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Aerospace Propulsion
Solid Rockets – Igniter, Depressurization

Lecture 29

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Good morning, in the last class we had derived the expression for the unsteady variation of pressure and the rocket motor right, we had considered the mass balance in the rocket motor to derive this equation. In this class let us look at how we can use that to predict what is the time required for ignition what is the time required for extinction okay, till now we had looked at only the steady part that is the burning in the steady portion right. This class let us look at the other two unsteady portions that is namely ignition and extinction.

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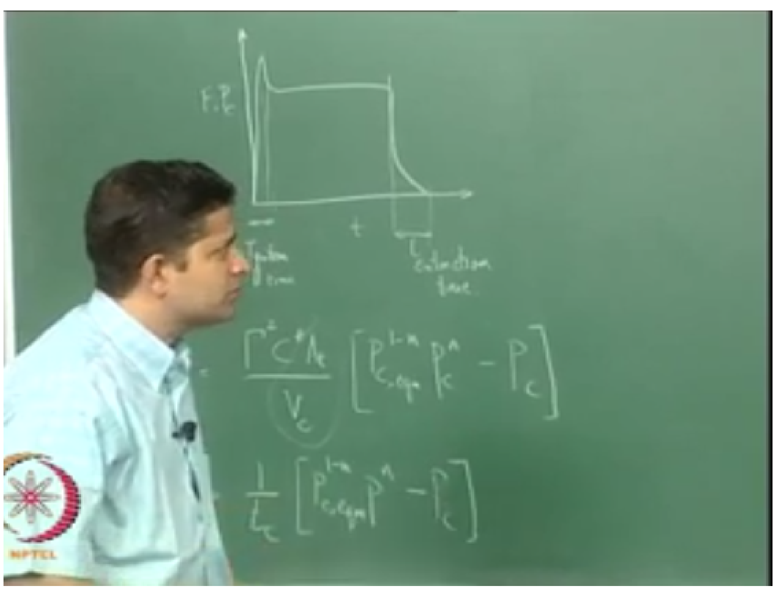

If you look at a typical thrust time curve or a pressure time curve this is ignition time and this is extinction time. Now in this class let us try and use the relations that we had obtained in the last class to find out how these vary okay, if you remember we had derived the equation for pressure variation as, if let us say the motor is operating at the equilibrium pressure itself let us say it is operating somewhere here.

Then this Pc this Pc is a time variant term okay, there is not an equilibrium quantity this Pc will also be equal to the equilibrium Pc and as a consequence these get cancelled out and you will get this dPc/dt as 0 okay, so in this equation we had identified the Vc/At as L* and this entire term as 1/Pc right, one by characteristic span so we can write this as. Now let us see how to use this to get what is the time required for ignition okay, and what is the time for extinction.

Before we go there we should understand this that why is this important in a rocket motor okay, ignition delay let us say if it is a very longtime then also it is a problem, it is a very short time then you can have a very high pressure burst in the beginning and then therefore affect the structure okay, you could actually burst the motor in that.

So either of the two is not what we want we want to operate it in a very narrow window typically even in a large motor the ignition should be over within 100 milliseconds, 100 milliseconds is it time that we are looking for. So let us try and derive the expression for the ignition time, now during ignition if you look at this portion this is a very small time as I said it is less than 100 milliseconds, right.

So if you are looking at that kind of a time scale one can make this assumption that the chamber volume and the burning surface area and C* do not change in this period okay, Vc is chamber volume Vc changes only because of burning in 100 milliseconds it does not burn too much so Vc and ab will be nearly the same and C* if we assume we will assume constant.

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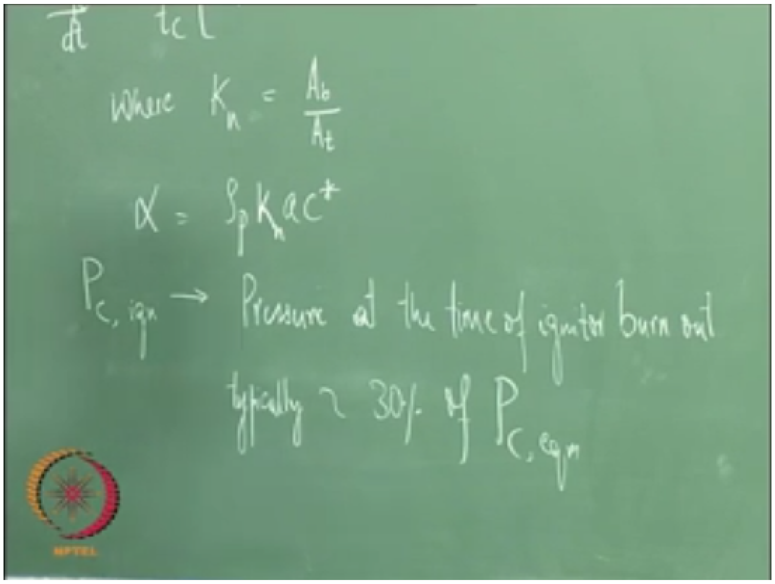

I can write this term Pc equilibrium 1-n as follows, where Kn=Ab/At I should also add here the throat area also does not change with time in this case right. During the initial phase of ignition so very small time and we are not looking at hundreds of seconds so, the burnings the throat area also does not change. So in this case Kn will be also constant this entire term is a constant and I can absorb it as α.

I will call α= ρp Knac*, so if I want to find the time for ignition all that I need to do is integrate this equation. Now the limits of integration need to be identified okay, typically the igniter is supposed to give something like 30% of the pressurized let us say this is this equilibrium pressure as 100 bar the igniter should give something like 30 bar on its own, okay so around 20% of equilibrium pressure.

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So if we integrate this we will get tign =∫ okay, this is the 1/tc into this sorry, tc into this, this is the equation that we need to solve and α we have identified what it is, so now we need to play a little bit of jugglery here if you look at the denominator we can express this as let us say $x=Pc^{1-n}$ okay, then what will be dx, dx will be $1–nPc^{-n}dPc$ this equation I can rewrite this as $tign=tcPc^{-n}$ dPc then I will be left with $α\text{-}vc^{1-n}$ okay.

So if I use this here there is nothing but the same equation rewritten, if I now use this substitute this here I will get I can change it to the x variable ∫xign to 2x equilibrium this is nothing but dx/1-n so I will get tc/1-n and this is α-x, okay. Now we can see that this is in the you can integrate it and get a logarithmic function.

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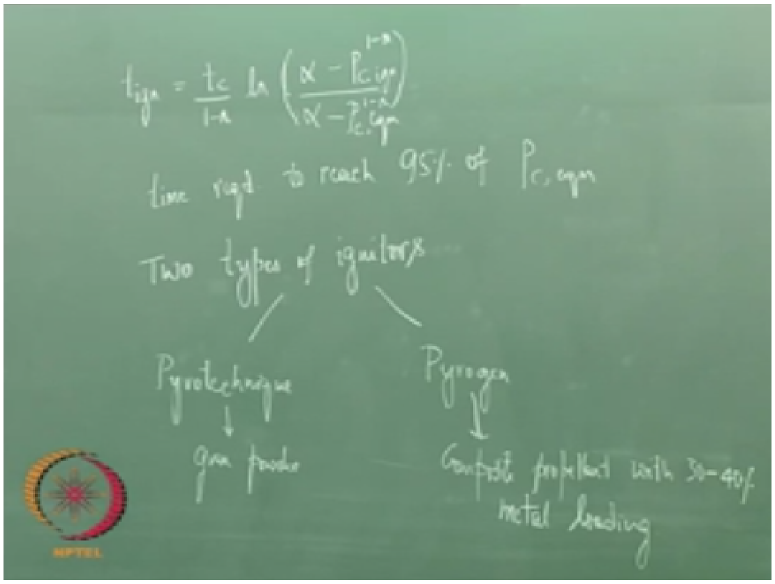

So I will get α- okay, this is the form we will get please note α is nothing but this one or this is also equal to right, α is nothing but this, this is also equal to Pc equilibrium to the power of 1-n. Now if you put that back in this equation here you will find that the denominator is going to 0 or the time will go to ∞ okay, so you cannot have infinite ignition time. So therefore what is usually done is we try to reach something like 95% of the equilibrium pressure what is the time so we calculate time required to and that will give us a realistic ignition time, okay.

So this is how we calculate ignition time, now if we want to look at what are the kinds of igniters that are used in the industry yes, I said 30% of the pressurize will have to be given by the igniter itself, pressurization is done by the igniter itself if you have the Gemma volume 30% of that initial pressurize has to be given by the igniter itself and the igniter burn sit should fill that volume up to the pressure of typically something like 30%.

So it usually starts from somewhere here so we are looking at this rise only okay, now let us look at what are the kinds of igniters that are available okay, there are two kinds of igniters one is called as pyrotechnic and pyrogen. Typically the pyrotechnique igniter is based on gun powder it is a derivative of the gun powder and this is nothing but a composite propellant with 30 to 40% metal loading.

If you remember when we discussed about composite propellants we said it has typically 18% of metal loading here the metal loading is increased to something like 30 to 40% so that the way this operates is it is not only the hot gases that come out but also the hot metal particulate matter they go and embed themselves on the solid propellant and they start a local ignition process okay.

So that is why you have a larger fraction of metal content in these propellants and usually they have very high burn rates. If you look at very small motors then pyrotechnic is used medium sized you have a pyrogen igniter and in large solid rocket motors like PSLV stage 1 etcetera what you use is you have this pyrogen igniter moving on rails from the head end to the nozzle end so as to ignite the entire motor, okay. Now if you look at what happens when the igniter is switched on.

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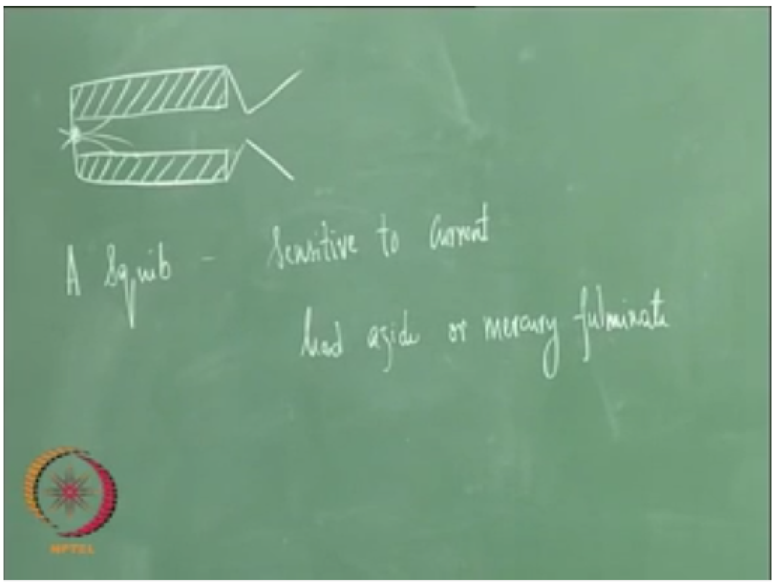

If you look at a rocket motor the igniter is placed at the head end okay, and as I said it also has particles that go and embed themselves on the propellant when these particles embed themselves on the propellant they cause local ignition in addition to that there is a hot gas flow in the chamber, okay. So both of this lead to ignition and if you look at the igniter, igniter will have something known as both the kinds of igniter will have something called as quib which is made of this is sensitive to current and is usually made from lead, azide or mercury fulminate, okay.

So when the current is supplied this is sensitive to that this starts to burn and then ignites the rest of the igniter and then this igniter will then ignite the rest of the motor, okay. As I said if you look at a motor like this we said that the ignition time needs to be even for a large motor less than 100 milliseconds right, and I said in the beginning that if we let us say do not do this in the 100 milliseconds then what happens if there is a slower ignition. Then we could get into combustion instability.

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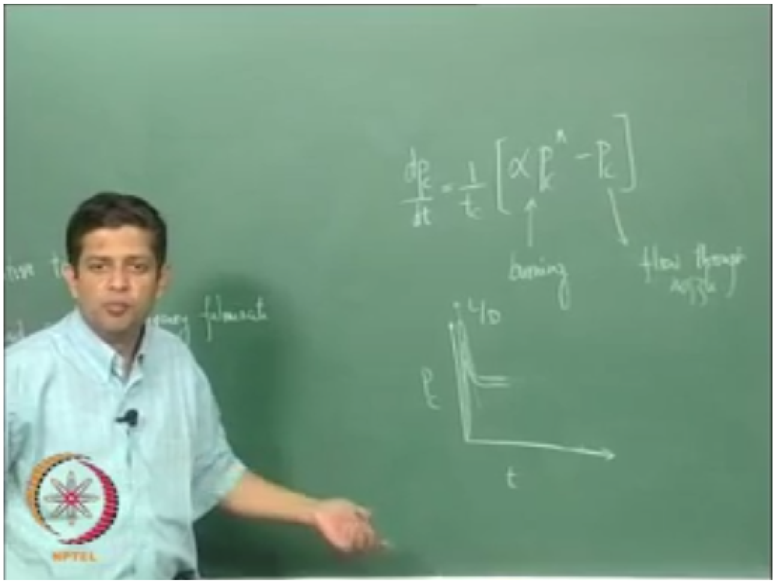

Could set in I am sorry, one minute I said this has to be completed within 100 milliseconds now let us say we have a certain igniter mass right, if we put on the required igniter mass we can achieve this within a narrow man. Let us say we put something more than what we should have put okay, then what happens there are two things firstly if you look at the motor of this kind a port motor if you have a very large l/d right.

If you have this length of the motor 2 I will consider this diameter as important or not the overall diameter primarily because this will be the port it gases that are generated here, if you remember this equation that we had derived dPc/dt=1/tcα this minus portion what does it do to this is because of flow going out through the nozzle this portion is because of burning right, mass addition due to burning and this is because of.

Now what happens it takes time for this to occur right, the length is especially large length to diameter is very large then it takes a longer and longer time for the flow to go out and therefore if you look at this equation the term that is contributing in a negative signs is not going to set in for a long time. As a consequence you will have in terms of pressure versus time let us not worry about this portion this is going to increase in this direction with increase in L/D right.

Because it is going to take a longer time for the gases to go out and therefore the pressure keeps on rising and this pressure overshoot will become higher and higher and at some point could be detrimental to the motor. In some cases of large L/D motors this is known to be one of the modes of failure of motors.

So one needs to take care of this so as to provide ignition such that this does not happen also okay, the other trouble is with regards to ignition if you look at this figure this is of a simple port yes. No, I am only looking at this it depends on the volume two but if you have the same volume and if you have a long pipe right, if you have a stubbier volume the same one and a long pipe then if you look at both of them this is what you will find right that is what I pointed it up.

This is also in some sense similar to if you have a tank overhead tank if you have a very long pipeline the changes at the other end will be felt after a long time right, so that is the reverse problem that is happening here right. Coming back I was talking about this motor here if you look at the trouble with ignition this is a very simple motor right we have a cylindrical green.

But usually we talked about this earlier if you want to get the required thrust time curves in the motor then the grain has to be either a star grain or a finna cell or something else, right which means that you are going to have cuts here and cuts here and you have to ensure that the hot gases or particulate matter flows into all this crevices and ignites the entire motor in the very short time that is available which is not very easy actually okay.

So and in addition let us say due to some reason we do not supply the pressure that is required by the igniter let us say we fall short then it is known to go into an instability mode if you do not supply the required pressure then it goes into the instability mode so either if you give it more pressure you could have a hard start like what we talked about or if you give it a lower ignition it could go into instability mode.

So we need to have the right amount of ignition energy so as to provide typically something like 30%of the initial pressurized as well as provide a smooth ignition. Now we can calculate what is the amount of igniter required based on this formula.

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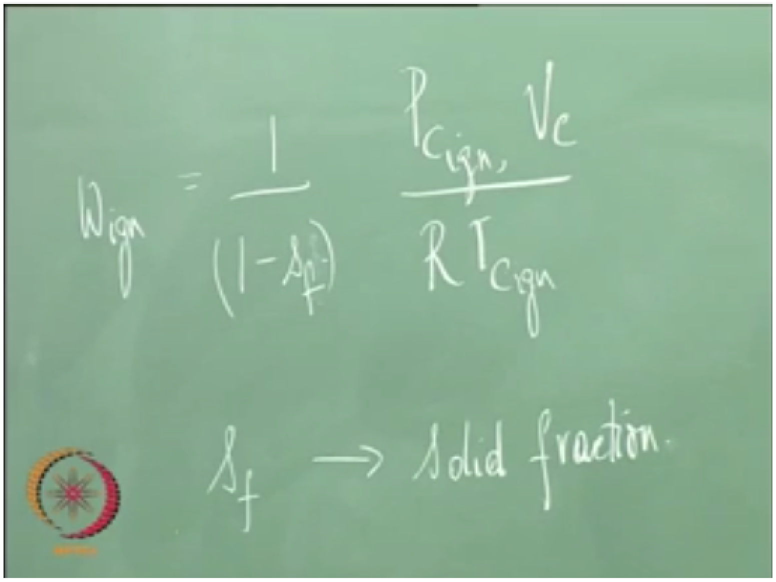

The Nitro mass is given by 1- sf Pc ignition now if you look at this relationship the sf stands for solid fraction it is assumed here that the solid fraction does not give rise to the pressure right, so you have to count that out and then you will get the pressurized that we are looking for this has to be typically 30%of the equilibrium pressure this is the chamber volume and this is ignition the temperature at the end of ignition, okay.

So using this we can calculate what is the amount of igniter that needs to be carried so as to get a good ignition. Now let us look at the other end of the spectrum that is the extinction part okay, we have looked at the ignition part the other end of the unsteady process is the extinction let us look at that now.

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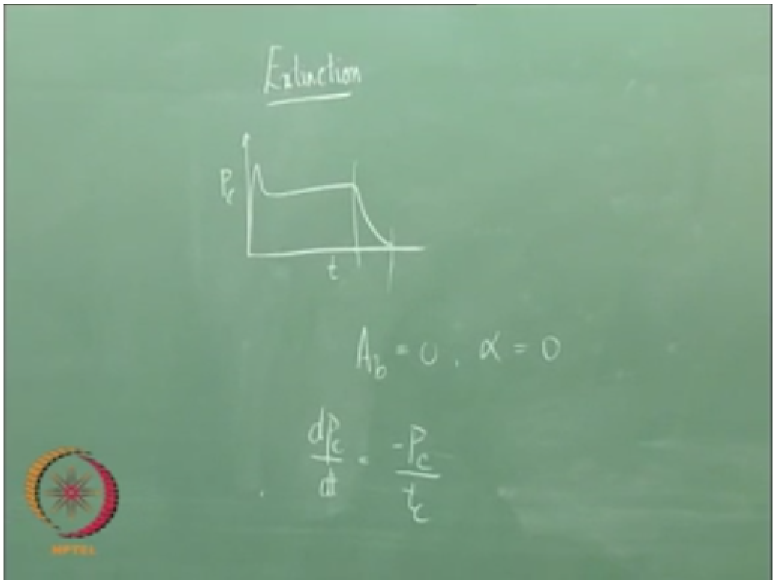

If you remember when we discussed about the burning of the web and other things we discuss something known as libel laws and I said this is something called unburned propellant okay, now let us find out why certain portions of the propellant do not burn and stay like that although it was burning up to sometime and suddenly why does it quench itself.

Now if you look at a missile or a launch vehicle both of these have the objective of placing its payload at a particular orbit with a particular velocity right. So as I said earlier that it is more so with missiles than with launch vehicles the temperature varies from place to place as well as day and night okay, and as a consequence the burn rate also varies.

Now with all this you still have to place it into the orbit at a given velocity and at a given altitude which means that if you could have in some sense a possibility of cutting of the thrust then it would be a lot more easier, it is very easy in liquid rockets that is you just stop the supply of the liquids or also in hybrids one of them is a liquid so you stop the supply of the liquid you will be able to stop the combustion process.

But how does that happen in a solid is what comes under extinction, but before we do that let us find out what is the time it takes for the extinction after extinction the depressurization, right. If you look at the pressure time curve we are talking about this time okay, what is observed here is that the combustion is completed we will see why should the combustion get completed at that point a little later.

Now if the combustion is completed what happens to the burning surface area, burning surface area we can assume it as 0 ab is 0 then what happens to α in the equation that we had derived in this equation what happens to α, α is nothing but ρp Ab/At ac* if Ab goes to 0, α also goes to 0, so α=0, then if you look at this equation what do we have this term goes off and we are left with –Pc/tc . So we get the equation as now we can integrate the equation and find out what is the time so very simple.

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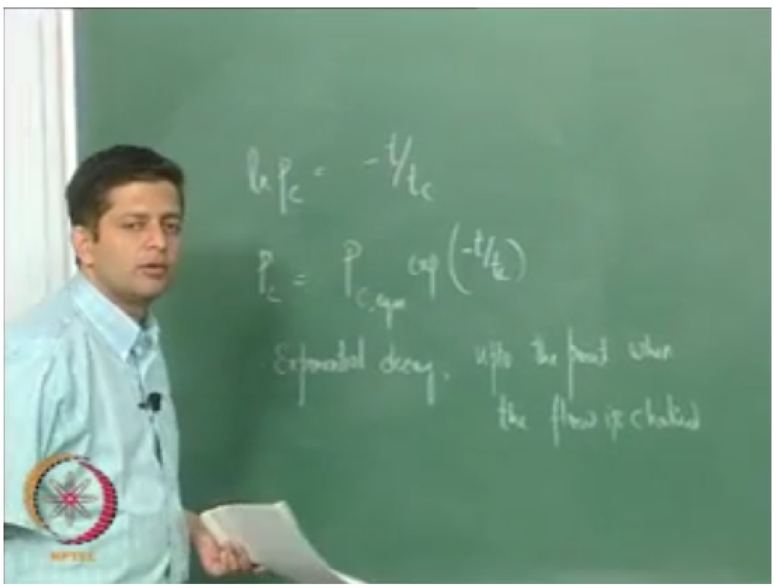

So you get ln Pc must be equal to –t/tc please remember that the tc there is a constant okay, so you will get this which means that Pc follows an exponential curve Pc we can write it as Pc equilibrium exponential of –t/tc that is the pressure here d quiz in an exponential fashion and please remember this equation is valid up to what point of this drop up to the point where the throat is choked okay.

If you remember the equation that we had is for a choke nozzle right, so this is valid upto the condition where the throat is choked, okay. Now this time is of importance because if you look at either a multi-stage launch vehicle or a multi-stage missile when you cut off the stage right, if it is still burning like this because the weight is very small it could accelerate and come back and hit the mother vehicle the remaining portion of the vehicle.

So you would not want that to happen and you would want to know what is this time in this time it can still be thrusting right, the pressure is decaying so it could still be thrusting and you do not want it to come back and hit the vehicle right. So in that sense this time is of importance now coming back to the question why should propellants quench when they are depressurized or why does it quench or why should there be a sliver loss, right. If you remember our discussions earlier we had said that.

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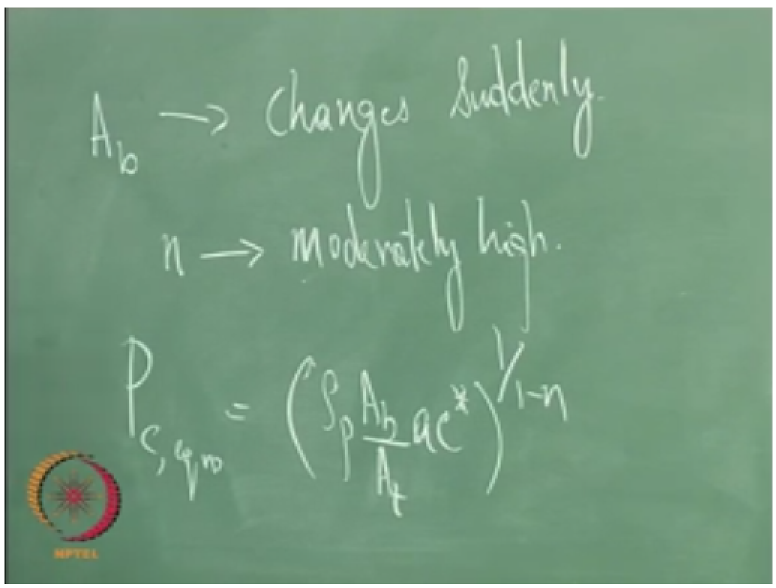

There will be some portions of the propellant that will remain unburnt if you look at the, if let us say this is the cross-sectional view of the rocket motor there will be some portions that will remain unburned. Now to ask ourselves this question why should it not burn upto this point it was burning right, and why does not it certainly or why should it suddenly stop burning. The answer lies in this fact that suddenly the burning surface area decreases.

If you look at it, it was earlier occupying the entire this entire circumference and suddenly it ceases and becomes only in some portions that you have a propellant right, so what happens the burning surface area Ab suddenly changes if Ab changes suddenly and if you have a propellant with high N or a medium N also I mean burn rate pressure index n is moderately high right, not we are not looking at 0.8 or something where even if it is 0.3 or 0.4.

What happens to the equilibrium chamber pressure when this happens when the Ab suddenly changes or it is a larger burning surface area and suddenly it decreases to a smaller burning surface area if you look at our expression for equilibrium pressure right, so if a bill changes suddenly then the pressure also changes suddenly and if Ab drops pressure drop suddenly in essence you are depressurizing the motor okay. So people who have done this experiment and try to find out what happens in this case, what happens when the motor is depressurized or when a propellant is depressurized.

This is one of the ways in which you can stop the propellant from burning further if you depressurize it prevents the burn propellant from burning or it inhibits the propellant from burning later on let us see why is this should happen.

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It is something like this let us say a propellant is this is the burn rate versus time that I have let us say a propellant is burning at some rate here suppose you depressurize it okay, then at the lower pressure which you bring it to let us say it has a burn rate something like this right, it has been known that if you do this process in a very smalltime that is if your dPc/dt is large right, then the propellant tends to quench.

If you do it very slowly it will go to this burn rate if you do it very rapidly at some point it could do this okay, if you do it further rapidly it is seen to quench like this okay. So there is a critical dPc/dt beyond which the propellant ceases to burn and people have kind of done the study wherein to find out.

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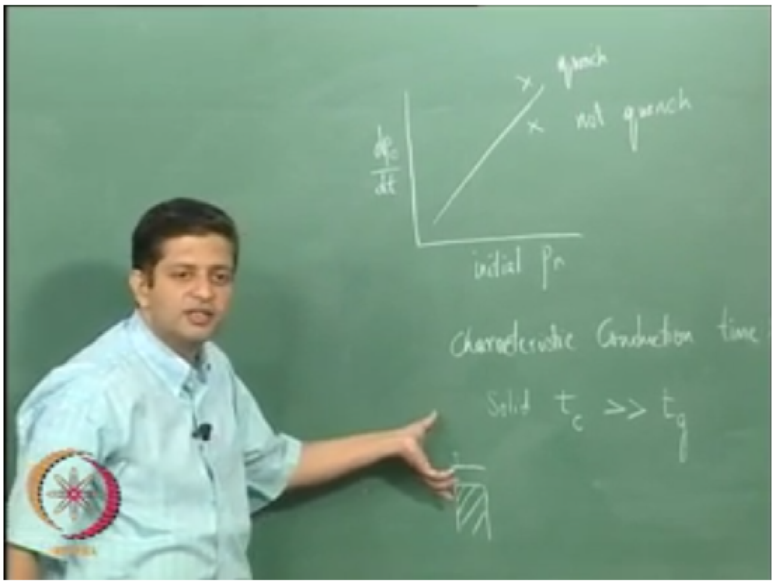

If let us say you have an initial pressure and this is the dPc/dt the curve follow something like this, if for an initial pressure somewhere here if you are using let us say this depressurization right, then it will easy quench but let us say if you are for the or it will not quench and let us say if your this is not quench and let us say you are here this will lead to quenching in a sense this line defines the boundary at which the quenching or the not quenching happens.

So this blinding defines the boundary at which quenching and no quenching takes place, so if you are above that it will quench if you are below that it will not quench, and also please remember this range is still even when there is a burning possible at that lower pressure it I snot as if we are taking it below a pressure where the propellant c is to burn right.

The answer for this is in some sense in the characteristic time of characteristic conduction time scale that is the for the solid the characteristic time scale is much, much greater than the characteristic timescale for the gas we will discuss this a little later as to why it should be for the solid it should be higher than the gas. So in a sense the gas responds very quickly to the changes whereas the solid is very, very slow and responding to changes.

Typically it is of the order of F of 100 times 1000 times one, now what happens in this case is if you have these gas respond very quickly let us say we have the situation wherein the propellant is burning in this fashion. Let us say there is a flame here, now if you depressurize this the flame tends to move up.

Because the pressures have reduced and the flame tends to move away from the surface when this happens. But the solid tends to feel that it is operating at the previous condition itself and tends to pump in more gases as a consequence you are filling in more inserts in a sense and this causes the flame to move even further away.

Whereas if you look at what happens inside the solid the solid will need more and more heat to operate at a lower and lower temperature, so in a sense you are moving away from the situation we are at the point where it was burning the solid was getting the ample heat that is required for it to continue burning you are now moving into a situation wherein it needs more heat then what is getting and the heat is also decreasing.

So in a sense you are pulling away from the stable point and therefore it tends to quench okay, that is the reason in some sense for this quenching. We will stop here and continue in the next class the next class we will discuss erosive burn, okay, thank you.

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