may require for quite some time. So, we should make sure that the availability of the raw materials is guaranteed for a at least some period of time or we can say the over the production and operating life of the propellant. And we need to have good control over the impurities present in the in the each of the ingredient like percentage tolerance how much percentage of impurities cannot be nullified fully, but the tolerance limit of the impurities we should know and we must have the good control over the impurities limit ok. So, that is one another important criteria the it must need to have like you know some prior experience or you know the risk of handling or performing or operating of the propellant should have like you know technical risk should be minimum should be like minimum.

We need to have some kind of a prior you know experience handling the propellant that will give us the confidence you know for choosing the certain propellants for certain application. Now, let us say we make the propellant grain, but if there is any kind of a you know external stimuli the ignition itself is an external stimuli, but there may be some in in I mean unintended external energy stimuli may be available. So, the propellant must have the enough insensitivity. So, the propellant should be should be insensible to like you know certain energy stimuli or certain energy sources certain energy sources which you know we need to order to avoid to avoid unintended ignition ok. What does that mean? That means, let us say we have loaded the propellant in the rocket motor.

Now, this rocket motor can be subjected to various you know while during transportation it may subjected to like vibration. Now, the vibration may cause some you know you know some segments may not be aligned properly there may be some little bit of you know tolerance is there. So, due to that it may cause some kind of a you know energy absorption into the grain. So, that should not lead to certain you know ignition. There may be some stray currents, there may be some impact like you know some dropping of something some materials dropped on the propellant, there may be bullet penetration also.

So, there are I mean should have the you know quality of the propellant in such a way that it can avoid the unintended ignition. So, there are certain energy stimuli like there may be like fires, fire may break out nearby areas. So, just due to the the radiation heat like it should not absorb enough heat that it may lead to some in unintended ignition. Because the ignition was given only through this igniter right what we have just said that igniter will create the ignition plume and it will create the ignition process. But if there is some other energy sources like heat or even dropping of the propellant or even the certain external like stray currents or even by the like you know bullet penetration or even by the vibration or even by the like electrostatic discharge which may be you know caused due to some friction of the insulating materials that should not lead to any kind of an unintended ignition that must be avoided.

So, the propellant should be insensitive enough to avoid the unintended ignition. So, that is another important qualities ok. We need to of course, you know low I mean low toxic materials we need to have like low toxic propellants and of course, this should lead to like you know non toxic exhaust. So, propellant is actually producing exhaust gases. So, we are talking about that it should not produce like toxic gases which is going to you know create environment for the members working nearby areas or also it is going to pollute the environment.

But you see for the general the very common ingredients for solid propellant rocket is the HTPB plus AP which is kind of a workhorse, workhorse oxidizer for most of the composite propellant. Almost all the satellite launch vehicle are using this this combination. So, if you look at this ammonium percolate which is a chlorine containing substance. So, on decomposition of ammonium percolate it is going to create some you know chlorine compound and it is going to create HCL which are not really good for you know environments because they are kind of you know very reactive and they are not really you know benign to environment. So, although we are saying these things, but the major oxidizer used for solid rocket still not having the environmental benign quality in terms of like the exhaust gases ok.

But of course, the choice of the propellant should be such a way that it should follow the non toxic exhaust characteristics ok this is another thing alright. Other choice is like it should not lead to should not lead to you know combustion instability. So, if there is any pressure fluctuations inside the combustion chamber the your propellant the burning of the propellant should not you know promote the combustion instability. So, the choice of the propellant should be such a way that it should somehow diminish the even there is a fluctuations which may be subjected to some instability, but the propellant should not further increase the fluctuations which may lead to like the complete failure of the motor. So, it should not you know it should not prone to the combustion instability.

So, these are the several you know characteristics of the propellant are considered while making the choice. Of course, there are certain characteristics will be there for the particular choice of the mission where a particular type of propellant is chosen. So, in spite of those things there may be some other criteria which need to fulfill for example, like the compatibility. So, it is not only the propellants only, but there are some insulator liners. So, the choice of the propellants will also depend on them that whether there is an issue with the competitive of the components or in between the propellants the if there is any competitive issue or not whether they are maintaining the enough you know mechanical properties.

So, it is like a you know tradeoff between the mechanical properties and the ballistic properties. So, the choice will be definitely depend on the propellants selection criteria ok. So, but majorly we have talked about these criteria which are which are supposed to be

followed by the designer while choosing a particular propellant ok. So, now let us move ahead and we will talk about what are the major ingredients of solid propellants ok. Since we understood pretty much the major characteristic of solid propellants, now let us look at the what are the major ingredients of solid propellants.

You know there are number of ingredients have been tried for solid propellants, but we will try to look at the major ingredients of solid propellants which are most commonly used, but you can we must need to acknowledge this the fact that the the principle ingredient if we say that without which the propellant cannot work the principle ingredients are the fuel and the oxidizer. So, these are must be needed in order to have it have it as a propellant without fuel it will not work without oxidizer is not going to work. Now, fuel and oxidizer they are the principle ingredients in addition to fuel and oxidizers there will be certain other ingredients which are going to have different kinds of role in order to have like they may increase the burn rate. So, there there may be burn rate modifiers. If we have a polymeric fuel which is in general liquid in nature, but if we have to make it like a cured propellant if you recall the definition of the grain we said that cured mass or safe mass.

So, maybe the initial state of the propellant mixture or the initial state of the fuel and oxidizer mixture was a liquid or even slurry. Now, later on we actually cured it and made it solid block of material which is grain. Now, there are certain ingredients required to I mean enhance the process of curing. So, there will be some curing agents there may be required to increase the burn rate of certain propellants. So, there may be like burning rate modifier or burn rate modifiers there may be some catalyst there may be some increasing burn rate or there may be some catalyst for decreasing burn rate also.

So, inhibitor for example, like they may actually reduce the burn rate. So, depending on the requirements there may be different type of ingredients which are used. So, it is not like just restricted to certain type of fuel or oxidizers, but there will be number of ingredients which have been tried, but in our discussions we will just focus mostly on the major ingredients. So, let us look at what are the major ingredients we will try to consider. So, as I said the fuel and oxidizer are the principle ingredients, but there may be like the name wise we can say it will have like fuel, it will have binder, it will have oxidizer, it will have it may have like plasticizer, it may have like curing agent, it may have likeburn rate, burn rate modifier and you know so on.

There may be so many things are added depending on the choice of the propellant and for what for what purpose the problem is being made. So, depending on that there may be like number of different ingredients have been tried or are being tried even now ok. Now, coming to the fuel what we just said about this one, if we just make like the propellant out of just the polymeric fuel plus oxidizer there we can say it is like the only the fuel and oxidizer which is acting as a binder also, but if you look at here we have just categorically mentioned fuel and binder, but once there is only polymeric fuel which is actually a binder.

So, binder is nothing, but it is also act as it also acts as fuel as well just because the polymer is hydrocarbon.

So, it will eventually burn. So, that will act as fuel. So, if we do not have any kind of other metallic ingredients if we just have like polymeric binder plus oxidizer. So, the polymeric binder is nothing, but it is a fuel. So, the principle ingredients we must need to have the fuel and oxidizer.

Now, here once we say categorically fuel. So, fuel means we are talking about like various metallic fuels. So, very common metallic fuels is the you know aluminum particles they are considered as the common metallic fuels it may have like diameter of you know 5 to 60 micron diameter ok. They are used you know widely we can say like used widely in various composite propellant ok. Now, the size we have mentioned here, but there will be some different size of aluminum particles have been used very fine particles ultra fine coarse particles. So, depending on the choice like and the availability aluminum particles are used, but they are used in various you know composite propellant applications.

Now, the problem with the very fine aluminum particles is that they will have some you know they will easily burn with air and there will be some you know oxide layers with the present on the surface of the particles. So, there is a chance of that the particles will contain some oxide layer and the core of the particle will have aluminum ok. Now, choice of the metal particles are coming from because they are having high energy you know density or compared to the normal hydrocarbon fuels even polymeric fuels considering their heating values and the metal fuels heating values the generally the metal fuel heating values are higher than the hydrocarbon fuels, but not always for certain metallic fuels the heating values are higher and particularly when it is the volumetric heating values. Volumetric heating value means the heating value per unit volume of the propellant or you can say mega joule per meter cube. So, if you compare the heating values of volumetric heating values of hydrocarbon fuels and the metallic fuels in many occasions the heating value of the metallic fuels are much higher compared to the hydrocarbon fuels.

So, later on I will think I will show you one comparative chart where we will see the heating values of various metallic fuels and the hydrocarbon fuels where you can see that boron is considered to be very high having very high volumetric heating value. So, boron is considered one of the prime choice, but there are some certain problems with boron particles although theoretically it shows that the heat release from boron combustion can be very high, but you know unfortunately the commercially available you know rocket motors utilizing boron as the fuel has not been utilized yet examples of using aluminum particles as fuels. So, here we are talking about mostly the metallic fuel. So, there are various choices considering the volumetric heating values the other choices can be like boron particles. Now, other consideration I did not mention here is the density.

If you recall the high density of the propellant is another criteria we discussed in the previous class. So, here the metal fuel the density of the metal fuels is higher than the density of the hydrocarbon fuels. If you look at the density of boron I think it is around 2.34 gram per cc. If you look at the density of aluminum the density is around 2.7 gram per cc. So, from the choice of the higher density of propellant definitely the metallic fuels are giving the advantage compared to the normal hydrocarbon fuels, but the problem is there how to burn the metal fuel efficiently. So, there is the you know deficit layers that efficient combustion of these metal particles are not properly done. So, if they are not burning properly the utilization of the energy is not very efficient ok. For example, like as we said the boron particles, boron particles has the inherent tendency that you will covered with the native oxide layer. Like core part of the boron will have pure boron, but the outside layer there will be B2O3.

So, which is going to cause inhibition to the ignition process and eventually that will not lead to the complete combustion of the boron particles within the given residence time of the motor. Because you see we do not have like abundant amount of time for burning the particles. The typical residence time in a in a high speed propulsion system the particles will not stay longer than few millisecond or maybe order of few 8 to 10 milliseconds. But within that amount of time the complete combustion of boron and giving the energy release the full energy release within the given residence time is somewhat not achievable. So, even though boron is kind of a prime choice in terms of the metallic fuel, but it still not yet achieved because of the issues with ignition and combustion process.

So, in the next class I think I will bring one comparative chart of heating values of various metallic particles or metal fuels compared to hydrocarbon fuels in order to understand the you know choice of various metal particles ok. With that let us close the lecture today ok. Thank you.