Indian Institute of Technology Madras
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Aerospace Propulsion
Hybrid Rocket- Basics

Lecture 39

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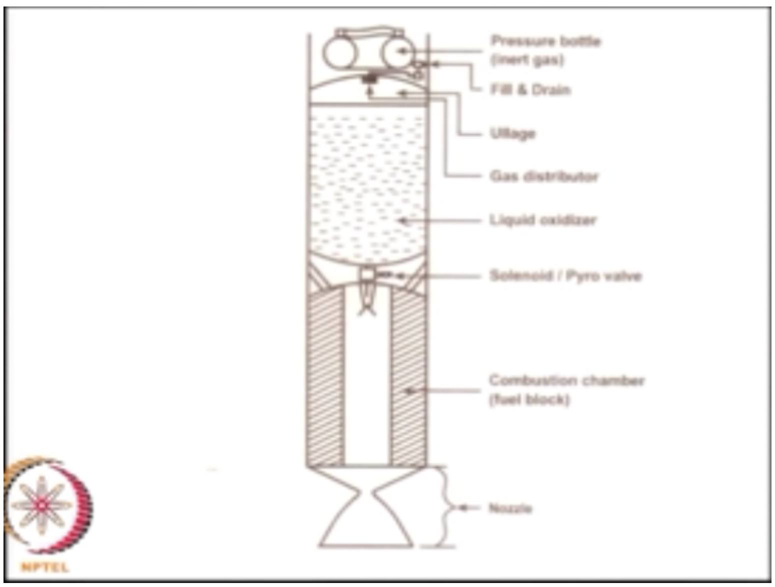

The last class we had discussed about solids and liquids rocket engines let us firstly summarize what are the various features of solids and how do they compare with liquids before we move on to hybrid rocket image.

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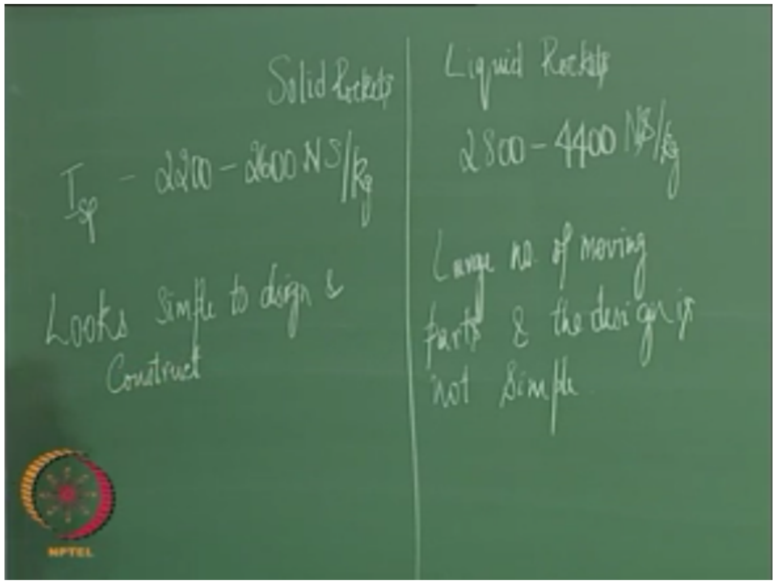

So if we take one of the key features that is different between a solid rocket and a liquid rocket is that if you look at the performance that is, ISP, ISP of solid Rockets varies between something like 2200 to 2608 this is at sea level what about liquids? That is for liquid oxygen liquid hydrogen but if you are looking at earth storable it starts somewhere at around 2,800 to something like 4400.

One of the reasons why this happens is as I said earlier that if you look at solid Rockets solid Rockets you need to have the fuel and oxidizer in close proximity and that is a serious constraint in the choice of what you can use as fuel and what you can use the oxidizer but whereas in a liquid rocket you store them in separate chambers and only inject them into the combustion chamber when require.

So that gives you the freedom to choose good liquid and a good fuel and a good oxidizer which is why you will find that specific impulse of liquid rocket engines are much higher now if you noticed the liquid rocket engine as such was a very complicated design it had a lot of valves moving parts right if you are using a pump set system then it has turbo pumps turbines everything there.

So the design is not very simple and we also said that it requires a lot of manufacturing probabilities to make a liquid rocket motor because you need to have various manufacturing abilities like drilling very small holes and then removing the bolts and other things which is sometimes not very easy so whereas if you look at a solid rocket motor all that you have is once you load the fuel and oxidizer the design looks very, very simple right.

So the other advantage in a sense of a solid rocket over liquid rocket engine is the following that if you look at a solid rocket engine or a solid rocket motor we discussed about this that the density impulse is quite high right because primarily you are using high density solids to make up this and therefore the density of this will be a density of the propellants themselves will be very high and consequently the density specific impulse will be higher or what it would indicate is also that if the density specific impulse is higher than the volume is much smaller right.

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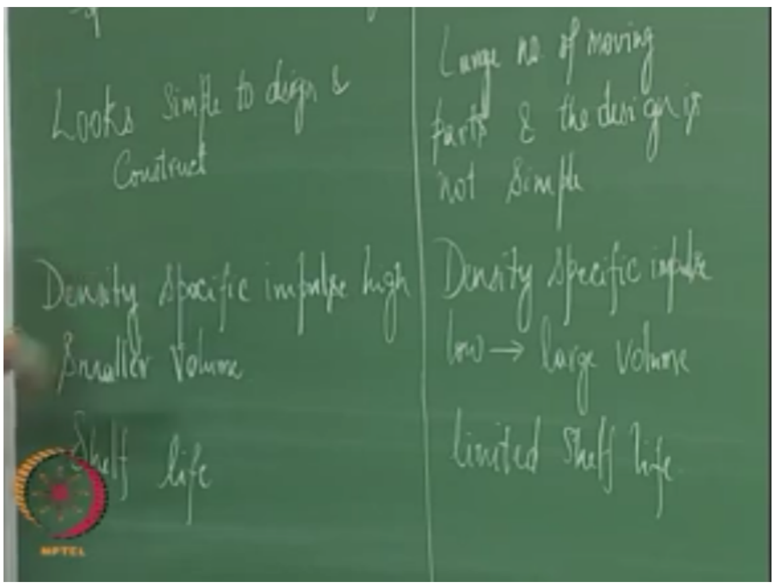

Now if you look at a liquid rocket engine and especially if you look at liquid hydrogen liquid oxygen systems for example the space shuttle if you look at the space shuttle the tank that is there on the backside of the orbiter that entire tank a large part of the volume of that tank is occupied by the liquid hydrogen tank simply because the liquid hydrogen density is very, very low and it is of the or it is around 70 kg per meter cube.

So you would require a very large volume for this so as a consequence its density impulses lower who does large volume others large volume contribute to a bad if you look at if its operation its operation in the atmosphere then the drag will be very high right then if you look at the solid rocket solid Rockets have what is known as shelf life that is you can make them and store them for a few years typically of the order of 10 to 15 years okay.

Because of this feature it is used predominantly in the defense industry simply because you will not know when to when you would require to use it and therefore it is better to make them and keep them so that you can use as in when required whereas if you look at a liquid rocket motor although your liquid rocket engine although the specific impulse is much higher you will still have to it does have some kind of shelf life but you cannot show them for such long time so typically what you will do is you will load this propellants as and when needed right so it has as a consequence it has very limited shelf life.

And therefore you will find liquid rockets hardly used in defense industry whereas it, it is predominantly used in the launch vehicle industry now if you look at liquid rocket engines we said that this is simple to design and construct and all that there is a flip side to this the flip side is if it is very simple then your controllability will also be very poor right if everything is simple then that is the price that you pay for it.

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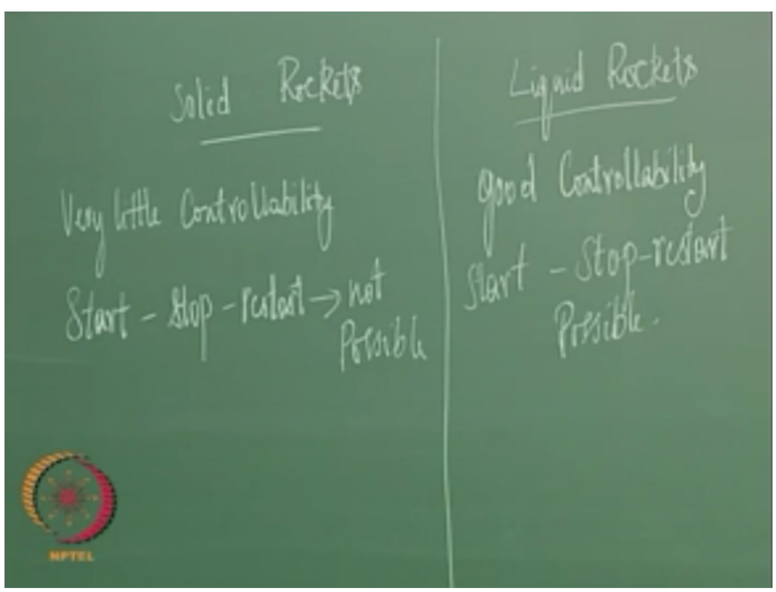

So as a consequence you will find that the solid Rockets have very little control ability that is once you start it, it is in some sense very, very difficult to switch it off okay so the start, start stop restart feature is not there in a solid rocket motor whereas if you look at a liquid rocket motor because the liquids are either fed into the combustion chamber through a pressure fit system or a turbo pump fed system you have the ability to control their flow rates or stop their flow and therefore you can have start stop and restart with liquid rocket engines.

Now in addition to this changes in the thrust level that is throttling of the thrust is not possible in solid Rockets it, it is certain through a design itself that is online you cannot change its thrust there is a set design and it will follow that particular set design whereas in liquids you can throttle the thrust by altering the flow rate of the of fuel and oxidizer the other thing about solid rocket says because you have them stored in the same chamber right.

There is a risk of either a fire or an explosion any time during manufacturing or storage transportation or even during operation the chances of it going wrong is very, very high so therefore it is not such a safe system you such a risk is not that when you look at a liquid rocket engine simply because the fuel and oxidizer are stored in separate chambers right they are only introduced into the combustion chamber during operation.

So in addition to this if you look at the solid rocket motor we this we discuss this in detail that it is burning rate is a strong function of pressure right so the burn rate is dependent on pressure and therefore any fluctuations in pressure kind of feeds back end is very, very disastrous can have very disastrous consequences.

Now if you look at liquid rocket engines we discussed this that even the engine portion needs cooling right whereas in a solid it is automatically taken care if, if the configuration is a port burning configuration because the propellant itself prevents the heat from reaching the walls of the combustion chamber.

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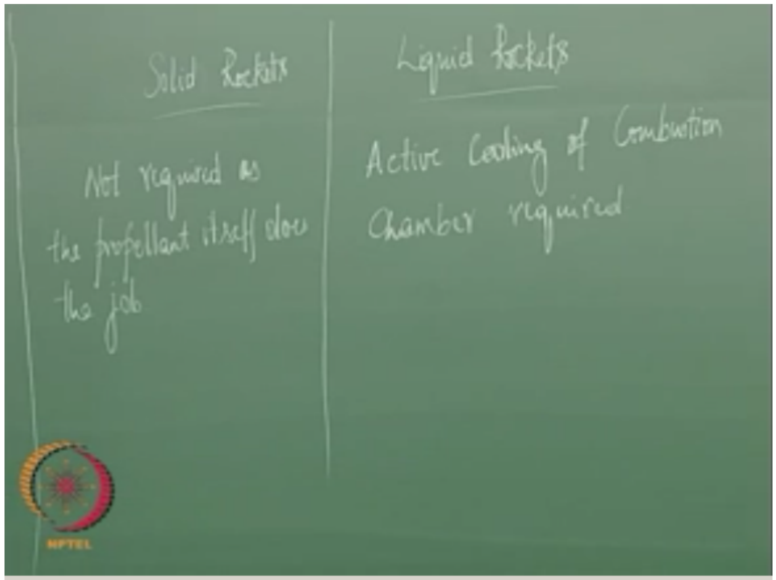

So whereas if you look at solid rocket motors as I said earlier because of the way in which it is designed the propellant itself acts as a inhibitor or an insulator sorry in this case right it does not allow the heat to be transferred to the walls of the combustion chamber okay now these are some of the advantages and disadvantages of or comparison of solid rockets vs. liquid rockets so these came in first and then people thought looking at it is it possible to have a hybrid of these two systems and which is what is essentially a hybrid rocket system.

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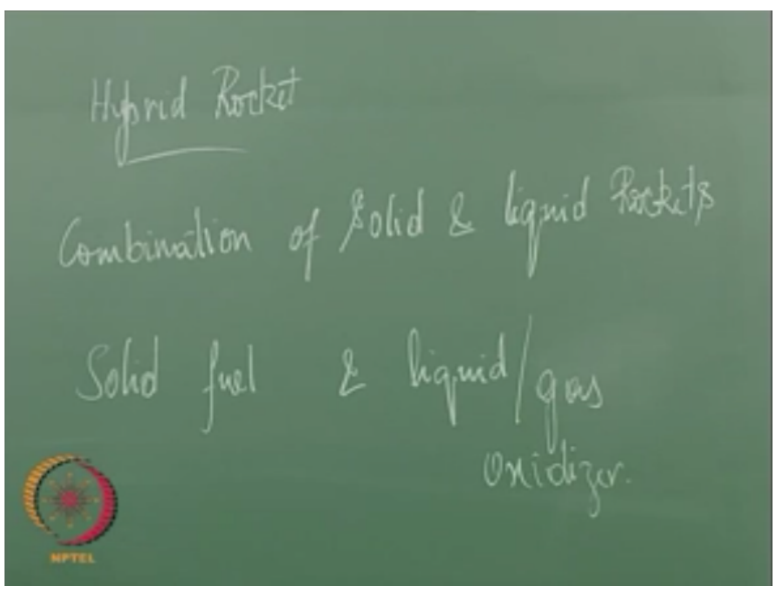

So here typically you will you can have either a solid fuel or a liquid fuel or a solid oxide or a liquid oxidizer but what is typically used as a liquid oxidizer and a solid feel simply because if you look at all the oxidizers that are known to us they are crystalline solids so it is very difficult to make a propellant grain with very good mechanical properties with these solid oxidizers with solid oxidizes.

So therefore in a any hybrid rocket system you will find that the fewer less solid whereas oxidizer is liquid this can also be in some cases and gas so liquid or solid liquid or gaseous oxidizer if you look at a typical hybrid rocket system it is as shown in this figure here.

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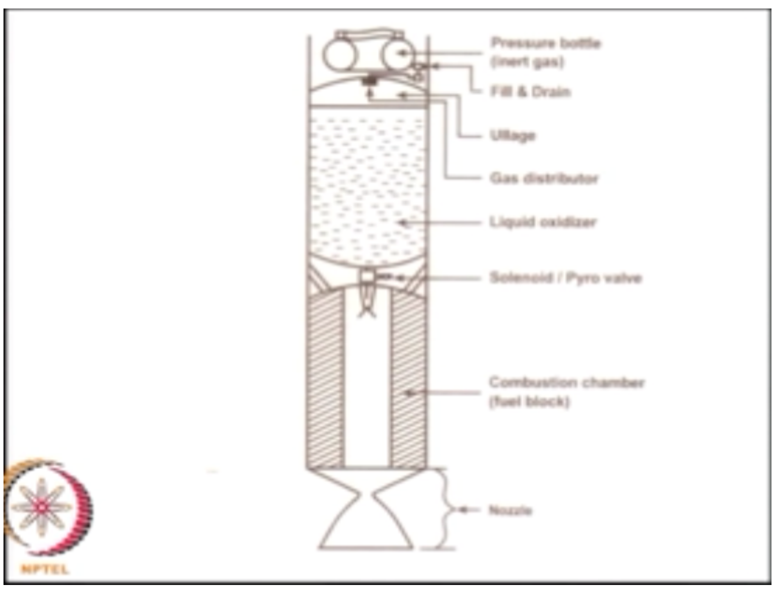

As I said it is a combination of both the solid rocket as well as a liquid rocket and the fuel here is solid and the port of this fuel acts as the combustion chamber right and the liquid is stored separately and is either fed through a pressure effect system or a turbo pump effect system depending on the thrust level and the time of operation so in a sense this combines the features of both solid rockets and liquid rockets in some cases you need to have an igniter system here so as to ignite the combination and then the combustion will take place.

There are designs which are hyperbolic that is if you use N_2O_4 and certain compositions of solid fuel you can have a hyperbolic combination so the design of this if you look at now how what are the advantages of this hybrid system right if you look at this design this design looks fairly simple right because if you look at it you are only handling one liquid line right whereas in a typical liquid rocket engine you had to liquid lines and that has been substituted with one liquid line here.

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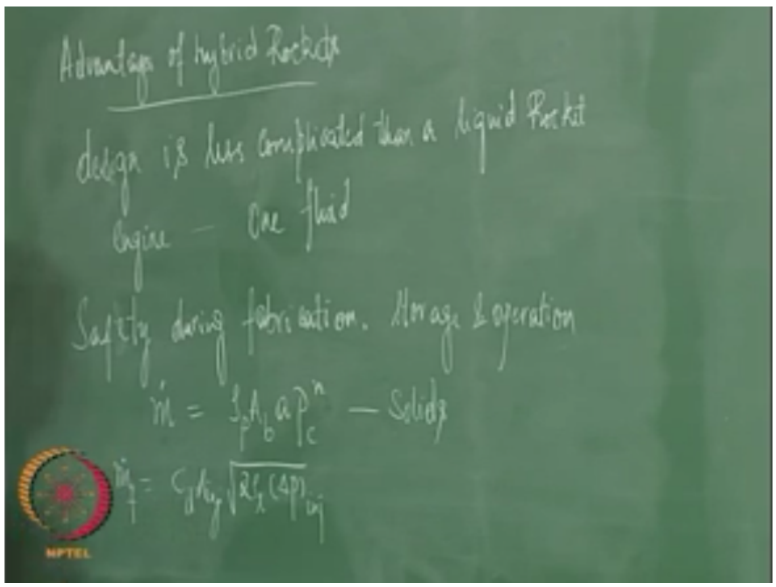

So the complexity has been reduced by half so let us look at what are the other advantages of the hybrid systems so in essence if you look at it its complexity of design is in between that of a hybrid solid and a liquid it is design is less liquid rocket engine because you are dealing with only one fluid so the number of valves pressure regulators I other things are reduced by half so in that sense the design is less complicated when you look at it as compared to a liquid rocket motor with the biggest advantage of a solid rocket as compared to problem hybrid rockets as compared to solid rockets is its safety.

If you look at why this happens we are saying safety even during fabrication storage and operation if you look at the how the mass flow rate is generated in solids liquids and hybrids if you look at solids firstly the mass flow rate m dot it is given by ρ Pab AC to the power of n so it is sensitive to the pressure as I had already said and they discuss this that if n is high the chances of explosion are much larger because the pressure gets amplified do too if there are changes to the burning surface area or other parameters then the pressure gets amplified.

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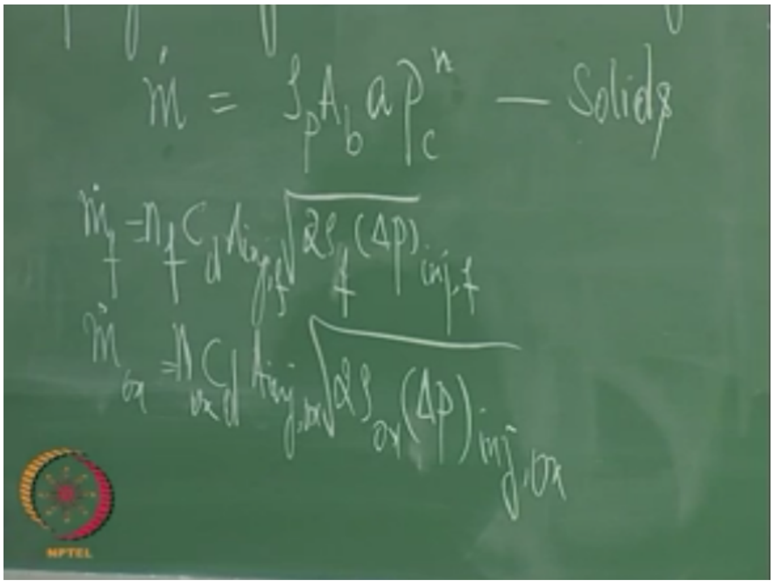

Because pc goes as 1/1- n so therefore if you look at solids this is how the masses mass is generated and if you look at liquids, liquids the m dot is given as a CD a injector this is mass of injector so mass of fuel so I will put this S and similarly you will have oxidizer also the N here indicates the number of injectors okay.

So this is how the mass is generated now if you look at what happens in a hybrid as I said earlier it is a mixture of these two so the oxidizer mass flow rate follows a similar thing whereas fuel will follow something similar to this but as I said the safety comes in because of something known as a boundary layer combustion right.

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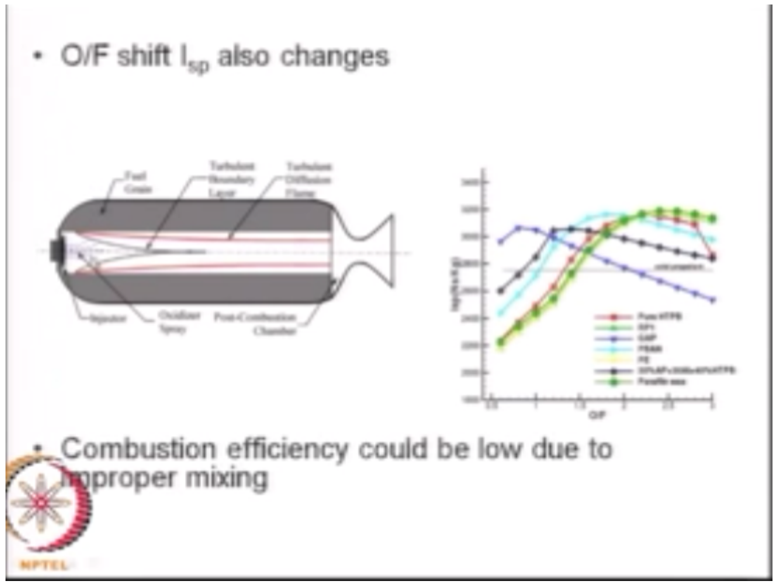

If you look at the oxidizer the oxidizer is injected like this in the port right the fuel is here and once you ignite it the oxidizer gets vaporized okay and there is a boundary layer that is formed fine the boundary layer is indicated by this black line here now once the boundary layer forms then what happens is the oxidizer diffuses in and the fuel comes out they mix and combust along this red line so the combustion is essentially diffusion dominated right what is it that we have learnt about diffusion combustion.

We had said earlier that if the combustion is a purely diffusion dominated then the pressure index is 0 right so it is independent of pressure and that is a very big advantage in terms of hybrid rocket safety and okay.

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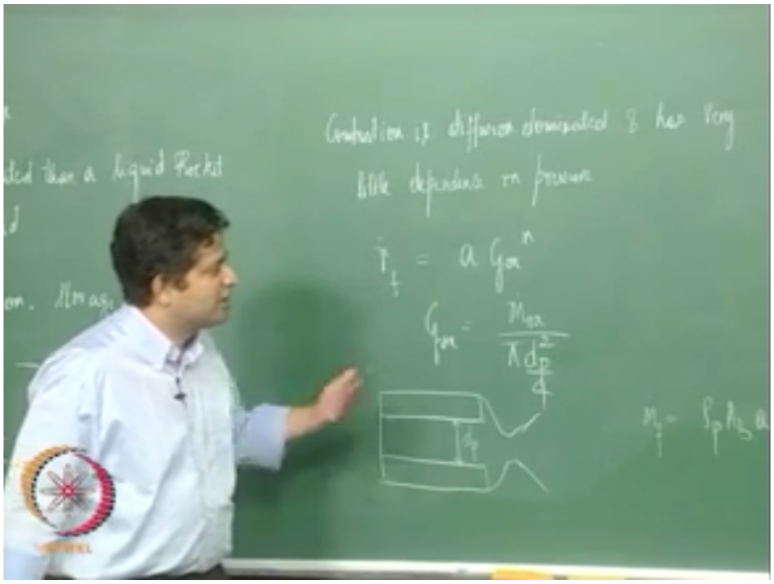

Now if you look at how the mass is generated in a hybrid rocket it is the fuel mass that I am talking about oxidizer is according to the relationship that we already have but if you look at the fuel mass it is still ρ PA BR dot but the burn rate here is given as whereas where g 0 x is nothing but mass flow rate of mass flux of oxidizer so if you have a hybrid rocket motor like this with this being DP or the pore diameter and m dot ox being the oxidizer flow rate the burn rate is a function of the mass flux of the oxidizer this is something similar to what we discussed earlier in terms of erosive burning of solid Rockets.

If you remember they are all so we said as you go from the head end to the nozzle and the Reynolds number keeps increasing the boundary layer thins and therefore you could have erosive burning the phenomena is very similar here too right it is a strong function of the thickness of the boundary layer and the boundary layer is dependent on the mass flux so that is why we have such a relationship.

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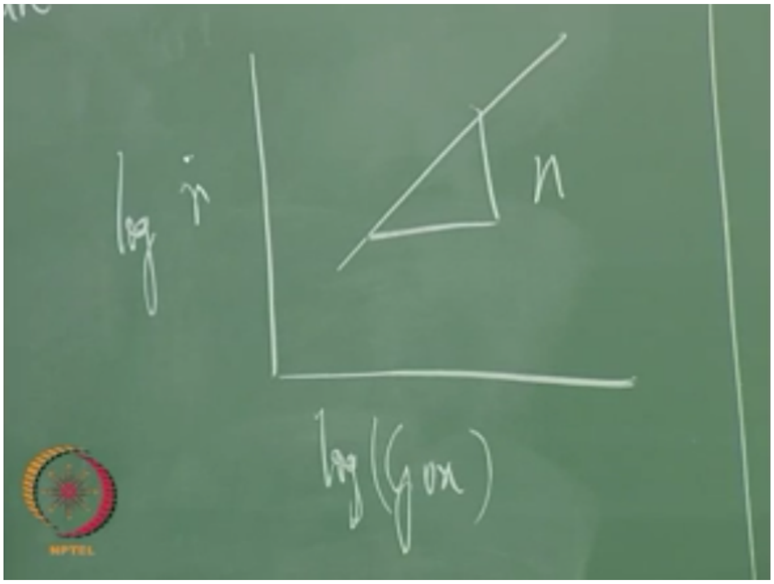

So the overall mass burn rate m dot shell in this case would be now a is nothing but justice and solid Rockets we had a there which we said is the burn rate at unit pressure this is also the burn rate at unit mass flux okay so what is typically done is we plot r dot vs 0 x on a log-log scale therefore if you on a log-log scale if you get a straight line then the slope of that straight line will give you n okay.

That is what you will get here they are very similar to what we had in solid Rockets so safety is one feature then the reduction in complexity is the other then if you look at it you can have start stop restart like a liquid rocket simply because you have one liquid right if you let the liquid flow you can start and then if you stop it you can stop the motor.

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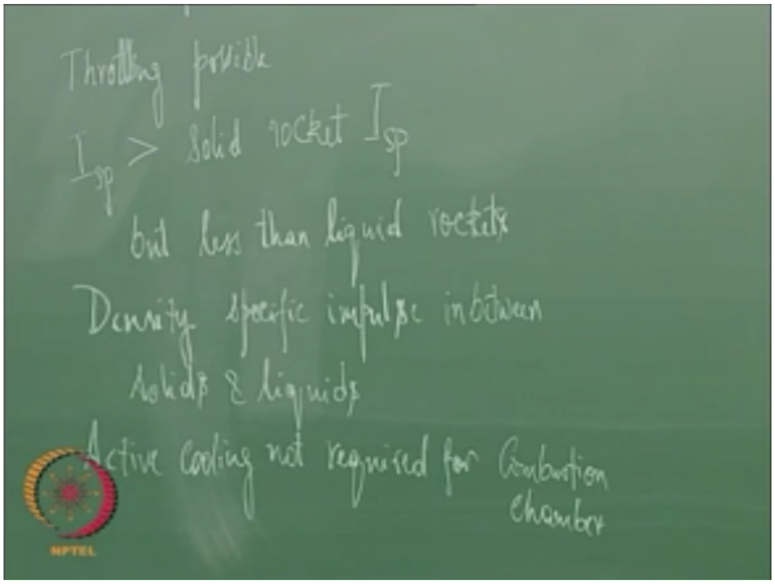

So then throttling is also possible in this case simply because you can vary the flow rate of the liquid and therefore you can get variation in there are something like a variation from eight is to 1 okay if you look at the specific impulse of these systems in some this is something similar to what you have in liquids right you can store fuel and oxidizer separately so therefore you will find that it is possible to get a higher specific impulse compared to a solid rocket but the specific impulse is lower than a liquid rocket then again the density impulse is something in between solids and liquids because you are using the fewer less solid.

So and if you look at this in comparison to a liquid in a liquid we said you need active cooling of the combustion chamber here because you have a fuel block that acts as an insulation between the combustion chamber and the motor casing so you do not need any kind of active cooling so the major advantage in this case in addition to safety is the cost if you look at solid Rockets because you need to have a certain set of mechanical properties and also you need to have them in close proximity you have to in some sense engineer fuels or binders the hydroxyl terminated polybutylene is one such chemical okay.

So you cannot use any kind of polymer and therefore if you look at it the costs of having a solid rocket motor would be very, very high and also if you look at solid rocket motors you need to have very elaborate procedure to check for cracks and other things because if the propellant has cracks then it is a very serious problem in solid Rockets so you have to kind of cast them in segments so that even if one segment goes bad you can replace it which again at two costs and then you have to have after you have done everything.

You have to have a non-destructive evaluation of the entire rocket motor which is again going to be expensive in the case of hybrids even if you have cracks it is not going to be detrimental simply because the burning rate does not depend on pressure whereas in a solid it used to depend on pressure and pressure used to be very sensitive to changes in burning surface area so that kind of coupling is not there in hybrids and therefore it is very safe and in addition it is very much cheaper compared to both liquids and solids in the case of liquids.

If you look at it the regenerative cooling right and the kind of care that one needed to have in designing the injectors all that is taken away to a great extent here you are only injecting one liquid so you do not need to impinge one on the other right and all those problems are taken away so the manifold ting is a lot more simpler because you are only dealing with one liquid so in that sense the cost of this is much lower than either solids or liquids.

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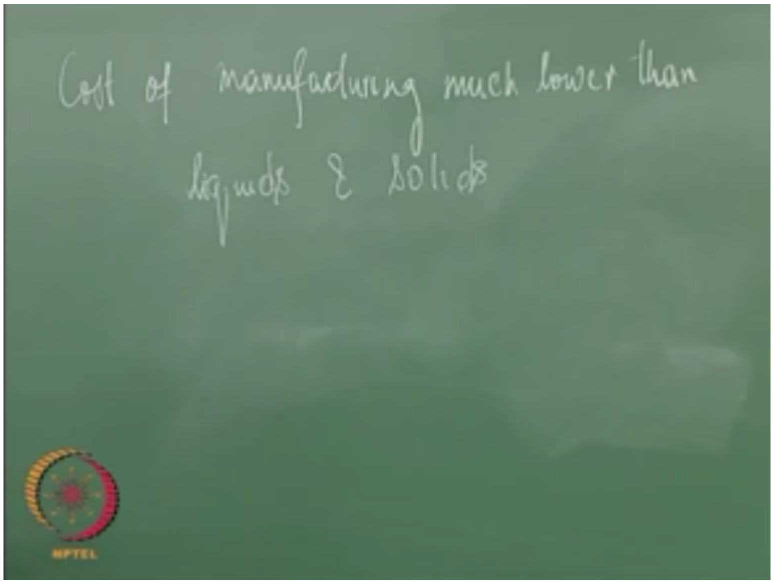

One of the other things is that if you look at it you are looking at a fuel any kind of polymeric material is good enough to be a fear so that is the reason why you can kind of choose any kind of polymer rubber right polyethylene all these things you can use and therefore the cause of it is very much less if you look at Soyuz rocket motor right Soyuz has the distinction of being this launch vehicle that has had many, many flights more than thousand flights okay.

And the reason that it is chosen as one of the vehicles to transport people from Earth to the space station is because it uses predominantly a liquid oxygen and liquid kerosene system if you look at a liquid kerosene system liquid oxygen liquid kerosene system the cost of it is much cheaper than any other system and that is one of the other advantages with so you so therefore it has been used very frequently for transportation of men and material to space station that is a liquid engine and I said the hybrids are even further advantage because if you look at any kind of polymer and a kerosene the costs are very similar right.

The kerosene use there is not something that is available it is an aviation grade kerosene because you have to take out sulfur there right the sulfur content has to be reduced very much otherwise it can be a very corrosive thing so the cause of hydrates can be even lower than what you have in liquid rocket engines okay so that is these are the advantages of liquids I have been kind of telling you things that make you think that you know hybrids of such a phenomenal advantage over solids and liquids now if you turn back and ask has it ever been used for I either in a launch vehicle or a missile the answer is no okay.

Now you might be wondering why are you know fast engineers so dumb they do not see these kind of advantages that we are see but the fact is there are a lot of disadvantages with hybrid systems which we are going to discuss in the next class which make it something like not usable current if you look at hybrids the only kind of application that it has had till date is that it has been used on spaceship one right do you know what a spaceship one the one this was the X and sorry price there was an price that was there for taking man to suborbital flight and bringing them back.

And repeating the mission within 15 days okay so any anybody who does that would have got the price the designer who got this was somebody known as Burt Rotan and the vehicle was a ship on they use the a gas turbine engine to take it to a certain altitude and Mach number something like point 8 Mach number beyond which this system that went to suborbital flight was dropped and then it worked as a hybrid rocket motor and then went up stayed there and then came back.

Now if you look at it, it is strictly speaking not a perfect mission if you look at launch vehicles and missiles at the end of the thrusting phase you need to have a particular velocity increment and a particular altitude achieved and the kind of tolerances that are there are very, very small in this case there was no such thing just had to go to a suborbital flight and come back even if it went five kilometers higher or four kilometers higher it did not matter and even if it had not the required velocity then matter either so if you look at it, it has not been strictly used in any kind of mission so in the next class we will discuss it what are the disadvantages, disadvantages this has which is preventing it from being used in any application thank you.

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