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Aerospace Propulsion
Liquid Rocket – Nozzle Cooling III

Lecture 34

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In the last few classes we have seen or the different cooling techniques namely the film cooling radiative cooling and regenerative cooling, these are primarily used in liquid rocket engines where you have liquid or if you look at radiation cooling it is primarily for satellite applications. Now let us look at how we cool a solid rocket motor okay you should look at a solid rocket motor as I said earlier the heat that is coming in to the nozzle is something that needs to be taken care of other than that, the if it is a port burning configuration the propellant itself acts as a thick insulation layer.

So you do not need to worry about cooling the thrust chamber or the entire motor but only the nozzle portion and the novel portion this is a more acute problem than in liquids because you essentially do not have any liquid on board okay and yet you need to have cooling. And let us look at water all the techniques that are available and how do they cool the solid rocket motor.

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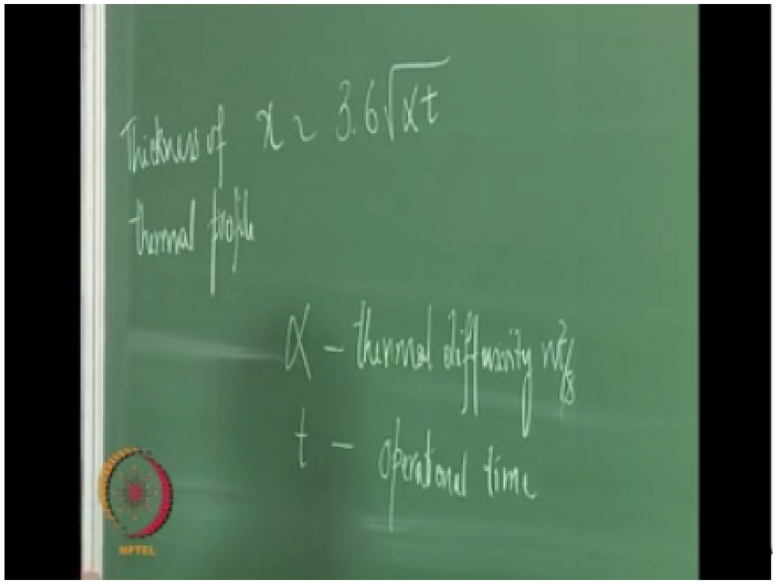

Now I remember writing this in with regards to radiative cooling also there are a few books that say radiative cooling heat sink and radiative cooling okay, because it just acts as a sink and then radiates on the other side but there is also this method that has been used to look at the throat region of a solid rocket motor. Now if you remember earlier lectures we had said that throat is a very critical region because the highest heat flux is at the root. So you need to cool it otherwise it is going to damage the throat region. Now one if could not it is to use high density graphite as shown in this figure.

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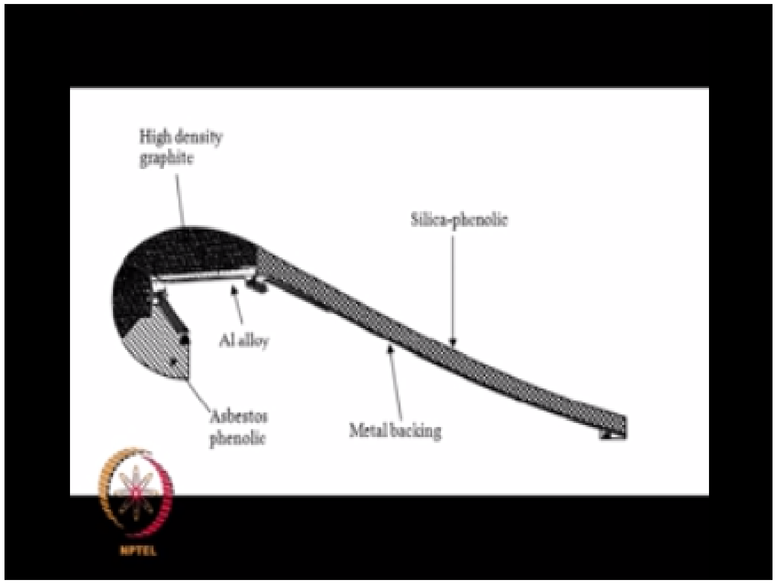

This is the throat region right and you have a high density graphite here which acts as a heat sink, now heat think is something like this if you have a particular thickness of this material and if it is a high temperature resistant material right, then if you look at how the temperature profile is for this material.

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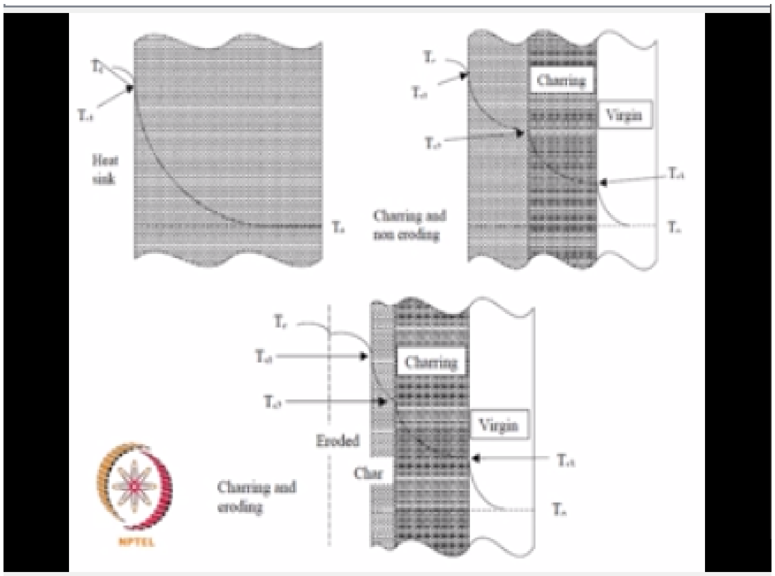

It is something like this shown in a here that is into the solid the temperature decreases and depending on the thickness this temperature is achieved right. So you need to know what is the thermal profile thickness in other words right and if you look at this figure here you see that there is high-density graphite and there is a backup material. There is some phenolic asbestos phenol and also a metal back up. As such are the graphite can take high temperatures but not high pressures you cannot use it to make the motor casing itself right.

So you need a metal that and this could with stand high temperatures and could be used about the metal portion, so what we need to know is how thick should be have this graphite to do that if you remember this is a problem of unsteady heat conduction okay and you can solve this and the thickness is given as thickness of the thermal profile is given as we are α where α is nothing but thermal diffusivity, that is in meters^2 per second and T_S operational time right. So depending on the on these two you will get a thickness right. It also depends on if you look at this figure here.

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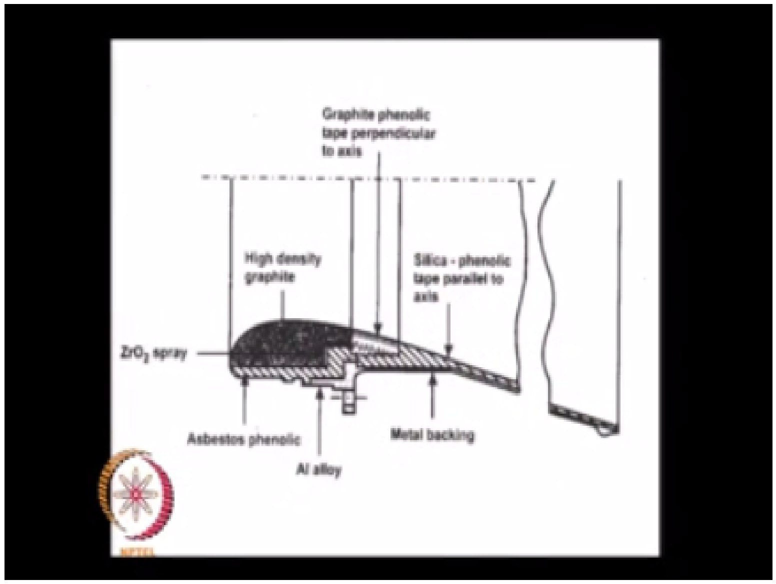

It also depends on what is the allowable T_0 you can have on the other side right on the other side.

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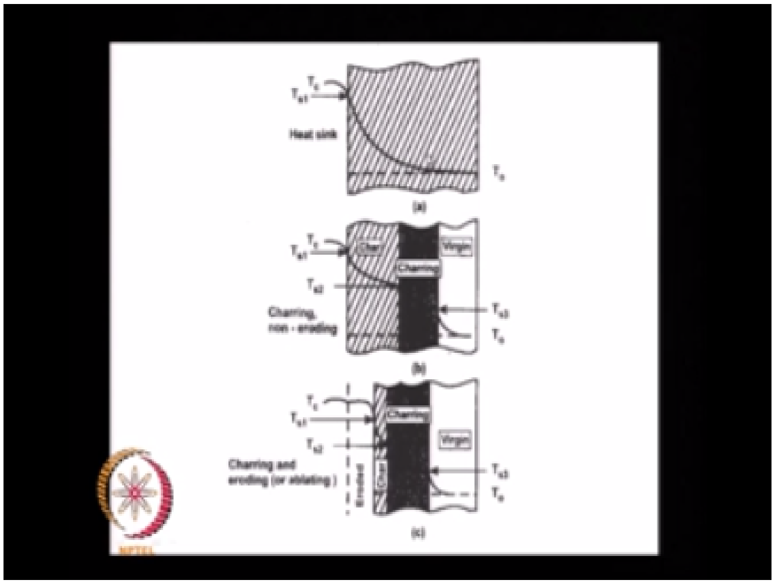

I remember I said there is either going to be a metal or asbestos phenol, so what is that temperature that you are looking to have on the other side is what determines what is this thickness going to be okay. So depending on that you can choose the thickness of this throat region with high density graphite. The next technique that has been used this ablative cooling okay.

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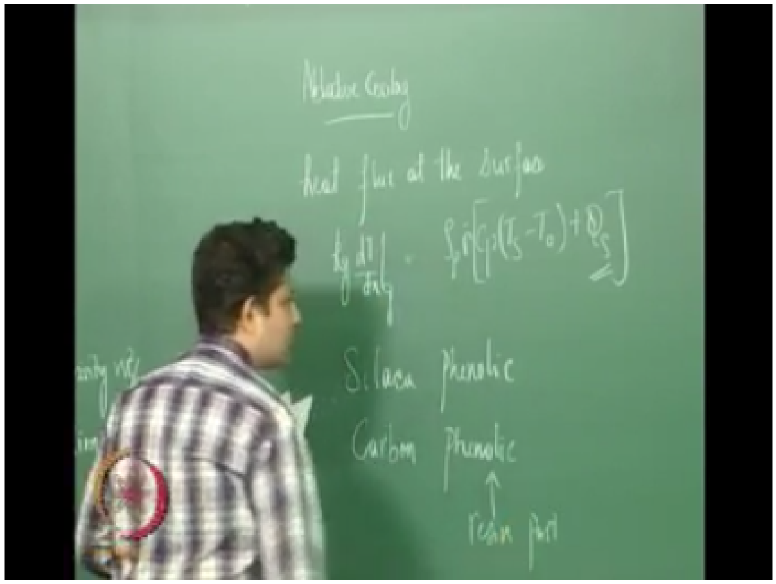

Now ablative material as such is a material that consists of two different terms things one is it has a base material and a resin okay. Now if you remember our discussions about solid propellant and how heat is transmitted in the solid right, we have the this equation for the heat flux at the surface, that is right now if you are looking at this ablative cooling what happens here is there is this resin portion that vaporizes, so it absorbs heat to change its state from solid to a gas phase. As this heat is absorbed it cools the rest of the material and there are two kinds of heat-resistant.

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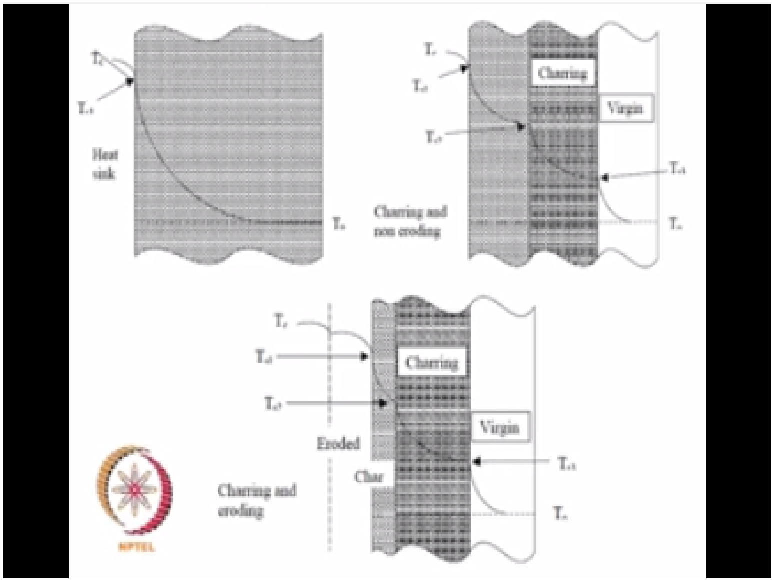

Ablative cooling techniques that are available one is charring and non eroding as shown herein B and the other one is charring and eroding where ablating are the basic difference here is in this case starring and monitoring it forms a chart but the char as you see here even in a flow cross flow this gate does not get eroded it stays as is okay. So the if you look at how the heat is going to be transferred there is a new material that in a sense you are going to have which is going to resist the heat transfer right.

You have now when you started out you would have had only two materials one is the virgin material and the other one is the charring material as time progresses you are going to have three layers with the char layer increasing and the Virgin decreasing okay, which means that you can see here very well that the temperature the file through this decreases any other side you can have a very low temperature. So the essential idea here is to have a hike us as possible right, then if you have a hike you hire Qsr yeah no matter what your T_S is going to be.

If you have a high us then this T_0 is going to be lower and more, so if you have different layers of this material right and the next set of materials that is used is the charring and eroding or ablative material, in this case because of cross flow the material gets eroded and you are going to have a region with cha you are going to have a region with job which is if this were the nozzle earlier indicated by the dotted line then that portion is going to move in this new light right. So the area is thinking right, so area is increasing and therefore the gas phase if you see is coming here as the charring portion moves into the virgin material.

It still has three layers as in the other case but the thickness of the char layer is very small here okay and the charring layer is the same thickness and the virgin material after that, so with this you can have a lower temperature T_0 at the other end right well this is in some sense the same idea which people used to burn camphor on their hand right you seen that people can hold comfort on their hand and have it burning and do the right essentially what they do is comforted burns.

So the temperature profile in the camphor will be something like this right, so you will have a fast-burning here and because of which are the on the other side the temperatures are really lower until the flame comes and hits the other portion but what they usually do is they will have a layer of oil right. So that protects their hand at the time when the flame reaches the other end and if that is a very short time it will go off without any major damage to the hand, so in a in a way one good way to protect the material is to have something burn off right in that sense it is taking away all the heat and that is what happens even inside a rocket motor as well as in ablative cooling.

The materials used for this silica phenolic and carbon phenolic this is the resin part which upon heating absorbs, the heat and evaporates so combination of if you look back at this picture here if you look at this picture here this is the conversion person doing the throat and this is the divergent person this is the axis. So we have shown only one side of the axis now if you see here the highest heat transfer is near the throat which is protected by two layers one is high-density graphite and then fit layer of phenolic resin.

And after which the heat transfer coefficient reduces as you move towards the exit, so therefore you can use some kind of ablative material to cool it right. So using a combination of both ablative material and heat sink a solid rocket motor protests or the nozzle is cool this is the same cooling technique that can be used in a hybrid rocket also primarily because hybrid rocket as we will discuss a little later we will have a fuel and it is also poured burning configuration. So the fuel itself protects eight in the combustion chamber and only the nozzle needs to be cooled which can be cooled using this kind of technique okay.

So we have discussed the various cooling techniques that can be used to cool both the nozzles and the first chamber, now let us look at what are the penalties and where do we use what kind of cooling if you look at the different kinds of cooling.

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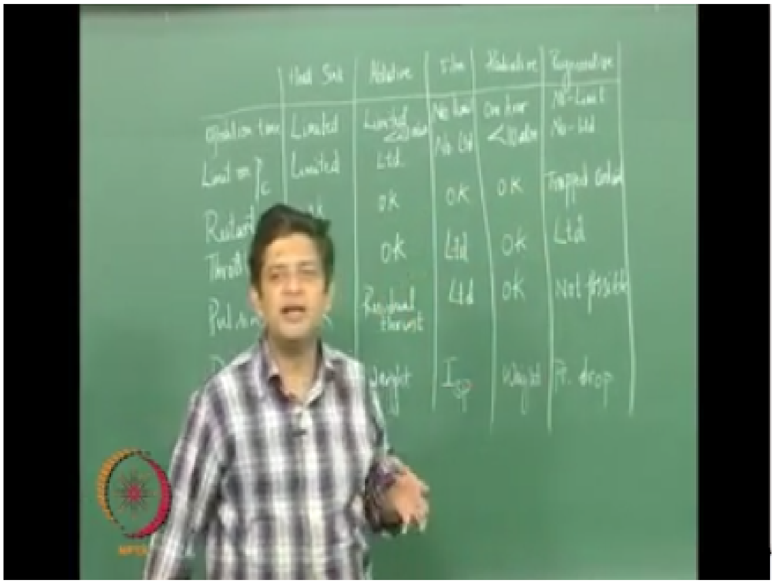

One was heat sink then ablative and film cooling radiative and lastly we had regenerated okay, now various considerations that we need to keep in mind this one is operation time then the limit on P_C remember when I when we discuss the equations and how we can rewrite the heat transfer equation in terms of pressure right. Using M. = P_C 80 by C * we found that if you go to higher pressures then the heat transfer coefficient will be higher. So in essence there is a limit on the chamber pressure and restart throttling pulsing and what are the penalties with this kind of cooling.

Firstly regarding the operation time if you look at the heat sink if you are given a particular thickness of the material that you have to you can use there is a upper limit on the time that which you can allow it for operation okay, because if you look at a steady state then the steady state would be at if it is a large fan then the actual chamber temperature will reach the other side also if you are giving it a very large stack and if you are not taking out heat on the other side. So in a sense the operation time is limited if we use a heat sink and same is the case for ablative cooling.

Here it is less than 20 minutes and then you have film cooling film cooling if you look at it you are constantly pushing out some liquid on the periphery therefore there is no limit as long as you have the liquid on board you can keep doing this and are there is no limit to the time you operational or time and this should be the same for regenerative cooling also, what about radiative cooling you think it is going to have some kind of limit, it should have a limit because it is also in some sense a heat sink and then on the other side you have radiation taking away the heat.

So this is something like typically one are now limit on P_C heats ink obviously cannot be unlimited, so this is again limited this is also limited this would have no limit as long as you have the coolant on board this is all, so new limit this is restricted to something like less than 10 atmospheres. So if you look at the radiative cooling it is only applicable we are in it the operational time was also not very large but the thrust of the motor is also very small.

Now there are a few things that are possible only with a liquid rocket engine that is restart throttling and pulsing throttling is you can change the trust level okay by adjusting, the flow rate of the liquid pulsing is as we had discussed earlier with reference to monopropellant thrusters if you look at the thrust versus time curve, if you have something like this, so there are a short pulses of thrust and there are no also times where there is no crushed. So what about heat sink can we have this with restart right.

It should be fine the only thing that will have a problem is regenerative cooling because if you look at regenerative cooling when the motors which is on the flow in the coolant pipes might not be that good because there is always some propellant that will be trapped right and that would have absorbed some heat and would have been a gas or something like that, so you need to be careful in only the regenerative cooling, so you cannot have too many restarts if you have a regenerative cooling till the time it reaches some kind of steady-state.

The flow will not be established and that might cause harm to the motor casing itself, so you need to be careful while using regenerative cooling but otherwise the rest of the things it is fine to have as many restarts then what about throttling other than these two right you are increasing, the thrust level or decreasing the thrust level again there are issues of what is the flow rate through the cooling pipes or how quickly can you take off tore through. The coolant pipes is an issue right if you are going up and thrust the coolant pipes could be having a lower flow rate and therefore it could be detrimental.

So in these two cases it is limited but otherwise for the rest of them throttling is no problem and pulsing in this case it is simply not possible and this is in some sense again limited because you have to have a flow on the surface of the chamber itself but for all others this is fine except of course ablative cooling because of let of cooling, if you look at it if you wanting to have a very sharp cut off and if you are having an ablative material that Tarzan erodes right there is some amount of gases that are going to be released.

So the crust cut off will not be as sharp and in you could have a residual thrust okay, so in this case, so let us now look at water the penalty is involved in using each of these techniques these two it is only the weight that is a penalty because depending on the time of operation you need to have a certain thickness and depending on the density of the material that you are using it adds to the weight of the system. So in both these cases weight is a penalty and in film cooling if you remember we are using one of the fluids that is a fuel or on board.

And this is not contributing a great deal towards I_{SP} right, so in a sense the penalty is here is Is_{P} right it is not contributing towards producing a thrust in that sense if you look at it you are going to operate it at a particular oh by f it is not that it does not participate in the combustion or something like that but in the chamber right, if you are wanting it to be used as a coolant you do not want it to be participating in combustion right. Ultimately it will happen but if you remember what you want to do is the length that is available is only up to the throat if it burns further beyond that it is not going to contribute towards thrust.

If the pressures and temperatures are increased beyond that is not going to contribute greatly towards thrust because we know from thermodynamics if you add heat at the highest pressure that is the one that is going to give you effectively a better efficiency right, if you are going to add things if things are going to burn later on beyond the throat portion we are not going to contribute greatly towards thrust although I am not saying this will not burn right this does but it is only a matter of Eric Byrnes it could as well burn in the atmosphere beyond the nozzle also.

So in that sense the I_{SP} the delivered Isp what I am talking about is how much of propellants you are carrying and what is the overall specific impulse that you get that will be lower than with regards to regenerative cooling or if you remember, when we talked about regenerative cooling I said the this is mainly for high thrust and long burn duration engines and I spoke of the Space Shuttle main engine with a liquid engine and there I said the chamber pressures are of the order of 200 bar right and I said somewhere in the pipeline it is going to be something of the order of 300 bar or above that.

If you look at the cooling pipes they are going to be very small right and there is an enormous pressure drop in pushing liquids at a very high rate through this small pipes, so if you are going to use regenerative cooling the penalty that you are going to pay is in terms of pressure loss pressure drop, in other words is also going to affect if you are using a turbo pump to pressurize it there is some amount of energy that is expended which is not going to impact the I_{SP} right. So in that sense it comes back to a reduction in Isp but as you as we said earlier in this method you are pumping back the heat that is lost to the walls.

So you are going to take it closer towards the adiabatic condition that we had assumed while we were deriving equations so in that sense there is gained in Isp because it is going to be adiabatic and there is some amount of loss because this something that you need to pay for the pressure rise or the pressure drop across, the cooling channels and radiative cooling as we discussed earlier I had clubbed it with heat sink because this also needs to have a certain amount of thickness right.

So again the penalty here is weight okay, so we have discussed all the cooling techniques that are used on board a rocket motor and if you look at it if you have a liquid engine regenerative cooling is probably the best method of cooling but if you look at some of these aspects you need to have a certain amount of backup or redundancy if you are restarting and if you have throttling and other things. So invariably people also tend to use film cooling to back it up or dragged redundancy into the system, so as to have a safer margin although it is not.

So efficient film cooling has been used and will continue to be used because it gives you that little bit extra that you can do even after designing everything right, even after you design the motor everything is done you still have that margin to play around with because you have this film cooling, so if we look at a picture where in what are the regimes that each one of them is going to be used in it is going to be something like this.

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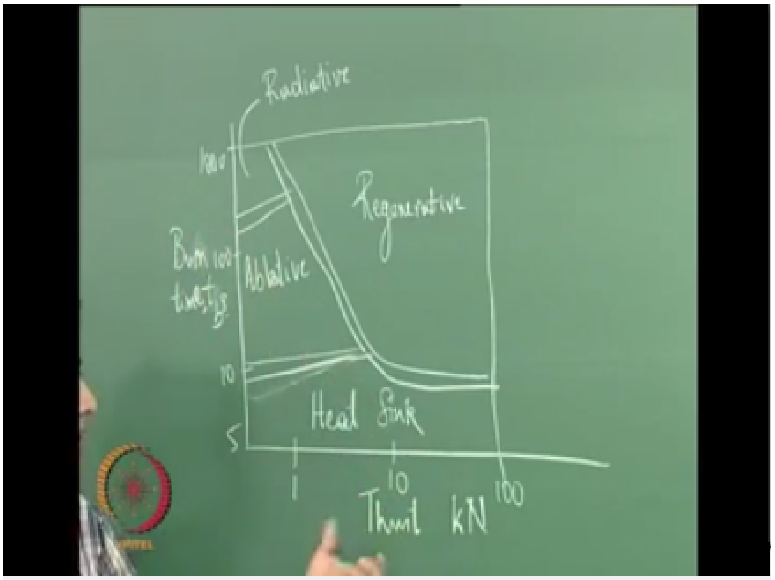

So if you have burned time on the y-axis in seconds and this is on a low note scale and thrust also on a log scale, so you can divide this into various regions if you see that you have a smaller burn tank and whatever thrust level that you want to have it is possible to use heat sink but as the burn time increases you also need to back it up with ablative cooling and for a very low thrust and large burnt it is better to use radiative cooling and the region for high thrust and high bond time it is regenerative cooling.

And have not indicated where film cooling is as I said if you are using a liquid engine it can be used everywhere in this domain, it is to add some kind of redundancy and therefore can be used all across the domain okay. So this completes our discussions on the various cooling techniques to cool the rocket motor nozzles. Now let us look at a we are discussing about a liquid rocket motor and we know that it has to have a feed system either it is going to be pressure fed or turbo pump it let us try and look at the design of the feed system. So firstly let us look at the pressure fed systems.

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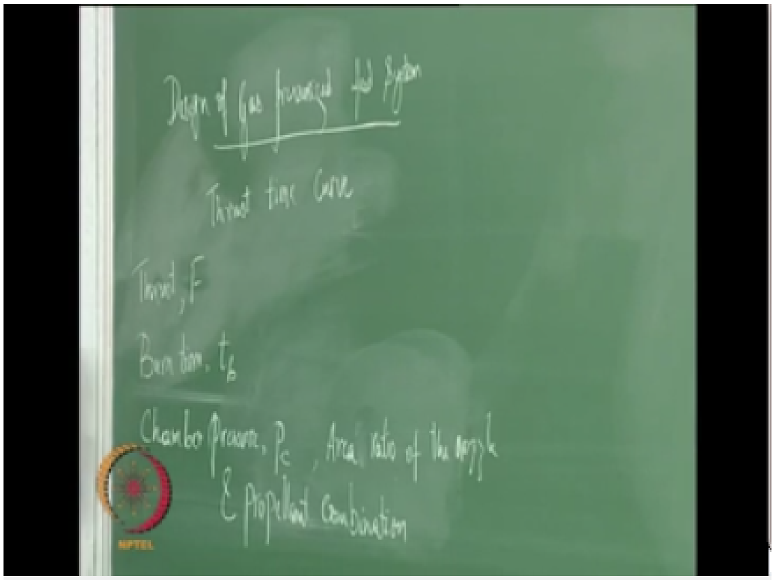

If you look at the figure of a pressure fed system here if you look at this figure.

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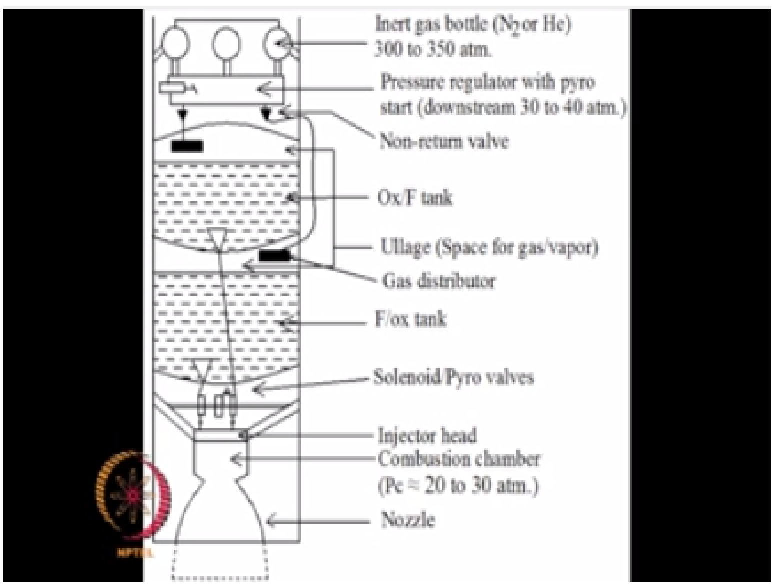

What we are essentially going to do is if you are given see when we are asked to design the pressure fig system what we are going to do is try and design this size of the gas bottle what is the size of the gas bottle, that we need to carry and at what pressure, so as to have a chamber pressure of certain value okay fine and for a burn time. So essentially you will be given for doing this going about doing this you will be given firstly the thrust time curve which means that you know what is the thrust F and you are also going to know what is the burn type T be right.

After knowing this let us say you are going to use some kind of propellants right if it is a buy propellant system or a monopropellant system you know what are the propellants that you are going to use and if you know the chamber pressure P_C and you also know the area ratio of the nozzle and propellant combination, so you are knowing from this propellant combination what you can get out of this is the chamber temperature and you know the area ratio and the chamber pressure and also the ambient pressure or its variation right.

So you can calculate what knowing all this you can calculate the specific impulse of the motor right, so at the end of this you will get to know what is the specific impulse if you know the specific impulse and if you know the thrust what can you calculate mass flow rate through the motor because, we know that M. is nothing but if x is P so you can calculate what is the M. and after knowing what is the M. you can get depending on the ratio of fuel a ratio of oxidizer to fuel ratio right.

You know the overall mass flow rate and the you know the ratio of fuel oxidizer that is let me call this as S, so okay then you can calculate the individual mass flow rates of oxidizer and fuel right. So if you can calculate the individual flow rates of oxidizer and fuel and then you also will know the density of these materials right, so you can get volume flow rate of oxidizer and fear and now you know the burn time.

So you can calculate the overall volume of the fuel and oxidizer that you will meet for the particular mission right but is that going to be enough if you just do this calculation and carry that much of liquid on board right you will know the burn time, so you carry based on this whatever is the volume of the liquid is that going to be sufficient for your fulfilling the mission no right what kind of losses, yes if you look at any kind of feed system there is some amount of fluid that you might not be able to expel out of the tank itself.

And obviously there is going to be some kind of fluid depending on what kind of cooling you have if you have regenerative cooling then a larger fraction of the coolant is going to be trapped in the pipes okay. So that is not going to be useful so you need to carry a slightly higher volume than what you get from this typically of the order of two to three percent extra so if you then estimate what is the volume it is going to be two to 3% higher than this volume.

So now you know what is the volume of the fluids you need to carry in addition to what we discussed if you look at, if you are using cryogenic propellants like liquid oxygen and liquid hydrogen after you store it in the tank right and keep the vehicle ready for takeoff as it continues with its operations because of the temperature difference, there is going to be some amount of boiling of this propellants right. So these are not going to be useful because it is already going to become a gas and therefore it is not going to be useful.

So you have to account for that also while calculating the overall volume that is required okay, so once you calculate all this taking into account all this you are going to calculate some volume now if you look at this design here you are not going to fill the tanks completely because then there will be no space for the pressure in to act, so you are going to have a small amount of volume that is left unfilled through which the pressure and can act right.

So if we were to design what is the pressure on how much is the amount of pressure and we need to calculate a carry on board we need to know the volume flow rate and from the volume flow rate calculate, the overall volume then account for losses like boiling and some coolant trapped in the pipes and also you want to have a small extra volume known as eulogy all you m, so if you account for all this and then you know what is the tank volume right.

Now this tank has to be filled at some pressure by the pressuring system at the end of burning if you look at it, so the pressure inside the tank should be the same as what we started out in the beginning if you are not doing any thrust variation. So you need to take into account what is the volume of the tank and what pressure it is going to be stored at it then and then calculate what is the volume you need to have and that will help you sighs the pressure and tack.

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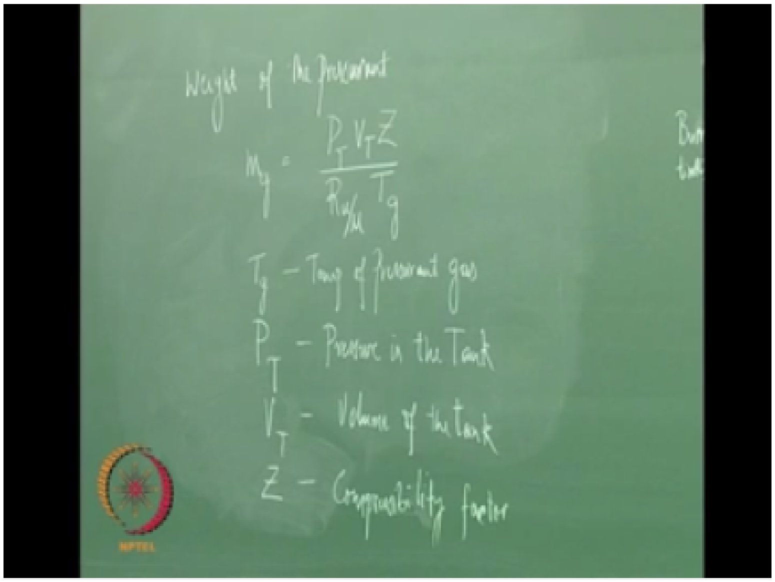

So if you look at the doing that so the weight of the pressure include Dmg is equal to this is given by ideal gas law x a compressibility factor, now this T_G is the temperature of the pressure and gas then P_T is the V_T is the volume of the tank and Zv you. So using this you can calculate what is the mass of the pressure okay, we will continue with this in the next class thank you.

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