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Aerospace Propulsion
Hybrid Rocket Performance

Lecture 40

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In the last class we were discussing about hybrid rockets and we had listed out the advantages of hybrid Rockets over both solids and liquids and I had made a point at the end of it saying it looks all very erosive with hybrid rockets why is it that it has not ever been used. We will try to list out the disadvantages in today's class and also discuss about the current efforts to overcome some of these disadvantage.

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One of the major problems with hybrid rockets is the burn rate if you look at what I said in the previous class that any polymer can be used right and if you use any polymer along with an oxidizer the burn rates that are obtained are very, very low okay, something it is typically around

1 to 1.5mm/s, so as a consequence what you will have is if it has very low burn rate okay, there is a particular O/F you can use right.

So if you use that particular O/F then the thrust delivered by this system will be because the mass flow rate of fuel is what we are going to get with the solid feel then you need to add the oxidizer mass flow rate oxidizer mass flow rate cannot be very, very large right then the 0/F changes and the temperatures or the ISP that you will get will be very low.

So it has to be within the range that it gives the best is be so if we do that then the thrust delivered by this system will be very low which is probably one of the biggest drawbacks. The other disadvantage with hybrid rockets is if you remember I had said that we can write the expression for the burn rate for a hybrid rocket as $\dot{r}=a0x^{n}$ where g 0x is nothing but mass flow rate mass flux of the oxidizer in the port, right.

So even if we keep this same if we keep this constant right it is possible to get the mass fuel mass flow rate as a fuel mass flow rate is nothing but this is the velocity at which it is getting consumed let us say we have a cylindrical port okay, then we need to multiply it by the area, so that is right.

Now this Gox is nothing but Gox we had seen earlier is nothing but $\dot{m}ox/x$ right, so this is Gox there is nothing but mass flux so if we expand this portion okay, this is the expression for fuel mass flow rate that we get. Now notice that there is a diameter in the numerator diameter in the denominator typically the values of n ranges between 0.7 to 0.8 okay, now what happens if you have that kind of thing you will have n to the power of if we take square 0.8 it will be 1.6 in the denominator and in the numerator 1.

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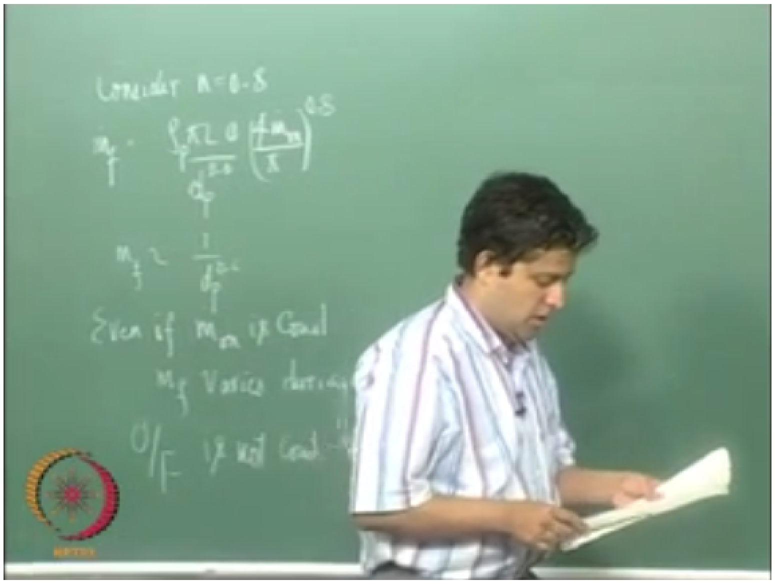

So effectively what you will have is if we consider something like then what we are going to get is $\dot{m}f$ = right, so what we have is the mass flow rate of fuel varies inversely as diameter to the power of 0.6 so even if you hold the mass flow rate of oxidizer constant the fuel mass flow rate keeps on changing right, so $\dot{m}F$ will be a function of so depending on the value of n you will have different powers here okay.

So what we can see is mass flow rate of the fuel is not a constant during operation because the diameter keeps on changing and the mass flow rate of fuel will also keep on changing, so what does this do if $\dot{m}$ varies even if you hold $\dot{m}0x$ constant what it will do is it changes your 0/f right, so essentially O/F F is not constant during operation.

Now this has are more serious consequences in terms of if we look at what happens to the specific impulse as a function of O/F okay, I will try to plot here.

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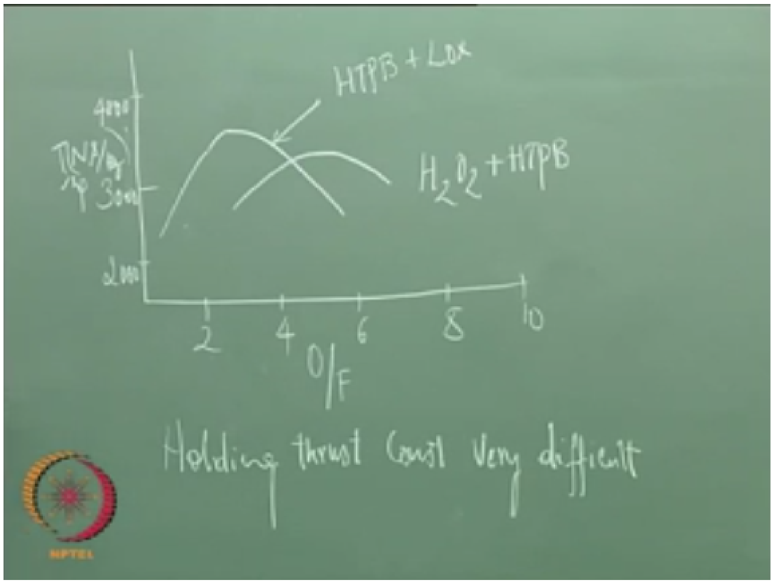

For a flow them okay, so typically you will know that it will have a maxima at some particular O/F in liquids and solids in solids this O/F is preset depending on the amount of oxidizer that you have so you can operate it at that set O/F in liquids you can use the valves to take it to the particular O/F that gives the best performance in terms of ISP and then operate your liquid motor a liquid engine at that point.

But here unfortunately with O/F is P will change and this is for HT PB plus liquid oxygen, now what we see here is that if the O/F varies then the ISP will also vary right. So if you are wanting to design a system wherein the thrust is maintained constant even nominally maintaining constant is very difficult with a hybrid rocket simply because the O/F changes during operation and then ISP will change.

So therefore thrust will change in addition to this the mass flow rate is also changing right, the mass flow rate of fuel even if you hold the oxidizer mass flow rate is changing, so therefore holding thrust constant during operation is very, very difficult. Now the other trouble with the hybrids is people have done this you know looked at okay we are saying that the burn rates are very low right, when we discuss solid rockets we discuss this that only the burn rate and burning surface area are under the designers control once you choose a particular propellant tank.

So you can increase the burning surface area and therefore make up for the lower burn rate is what we talked about right, so people have also considered that that is.

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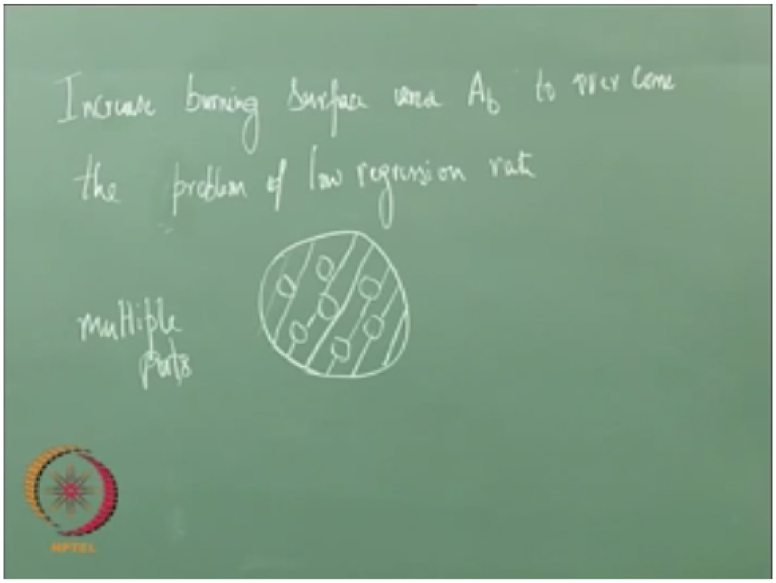

But what happens is they have come up with this kind of a design that is instead of having just one port, let us say I have multiple ports right instead of just having one port all these are ports that is you are taking a sectional view right, so there are multiple ports here but if we do this yes, we might be able to increase the thrust but what about volumetric loading of the propellant that will go down right.

So we had said in one of the advantages of hybrids over liquids that the volumetric loading of the propellant is much higher compared to liquids, but that is no longer possible okay, if we go in for multiple ports. Also if you look at it as they burn further towards the end this could lead to very serious problems regarding the integrity of the grain and other issues might come in.

So multiple port design although looks feasible on the outside it has various problems so therefore this is something that is also not looked at. Now we have kind of listed out some of the major drawbacks in addition to this if you look at hybrid rockets the other outstanding problem is what happens to the burn rate from the head end to the nozzle.

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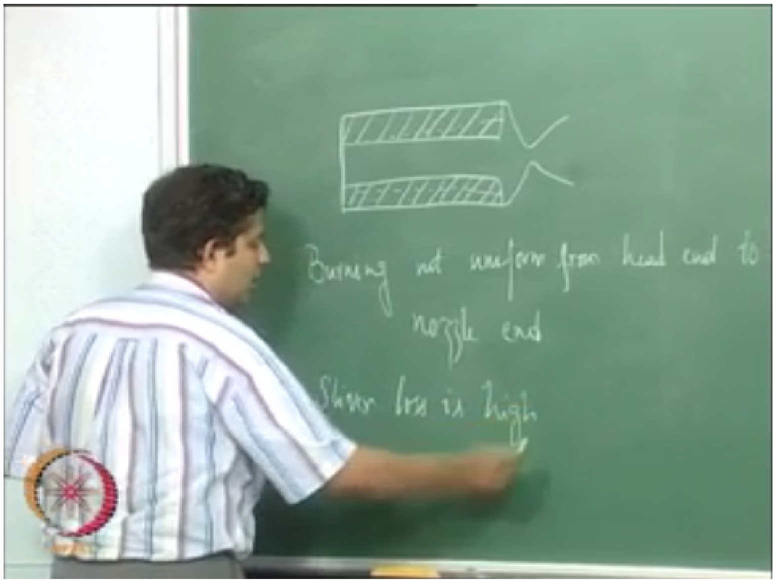

So if we take a hybrid rocket motor let us consider only the fuel portion okay, now if you look at this remember when we discussed about solid rockets we talked about something called arrow erosive burn right, and we said that if you look at what I what is happening the mass addition that is coming into the port is increasing from the head into the nozzle end right, and therefore what happens to the boundary layer thickness the boundary layer thickness continuously decreases.

And as a consequence there is a higher burn rate observed at the nozzle and this is a system that works on this principle, so therefore what you will normally observe is that the burning is not uniform from the head end to the nozzle, this also leads to the other problem that slider losses remember we said sliver is unburned propellant right.

So if you continue burning this motor at some point there will be some propellant unless burnt at the not burnt at the head end whereas the propellant would have completely burnt near the nozzle end and that is a point at which you will have to stop because this would then affect the motor casing itself right, so therefore as a consequence of this the slider loss is going to be high.

Now this looks like as such looks a big list that of problems that we have discussed which makes it very difficult for hybrid rockets to overcome in addition to this there is something known as a problem of scaling.

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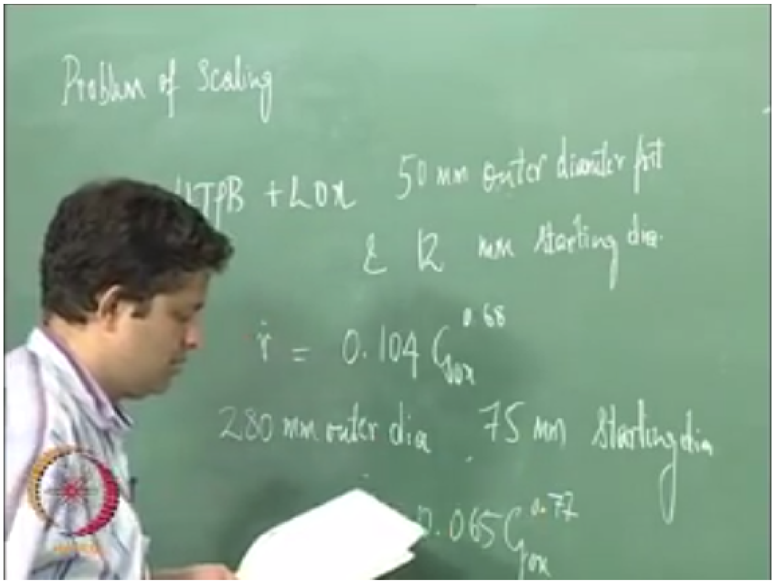

What do we mean by this, it simply put if you do a lab scale test and if you do an actual motor remember when we talked about solid rockets we can get a very good feel of what how does the burn rate vary in a strand burner and then in a ballistic evaluation motor and it has very good the very close to what you will get with the large motor there is going to be some difference but it is not a very large difference.

Now similarly what happens in a hybrid rocket is that if you burn a very small motor in a lab scale because those are experiments that you can do very frequently and it is less expensive to do them, what is its bearing to a large motor unfortunately in hybrids the scaling is not very good from what you get with a small motor to what you get with a large motor. So people have done this experiment at lab scale and for HTPB+ logs.

If you do something like 50mm outer diameter port and 12mm starting diameter this is the same propellant oxidizer same fuel same if you do with this the burn rate law that people get is something like right, now if they do with the same propellant on a larger scale motor right, that is something like 75mm starting and by 280 mm outer dash right, the burn rate law that the gate is very different.

Now this makes it very even more difficult to have a realistic motor because if you want to design a large-scale motor it looks like you have to do all the testing at the large scale itself there is no way you can do a small-scale testing get some measurements done and then use them for the large scale, because the burn rate lost themselves are not valid for I mean or not hope being the same for small-scale and large-scale even the N is very different right.

So these is a this is another major problem with hybrids so because of these problems hybrids have not been able to you know be of the technology of hybrids is not at such a level that it can be used in a launch vehicle. Now some of these problems have been there for a very long time and people have been looking at trying to resolve this and there are various things that people have done to overcome some of this we will discuss that briefly.

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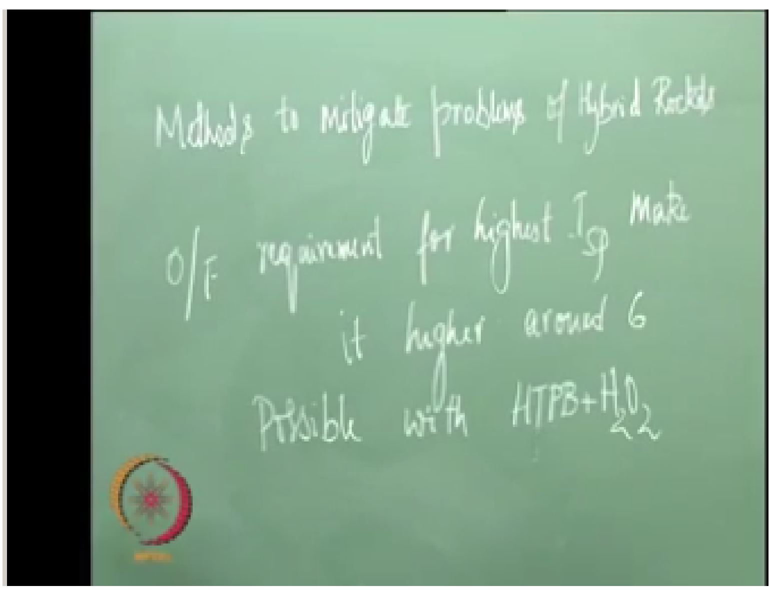

Now the first problem that we discussed was with regards to burn rate of the propellant one of the thoughts that people have come up with this if you look at the of require or highest ISP right of requirement for highest is p if we can shift it to a higher value of a wife that is you choose a fuel and oxidizer combination such that it gives the best performance at let us say six there is such a propellant combination possible if you look at a hydrogen peroxide.

And HTTP be the highest ISP is achieved somewhere around six what it would mean is you need to push in more mass flow rate of oxidizer which also would mean that the fuel mass flow rate will be higher because the two are related so that is one of the suggestions to overcome this problem of low burn rate.

This is also not such a great idea because if you look at the specific impulse overall even if you take this the specific impulse that you will get even with h2o2 systems will be somewhere around three thousand seconds I mean 300 seconds or 3000 Newton second per kg which is not a very large value that will force the industry to take a very positive view of this so in essence this idea does not sell itself.

So much now the second this thing was to use ultrafine aluminum powder or manual mm how people have done these experiments they found that if you use nano aluminum you can increase the burn rates to something like four times what you get that is the fuel burn rates can be of the order of four millimeters per second which is probably very good.

And you can make a very good or a very high thrust motor with this simply because if you look at what we are talking we are only talking of fuel flow rates right in addition to this if you have if you take the oh by F into consideration the oxidizer flow rate will also be there so the overall mass flow rate will be much higher okay but the flip side of this is if you look at nano aluminum the cause of it is very, very high something like 50,000 rupees a kg okay.

So this is why it is again there are also issues when you make a motor of a large scale how do you cure it because the number of particles becomes much larger if you are using micron and suddenly you go to a nano scale you are reducing the particle size by 1000 right as a consequence the number of particles will increase it will go as cube of this thousand so sometimes it is very difficult to get a good cured propellant.

That good mechanical properties if you go in for something like nano level okay so then what people have also looked at as something called a mixed oxidizer concept instead of just having a fuel alone instead of having just htp be alone if we add ammonium per chlorate to it right if you add too much of ammonium per chlorate then it will become like a solid propellant right there is a percentage of ammonium per chlorate.

That you can add such that it does not burn on its own it should not start burning on its own like a solid propellant so you can add a little bit of ammonium per chlorate so as to increase the burn rates so people have done this also oh.

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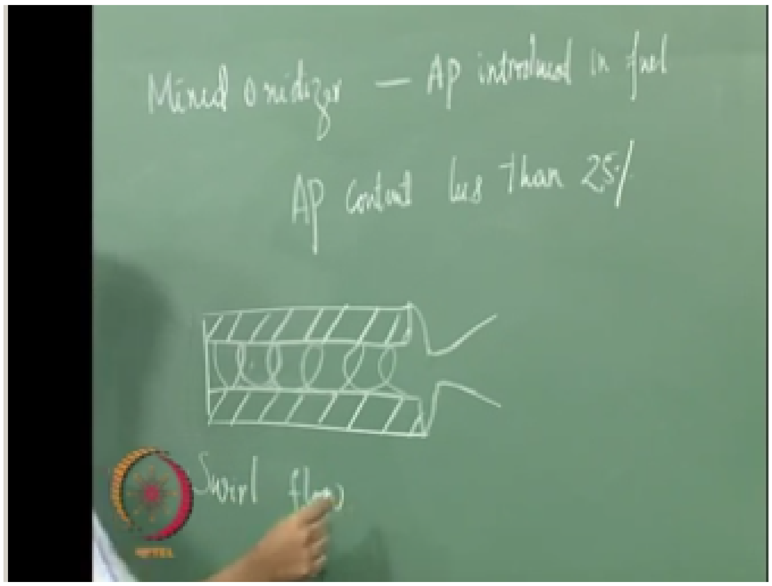

This is known to give burn rate of the order of 4 millimeters per second which is very good to kind of make a solid hybrid rocket engine but the flip side is you cannot use beyond sub percentage it has to be something less than something like twenty five percent if you use more than that then one of the advantages that we talked about hybrids that if you switch off the oxidizer supply it will stop burning that would not happen.

So there is a this is somewhere on the critical content of AP that you can use then people have also come up with something known as a swirling if you if you inject the oxidizer in an axial fashion right let us say you this is the fuel block now instead of injecting the oxidizer axially that is instead of this if you are able to introduce the give it as one right then there are two advantages that you will get one is if you look at the actual surface area.

That the oxidizer gets to see right that will be larger because it is taking every helical path right so therefore the actual surface area that the oxidizer sees is much more than the apparent surface area and in addition you are injecting the if you look at swerved flow because these fluid tries to because of the swirling nature of the flow the fluid tries to stick to the walls right it tries to go close to the walls.

So the actual velocity profile if you look at close to the wall that will be very high and that will lead to very high burn rates rather than if you inject it Axle because the flow most of the if you look at the velocity profile for an axial flow it will be something like this right so there is a larger fraction of the flow is along the center line whereas if you swirl it most of the flow will be close to the walls.

And therefore the burn rates are going to be higher with a slower flow and this is been found true so this can lead to high bondage but on the flip side you are injecting the oxidizer in a swell flow what happens to the exhaust will also have a swell component which could if it is only one motor it is fine it does not have a problem.

But if you have two motors then you have to look at having this was in an opposite direction and you are not too sure whether they will cancel each other out or it will introduce a moment on the entire vehicle which could take the Motrin to MN entire vehicle into a spin which is something that you might not want so therefore this is also not such a feasible solution the other two solutions that people have come up with are one is.

So you know wax that is used to make candles if you can use that as a fear simply because wax is a very low melting point now because of this low melting point what happens when you have a transverse flow is the wax that is in a molten state right when you have a flow there will be droplets of wax that you get entrained into the flow so therefore the mass burn rate of the fuel will be much higher.

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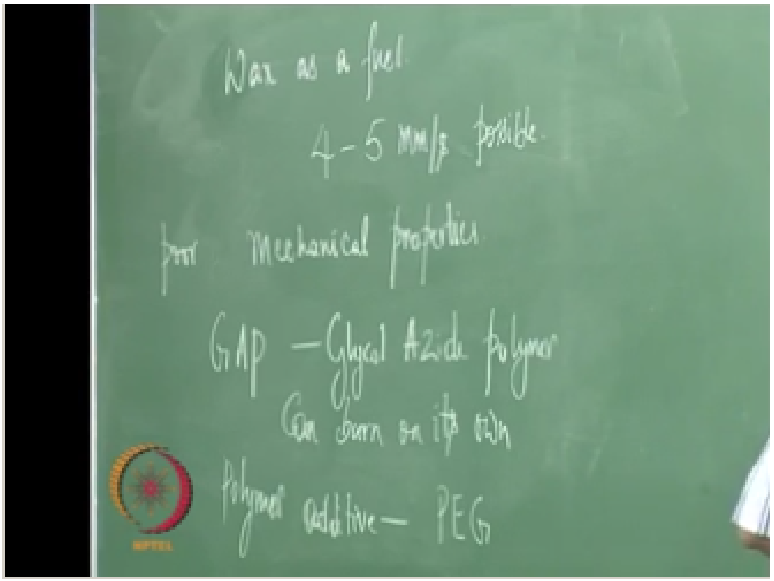

And what they found in experiments is that if you have a wax and oxygen system you can get burn rates of the order of five millimeters per second but the flip side of this is if you look at a candle or if you have ever used a crayon is basically wax it is very, very brittle the structural or the mechanical properties of wax is very poor and therefore as such it does not kind of it cannot be used you have to tailor the mechanical properties with certain additives.

So as to improve its mechanical properties so currently it is mechanical properties is something that is a problem there is also another solution that people have come up with just like you have ammonium per chlorate that can burn on its own right there are oxidizes that can burn on their own at certain conditions is it possible to have fuels that can also burn on them right one such fearless glycol as I will polymer or gap.

So the burn rates that you can get with this is very, very high it also has the other problem that is even when you switch off the oxidizer flow rate it will not quench because this can burn on its own so what people have done come up with this you add another polymer of similar density such that the overall thing does not burn on its own.

But when you have oxidizer flow and when you ignite it is will burn right but the polymer are used for that is EEG or polyethylene glycol which has very similar densities now the trouble with this system is firstly burn rates are lower because you have added up inert polymer the other thing is again the costs that are associated with gap remember when we spoke about hybrids we said a cost of it is very low.

Because you can virtually use any kind of polymer you need not have a very special polymer and therefore the cost can be much lower but that takes away that advantage because you are now going to use something like a very expensive something of the order of again 50,000 rupees or if I am not mistaken $50,000 or rupees I'm not very sure per kg okay which is very expensive.

So even if you build a practical system people will say why use this when we have established systems if you look at the ISP variation with the oxidizer or the oh by F ratio what you can get with a hybrid system is something that you can get with kerosene lock systems okay it is not very different and so in a sense if you look at most countries all of them have kerosene locks engines India is probably the only country that does not have a kerosene locks engine.

So most countries look at it as something that you need to do in addition to what you already have but you will still end up getting the highest performance that you can get is something similar to what a kerosene locks engine would give why do take all the trouble and do something that is not any better.

So therefore you will find that most countries have not really bothered themselves with corn hybrids but there is a silver lining to it in that sense that there is something called as aluminum hydride now aluminum hydride is considered as something that has a higher storage of aluminum per unit volume even if you store a low hydrogen on its own right the density of hydrogen that you will get a 70 kg per meter cube.

But if you use aluminum hydride and the volumetric loading of hydrogen that you can get is much better than what you can get with the liquid hydrogen but the technology of this making this, this is a very or should I say very explosive compound it is very difficult to have stabilized this it is very reactive with it because of the hydrogen and if you have oxygen it will tend to react and lead give rise to water.

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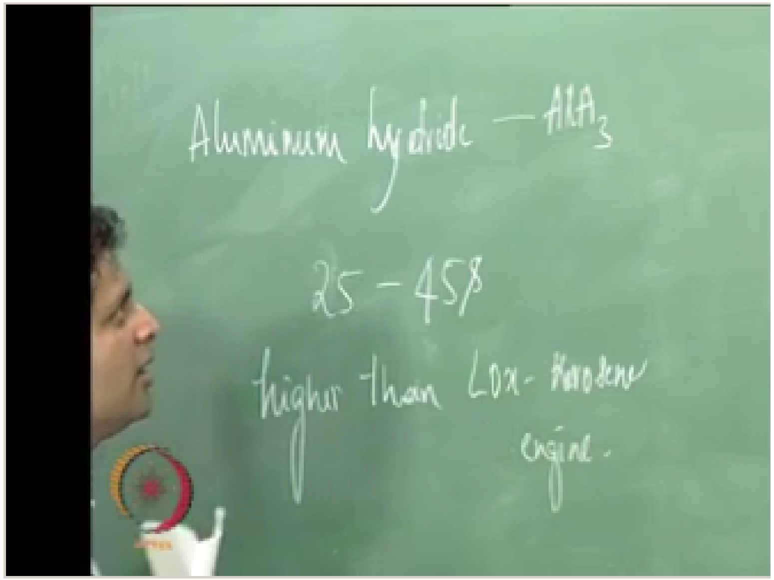

So it is a very unstable compound and very difficult to control it only the Russians till now have the technology of making this but if this were available then you can get over LOX kerosene the is ps that you get with this aluminum hydride being used is something like 25 to 45 seconds higher than that is if you use in a hybrid this aluminum hydride.

And you make a engine out of it the is ps that you get with those are going to be higher than what you will get with LOX kerosene so in some sense this is driving the research forward that is if you can get a system that is has a much higher ISP then LOX kerosene engine why not use it right there was one, one other drawback of hybrids that I missed out on that is something to do with.

If you remember combustion efficiency when we discussed with regards to liquid rockets and solid Rockets we expected a value of greater than 98% right which also indicates what is combustion efficiency in essence indicates how much of the stated ISP you will be able to achieve if this is very poor then the ISP is that you get will be much lower than what the theoretical calculations will give.

Now in hybrid rockets if you look at it the oxidizer is injected here right and one needs to be careful here because if the oxidizer does not mix with the fuel that is coming in fuel is coming in like this and it needs to mix with oxidizer that is going along this direction right if you look at this geometry the oxidizer in the center finds it very difficult to mix with the fear so some of it might just escaped without mixing with the fuel.

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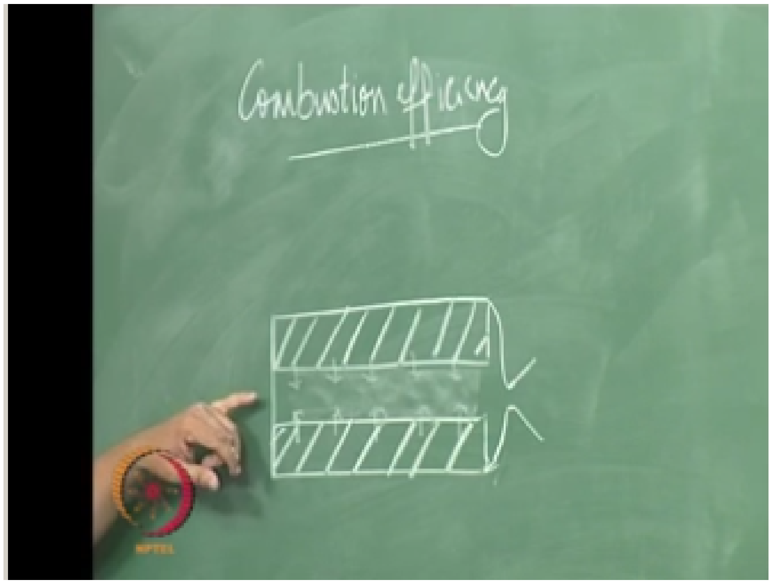

So as a consequence the combustion efficiencies are quite low so therefore whatever isp is that you get from theoretical calculations only a fraction of it you can get so there are efforts to ensure that this combustion efficiency is also higher so as such if you look at the hybrid rockets as a whole.

There seems to be a whole lot of problems associated with it which is why it has not been used till now and in a sense if you look at it a little differently it also is an opportunity for doing research in that area simply because it has very good features if you can somehow Taylor some of these problems I mean if you can overcome.

These problems by tailoring the fuel or some other means then you can have a system that can have very good ISP and also is very safe which would be something that you would require if you are planning to have you know missions where in men or on board some of these rockets safety becomes a very, very critical issue then right so for such missions it is probably a viable option and therefore there is a lot of interest in this area thank you.

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